Developmental Science

WILEY

Developmental Science

RESEARCH ARTICLE OPEN ACCESS

Influence of Child-Level Factors and Lexical Characteristics on Vocabulary Knowledge of Children With Cochlear Implants and Hearing Aids

Emily Lund[1] | Krystal L. Werfel[2,3]

[1]Davies School of Communication Sciences and Disorders, Texas Christian University, Fort Worth, Texas, USA | [2]Center for Childhood Deafness, Language, and Learning, Boys Town National Research Hospital, Omaha, Nebraska, USA | [3]Department of Communication Sciences and Disorders, University of South Carolina, Columbia, South Carolina, USA

Correspondence: Emily Lund (e.lund@tcu.edu)

Received: 19 September 2024 | **Revised:** 13 February 2025 | **Accepted:** 15 February 2025

Funding: The work reported herein was funded by grants from NIH/NIDCD (R03DC014535 to Krystal L. Werfel; R01DC017173 to Krystal L. Werfel and Emily Lund).

Keywords: cochlear implant | deafness | lexical | word learning

ABSTRACT

Recent studies indicate children who are deaf and hard of hearing who use cochlear implants or hearing aids know fewer spoken words than their peers with typical hearing, and often those vocabularies differ in composition. To date, however, the interaction of a child's auditory profile with the lexical characteristics of words he or she knows has been minimally explored. The purpose of the present study is to evaluate how audiological history, phonological memory, and overall vocabulary knowledge interact with growth in types of spoken words known by children who are deaf and hard of hearing compared to children with typical hearing. Children with cochlear implants ($n = 36$) and hearing aids ($n = 39$) were compared to children with typical hearing ($n = 47$) at ages 4 and 6. Children participated in measures of phonological memory and vocabulary knowledge, inclusive of an experimental measure with words of varying phonotactic probability and neighborhood density. Results indicate that children with hearing aids and with cochlear implants tend to know fewer words across all lexical conditions than children with typical hearing. For children with cochlear implants, overall vocabulary knowledge was the best predictor of a mis-matched probability and density condition, whereas it was the best predictor of matched condition for children with hearing aids. Children with cochlear implants and children with hearing aids, then, appear to have different underlying skills that interact with the lexical characteristics of words to support vocabulary growth.

1 | Introduction

More than 90% of children who are deaf and hard of hearing (DHH) are born to at least one parent who uses spoken language to communicate, and the incidence of children receiving a cochlear implant has increased in the last 10 years (Mitchell and Karchmer 2004; Nassiri et al. 2023). Cochlear implants provide access to sound to children who have a severe-to-profound sensorineural loss bilaterally (per FDA recommendations, Tan et al. 2024), whereas hearing aids are typically recommended for children whose hearing loss falls in a lower range (e.g., mild to moderate-severe). The development of the auditory system,

Krystal L. Werfel began this work when affiliated with the University of South Carolina and completed it when affiliated with Boys Town National Research Hospital.

Summary

- Children who use hearing aids and cochlear implatns tend to know fewer words than children with typical hearing across all lexical conditions.
- Children across groups were more likely to know low-density rather than high-density words, and low phonotactic probability rather than high phonotactic probability words.
- Overall expressive vocabulary knowledge predicted knowledge of low-density, low-probability words for children with hearing aids and typical hearing, but not children with cochlear implants.
- Expressive vocabulary knowledge predicted knowledge of low-density, high-probability words for children with cochlear implants, which may indicate children with cochlear implants use lexical characteristics in a different way to support learning than children with typical hearing or hearing aids.

however, begins in utero and many children with a hearing loss diagnosis are not identified or aided until a later time (Moore and Linthicum Jr. 2007; Walker et al. 2017). Although some children who are DHH are born to parents who use sign language, many are not and their access to linguistic input is delayed (Hall et al. 2017). Studying the vocabulary development of children who are DHH who go on to learn spoken language, then, presents an opportunity to explore the impact of sound access and experience on spoken vocabulary development.

For children who are DHH who use spoken language via cochlear implants or hearing aids, vocabulary outcomes are not equivalent to those of children with typical hearing (CTH). DHH children not only tend to know fewer words than peers matched for age (Lund 2016; Yoshinaga-Itano et al. 2017; Walker et al. 2019), but they may struggle to learn specific types of words (e.g., concept vocabulary; Lund et al. 2020) and to make connections between words (Rush et al. 2023; Walker et al. 2019). It is not enough, then, to know that DHH children tend to know fewer words; researchers must ask why DHH children know fewer words than CTH and which words they know. Research must explore how the auditory profile of a child who will learn spoken language interacts with the lexical characteristics of words, which provides insight into word-learning processes, to yield vocabularies that vary between children who are DHH and CTH. The purpose of the present study is to evaluate how use of a hearing aid or cochlear implant, age, length of device use, phonological memory, and overall vocabulary knowledge interact with growth in the types of words, differentiated by word-level lexical characteristics, that DHH children know as compared to CTH.

1.1 | Child-Level Influences on Vocabulary in DHH Children

An obvious answer to why children who are DHH and learning spoken language know fewer words than CTH is auditory: when it is difficult to hear words, it stands to reason that fewer words are acquired and maintained in one's lexicon. Even when children use devices to gain access to sound, that access does not perfectly mirror the sound access available to CTH (e.g., Sharma et al. 2020; Stiles et al. 2012). Cochlear implants give children access to duration and timing cues in words, but spectral processing is less well-conveyed through an electrical signal (Nittrouer et al. 2021). Hearing aids provide acoustic access to sound that is more like the access of CTH, but can still be limited (Stiles et al. 2012). If a child who is DHH has less clearly defined access to sound when learning new words in the environment, learning new words may be more difficult.

Other auditory factors like age at amplification, time using a listening device, and degree of hearing loss also affect variability in vocabulary outcomes for children who are DHH (e.g., Duchesne and Marschark 2019). These auditory factors also tend to be highly related to one another: age at amplification clearly relates to a child's time using a listening device, and children with more severe degrees of hearing loss tend to be identified earlier than children with less severe configurations (Walker et al. 2017). Children with more severe degrees of hearing loss are also more likely to meet criteria for cochlear implantation (e.g., Cochlear 2021). Children with higher ages of amplification and less experience with a listening device tend to know fewer words than children amplified early (e.g., Ching et al. 2013). However, children with more severe degrees of hearing loss (who are often earlier identified) also struggle more to learn new words than do children with milder hearing loss (e.g., Tomblin et al. 2015). Thus, a child's type of device, current age, and age at amplification must all be considered to determine how an auditory profile might be influencing vocabulary acquisition.

Children who are DHH and listening through devices also demonstrate difficulties with working memory outcomes, particularly phonological working memory. For example, Davidson, Geers, Hale et al. (2019) evaluated the working memory of children with cochlear implants as compared to CTH and found that children with cochlear implants had a lower performance, particularly for phonological working memory. Similarly, Nakeva von Mentzer et al. (2020) documented that children using hearing aids and children with cochlear implants performed more poorly than CTH on a working memory task, even following phonics training. Working memory also influences word learning, and consequently, vocabulary size and composition. In CTH, working memory predicts word learning above and beyond expressive vocabulary size and nonverbal intelligence, likely because phonological memory influences retention of new words (Gray et al. 2022). Children who are DHH may be doubly disadvantaged: as early as Pisoni and Geers 2000 identified correlations between working memory and spoken word recognition in children with cochlear implants. More recently, AuBuchon et al. (2015) confirmed that deficits in working memory for children with cochlear implants are not due to audibility and instead likely related to lower efficiency creating and sustaining phonological representations. Children who are DHH may be doubly disadvantaged: McCreery et al. (2019) determined that working memory performance of children who were DHH influenced speech recognition in noise and reverberation. If children who are DHH are likely to struggle with working memory, they may consequently have difficulty with speech recognition as a necessary first step in learning and then also with retaining new words.

Additionally, the existing vocabulary knowledge of an individual likely influences ability to recognize and retain words (e.g., Gray et al. 2022). CTH who have a large vocabulary tend to learn words more quickly than children with a smaller vocabulary, and scholars speculate that this relationship is not unidirectional: having a larger vocabulary may make it easier to learn and organize new words (Adlof and Patten 2017), and children who are skilled word learners are likely to have larger vocabularies than children who are not (Rajan et al. 2019). Lederberg et al. (2000) documented that word learning in children who are DHH is related to vocabulary size. Thus, there are many possible and interrelated child-level factors that influence how many and what vocabulary words children who are DHH know. Children may have imperfect access to a new word form through their device, have limited experience learning from audition and may struggle with phonological memory. These factors may influence a child's vocabulary size, which then goes on to influence which new words a child learns.

1.2 | Influence of Lexical Characteristics on Vocabulary in DHH Children

In CTH, research has explored how lexical characteristics of words themselves, such as phonotactic probability and neighborhood density, also contribute to child vocabulary knowledge and provide insight into word-learning processes of those children. Phonotactic probability refers to the likelihood that a set of sounds will occur in a particular language. In English, for example, the word *car* has high phonotactic probability because the sounds in that word are likely to occur, in that order, in English words. The word *merge*, on the other hand, has low phonotactic probability (Storkel 2013). Neighborhood density refers to how much a word is like other words in a language; that is, a high-neighborhood density word is one where one phoneme can be changed to make many other words. For example, the word *cat* is high-density and a neighbor of *bat*, *sat*, *cot*, *cap*, *cash*, and many others. The word *orange* is low density—you cannot create another English word by changing only one phoneme. These two types of lexical characteristics tend to be positively correlated: it is likely that high-density words are also high-phonotactic probability. However, it is possible to have words that are high-probability and low density, or low probability and high density.

Phonotactic probability and neighborhood density appear to influence word learning and word retention in children. Phonotactic probability supports the process of triggering. Triggering is an early stage of word learning wherein a child must recognize that a word is novel and needs to be attached to a referent (i.e., learned; Storkel et al. 2006). Rare sequence (low probability) words trigger rapid word learning more easily than common-sequence words in adults and in children (Hoover et al. 2010; Storkel et al. 2006). Neighborhood density, on the other hand, is thought to support the word learning stages of configuration and engagement. Configuration involves building a phonological, lexical and semantic representation of a word and engagement involves integration of that word into one's lexicon (Leach and Samuel 2007). Words that are high density appear easier to retain when phonotactic probability is held constant (Storkel and Lee 2011); that is, it is easier to retain new words that sound like words that already exist in the lexicon. When the two lexical characteristics are considered together, it seems children are best situated to learn new words when characteristics are matched: words with low phonotactic probability and low neighborhood density trigger learning and words with high probability and high density help with configuration and engagement (Hoover et al. 2010). Age also appears to influence the effects of phonotactic probability and neighborhood density on word knowledge in CTH (e.g., Jones 2019). Jones (2019) found that children's word productions were more accurate for high density words for children in the older end of the tested age range (near 4 years old), but not for the lower end of the age range (1 year old).

The influence of lexical characteristics of words on vocabulary composition of children who are DHH is less well understood. Children who are DHH are more likely to recognize words with low neighborhood density than words with high neighborhood density during speech perception tasks, whereas CTH appear to take advantage of high-density cues in recognition tasks (Dirks et al. 2001; Eisenberg et al. 2002; Kirk et al. 1995). Retrospective analyses of the vocabulary of DHH children confirm the influence of high neighborhood density on vocabulary knowledge of children who are DHH but cannot differentiate the effects of neighborhood density and phonotactic probability as they varied freely in target words assessed (Guo et al. 2015; Han et al. 2015). Lund (2019) built on this finding by using a vocabulary probe to distinguish the effects of phonotactic probability versus neighborhood density on the vocabulary knowledge of children with cochlear implants at one time point in a group of children between the ages of 6 and 8 years. Findings indicated that children with cochlear implants tended to know words with matched characteristics, similar to CTH (e.g., high density/high probability). However, children with cochlear implants tended to know more high density than low density words, whereas age matched CTH peers tended to know more low than high density words. Patterns of word knowledge for children with cochlear implants more closely mirrored younger CTH, matched for overall vocabulary size, in the study.

The limited work addressing the effects of lexical characteristics on word knowledge of children who are DHH presents opportunities to better delineate interactions between development over time, child-level characteristics, particularly audiological profiles, and lexical characteristics on vocabulary knowledge outcomes. Understanding which children who are DHH are likely to learn different words from CTH provides a basis for developing hypotheses about why learning might look different in this population. The purpose of the present study is to extend the Lund (2019) findings to evaluate how use of a hearing aid or cochlear implant, length of device use, age, phonological memory, and overall vocabulary interact with the lexical characteristics of words known by children who are DHH and CTH. Additionally, this study seeks to extend findings to a younger age group: the Lund (2019) sample was between the ages of 6 and 8, so a next logical step in this line of inquiry is to determine how differences emerge in a younger age range. The following research questions guided this study:

a. Do trajectories of growth in vocabulary knowledge from ages 4 to 6 differ for children who wear cochlear implants, children who wear hearing aids, and CTH differ when lexical characteristics are accounted for?

b. Is there an effect of lexical characteristics (neighborhood density and phonotactic probability) on word knowledge and does that effect vary for children with cochlear implants, children with hearing aids, and CTH?
c. Do length of device use, phonological memory, or vocabulary knowledge at age 4 predict word knowledge outcomes for varying lexical characteristics at age 6 for children with cochlear implants, with hearing aids, and CTH?

2 | Method

The University of South Carolina (Institutional Review Board of record) and Texas Christian University Institutional Review Boards approved procedures for this study. Participants were part of the longitudinal study of a national sample of children who are DHH (NIH/NIDCD R01DC017173 to Werfel and Lund). Children with typical hearing, children who wear hearing aids, and children who wear cochlear implants and are developing spoken language were invited to participate in the study.

Within the longitudinal study, children were tested at 4 years old and then at subsequent 6-month intervals until age 6. Children were invited to participate if they were developing spoken language as a mode of communication; consequently, this study did not include children who were only using a signed language (e.g., American Sign Language). Children could not have additional diagnosed disabilities that typically affect cognitive or language development at the time of enrollment (e.g., Down syndrome).

The present study included a total of 123 children: 47 children with typical hearing (TH) and 75 children who are DHH. Of those children who are DHH, 39 wore hearing aids (HA) and 36 wore cochlear implants (CI). Children completed the experimental probe task that provided information about word knowledge at age 4 and again at age 6, however, not all children completed all time points. For the group with TH, 39 children completed the task at age 4 and 45 completed the task at age 6 (one completed only age 4 and seven completed only age 6). For the group with HA, 30 children completed the task at age 4 and 34 completed the task at age 6 (six completed only age 4 and eight completed only age 6). For children with CI, 32 children completed the task at age 4 and 31 completed the task at age 6 (six completed only age 4 and five completed only age 6).

A description of years of maternal education (used as a proxy for socioeconomic status and known to influence vocabulary size; e.g., Harding et al. 2015) and ratio of males to females (sex assigned at birth) can be found in Table 1. The are proportionately fewer females in the group of children with HA at both time points, and at both time points, maternal education level reported for the children with HA is significantly lower than for children with TH (p = 0.02) but not children with CI (p = 0.13). However, years of maternal education is reported as years post-Kindergarten, and 16 years of maternal education represents the equivalent of an undergraduate post-secondary degree. The average parent education level of all three groups is at least that of a college graduate. Parents were asked to disclose the race and ethnicity of their children if they felt comfortable doing so and they could indicate more than one racial background. In the CI group, 1 child was identified as Hispanic/Latino (and 2 preferred not to disclose ethnicity), 2 as Asian, 1 as Black/African American, and 37 as White. In the HA group, 5 children were identified as Hispanic/Latino (2 did not disclose), 4 as Asian, 1 as Native Hawaiian/Pacific Islander, 2 Black, and 30 White. In the TH group, 5 children were identified as Hispanic (1 did not disclose), 1 as Asian, 4 as Black, and 42 as White.

Table 1 also presents auditory characteristics of the DHH children. Children with CI had a hearing loss identified significantly earlier than children with HA ($p < 0.001$), consistent with prior literature (Walker et al. 2017). Children in the CI group also tended to have more severe degrees of hearing loss than children with HA and were fitted HA earlier than the children who wore HA but not CI. When time spent listening, defined as time post-hearing aid for the HA group and time post-cochlear implant for the CI group are compared, there is no significant difference between groups (CI M at age 6 = 50.28 months, SD = 14.29; HA M at age 6 = 52.22, SD = 16.24).

2.1 | Measures

In the ELLA longitudinal study, children participated in a variety of language and literacy assessments. Testing took place all over the United States in a location convenient to participants; testers traveled to assess participants. Participants' states included Alabama, Arizona, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Idaho, Illinois, Iowa, Kansas, Kentucky, Maine, Maryland, Massachusetts, Michigan, Mississippi, Missouri, Montana, New Jersey, New York, North Carolina, North Dakota, Oklahoma, Pennsylvania, South Carolina, Tennessee, Texas, Utah, Vermont, Virginia, and Washington. At age 4, approximately one-third of each group (TH, CI. and HA) lived in an area eligible for a rural health grant (Lund et al. 2022). They were assessed by a trained examiner in a quiet room, either in university laboratory, local public library, their school, or a quiet room in their home. Examiners were certified speech-language pathologists, who verified that listening devices were working at the onset of the session. All sessions were video recorded to ensure procedural fidelity of administration and to calculate scoring reliability.

2.1.1 | Phonological Memory

Phonological memory at age 4 was assessed using adaptations of Gathercole and Adam's (1993) Nonword Repetition and Digit Span tasks, as reported in Werfel et al. (2023). The Nonword Repetition task asks a child to repeat 15 non-words. Words have one, two, or three syllables each, and must be repeated correctly in their entirety to be scored as correct. The Digit Span task requires a child to repeat strings of digits. Starting with two digits, a child is asked to repeat two strings of digits of increasing lengths. Testing is discontinued when a child cannot repeat two strings of digits of a particular length.

2.1.2 | Overall Vocabulary Knowledge

To assess omnibus vocabulary knowledge at age 4, a norm-referenced measure, *Expressive One Word Picture Vocabulary Test, Fourth Edition* (EOWPVT-4; Martin and Brownell 2011), was

TABLE 1 | Group characteristics across data collection time points.

Amplification group	Time point	Sex assigned at birth	Maternal education (years)	Age of hearing loss identification (months)	Age at first hearing aid (months)	Age at first cochlear implant (months)	Degree of hearing loss
Typical hearing	Age 4 (n = 39)	Female = 20 Male = 19	M = 17.90 SD = 2.13	Not applicable	Not applicable	Not applicable	Not applicable
	Age 6 (n = 45)	Female = 21 Male = 24	M = 17.92 SD = 2.22	Not applicable	Not applicable	Not applicable	Not applicable
Hearing aid	Age 4 (n = 30)	Female = 10 Male = 20	M = 16.35 SD = 2.50	M = 15.92 SD = 17.39	M = 19.34 SD = 16.51	Not applicable	Severe to Profound = 2 Severe = 1 Moderately Severe = 11 Moderate = 4 Mild to Moderate = 12
	Age 6 (n = 34)	Female = 13 Male = 21	M = 16.91 SD = 2.02	M = 16.73 SD = 17.78	M = 20.89 SD = 17.02	Not applicable	Severe to Profound = 3 Severe = 2 Moderately Severe = 13 Moderate = 6 Mild to Moderate = 10
Cochlear implant	Age 4 (n = 32)	Female = 13 Male = 19	M = 17.97 SD = 2.29	M = 4.78 SD = 10.18	M = 9.08 SD = 10.84	M = 24.44 SD = 16.61	Profound = 17 Severe to Profound = 9 Severe = 4 Moderately Severe = 1 Moderate = 1
	Age 6 (n = 31)	Female = 16 Male = 15	M = 17.51 SD = 2.10	M = 5.24 SD = 10.55	M = 9.12 SD = 11.25	M = 25.38 SD = 15.92	Profound = 17 Severe to Profound = 10 Severe = 2 Moderately Severe = 1 Moderate = 1

administered. On this measure, participants view a color picture representing a particular vocabulary target and they are asked to respond with a word naming that target. The measure includes practice items, and the assessment was administered according to manualized rules about repetition and prompting and scored according to the manual.

2.1.3 | Lexical Characteristics Probe

At ages 4 and 6 years old, children participated in the probe task developed for Lund (2019). The vocabulary probe included 40 words divided across four categories: high neighborhood density and high phonotactic probability, low neighborhood density and low phonotactic probability, high neighborhood density and low phonotactic probability, and low neighborhood density and high phonotactic probability. High- and low-neighborhood density and phonotactic probability were defined as words that fall in the highest and lowest quartiles of a child corpus (Storkel and Hoover 2010). The 40 words on the final probe had an age of acquisition rating of less than 7 years old (Kuperman et al. 2012), and age of acquisition did not differ across lists (list means ranged from 5.08 and 5.36 years). Children were shown a picture (validated in Lund 2019) representing each of the words and, as in the EOWPVT-4, asked to identify those words. If the child produced a response that was close to the target (e.g., *noise* for *loud*), the child was re-prompted with "yes," but can you think of another words for this picture?). Responses were phonetically transcribed and marked as correct or incorrect. Children were not penalized for articulation errors consistent with errors made during other articulation testing (e.g., *wabbit* for *rabbit*).

All scores and score entry were verified by a second scorer (an SLP masters student trained by the first author). The second scorer's data were compared with the original examiner's score to compute point-by-point reliability. Point-by-point agreement was above 95%, so the original scorer's responses were used for all analyses.

2.2 | Analysis

To answer the first and second research question, linear mixed growth curve models were used to analyze change between ages 4 and 6, and to capture the effects of device use (CI, HA, or TH) and lexical characteristics (high vs. low neighborhood density, and high vs. low phonotactic probability) on that growth. Missing data was estimated using full information maximum likelihood (providing unbiased estimation consistent with common missingness management). Time was centered at age 4 and individual intercepts were treated as random effects. The effects of time, group membership and neighborhood density and phonotactic probability were treated as fixed effects. Group was coded as a dummy variable, with the TH group used as the reference group. Neighborhood density and phonotactic probability were also coded dichotomously, with high-quartile values represented as "1" and low-quartile values as "0." Beyond main effects present in the model, specific interaction analyses were planned. To answer the first research question, interactions between device type and age were conducted. To answer the second question, interactions between density, probability, and device type were conducted.

To answer the third research question, four regression models were built for each of the three groups: CI, HA, and TH. For all groups, the dependent variable for each of the four models was one of the lexical characteristic outcomes from age 6 testing (high density-high probability, low density-low probability, low density-high probability, or high density-low probability word knowledge). Predictors for models included time with listening device (except for in models for TH), Digit Span task performance, Nonword Repetition task performance, and EOWPVT-4 standard score. All assessment scores used as predictors were age 4 scores.

Because the regressions within each group used the same predictors for different dependent variables (separated item responses for each of the four categories of lexical characteristics), a Bonferroni correction was applied to account for the comparisons run across four models. Consistent with recommendations for comparisons across models, within the single regression, predictors were not considered as four separate comparisons (which would be 16 within each group) because the predictors are tested simultaneously in the same model and consider shared variance (e.g., Anderson 2023). The cut-off level for significant findings was adjusted to $p < 0.0125$ (which is 0.05 divided by four models within each population group).

3 | Results

The first research question asked about vocabulary knowledge differences in growth across children with CI, HA, and TH, and the second question asked about the effects of lexical characteristics on word knowledge of children across device types. Linear mixed growth models yielded a variance of residuals within subjects across time (at the first level of the model) estimated at 1.41 ($p < 0.001$) and variance of residuals between subjects (at the second level of the model) was estimated at 1.24 ($p < 0.001$). The results of the full model (presented in Table 2) indicate a significant main effect of age ($\beta = 0.74$, $p < 0.001$), of neighborhood density ($\beta = -2.25$, $p < 0.001$), and of phonotactic probability ($\beta = -1.47$, $p < 0.001$). Additionally, both the CI versus TH and HA versus CI contrast terms were significant ($\beta = -1.98$, $p < 0.001$ and $\beta = -1.49$, $p < 0.001$).

The first question considered vocabulary knowledge levels and growth across groups. Figure 1 illustrates the influence of device type on performance over time according to lexical characteristics of words probed. The intercept term in the model indicates that the expected average performance for all participants, across all lexical categories at age 4 is 6.41 words, and children grow, on average, by 1.13 words per year. Children with HA and with CI knew fewer words than children with TH as indicated by the main effect of device type and negative coefficient. Additionally, the CI (referenced to TH) by age term was significant, as was the HA (referenced to TH) by age interaction term. These positive, significant interactions indicate that children with CIs and children with HAs grow in word knowledge at a faster rate between ages 4 and 6 than children with TH when lexical characteristics are controlled.

TABLE 2 | Linear mixed growth model parameters.

Parameter	Estimate	*t*	95% Confidence Interval LL	95% Confidence Interval UL	*p*
Intercept	6.34	30.43	5.93	6.75	<0.001
Age	0.74	10.77	0.61	0.88	<0.001
Device type					
Cochlear implant[a]	−1.98	−6.72	−2.56	−1.40	<0.001
Hearing aid[a]	−1.49	−5.07	−2.08	−0.91	<0.001
Device type × Age					
Cochlear implant × Age	0.42	3.94	0.21	0.63	<0.001
Hearing aid × Age	0.46	4.25	0.25	0.67	<0.001
Neighborhood density	−2.25	−19.06	−2.48	−2.02	<0.001
Phonotactic probability	−1.47	−12.48	−1.70	−1.24	<0.001
Density × Probability	2.68	13.09	2.28	3.08	<0.001
Device type × Density × Probability					
Cochlear implant[a] × Density × Probability	0.26	1.11	2.7	−0.20	0.27
Hearing aid[a] × Density × Probability	0.07	0.31	0.76	−0.38	0.53

[a]Dummy-coded reference group is a typical hearing group.

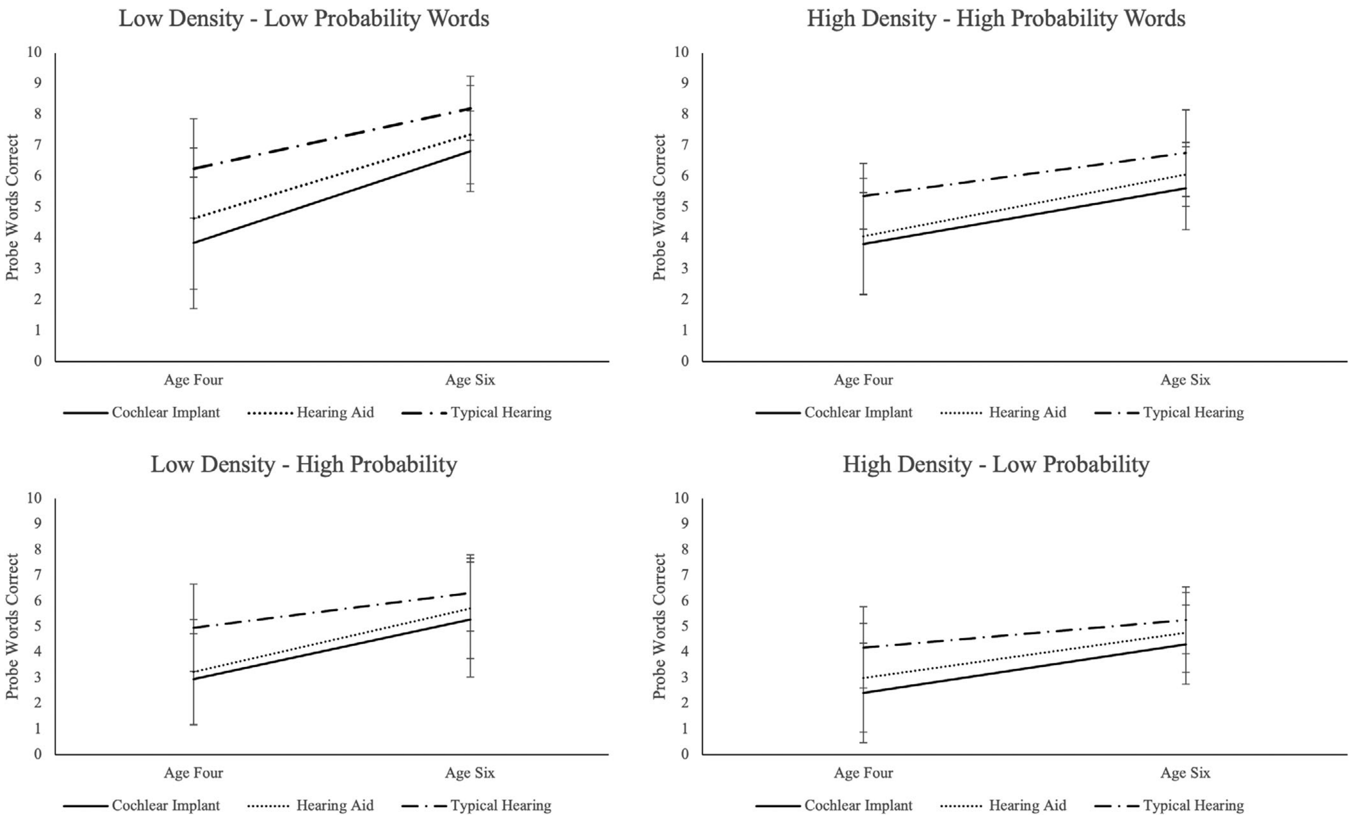

FIGURE 1 | Knowledge of words according to lexical characteristics by amplification group.

The second question asked about the effects of neighborhood density and phonotactic probability on word knowledge, and whether the effect varies for children by device type. The significant main effects of neighborhood density and of phonotactic probability and their negative coefficients indicate that children tend to know more low density words (when probability and device type are controlled) and low probability words (when density and device type are controlled). Additionally, the significant interaction effect with a positive coefficient indicates that children tend to know matched density and probability types (e.g., high density and high probability) rather than unmatched types (e.g., high density and low probability). However, an evaluation of contrast interactions of density, probability and the device types did not indicate significant effects ($p = 0.27$ for children with CI and $p = 0.53$ for children with HA). Thus, children with CI and children with HA do not appear to learn words with differing lexical characteristics than children with TH over time.

The third question asked if length of device use, omnibus vocabulary knowledge or phonological memory predict word knowledge outcomes across the different combinations of lexical characteristics for the three groups. To answer this question, regression models were constructed for each group with those predictors (length of device use at age 6 in months, EOWPVT-4 standard score at age 4, Digit Span performance at age 4, and Nonword Repetition performance at age 4). A descriptive evaluation and comparison of the assessments included as predictors in a one-way analysis of variance reveals that groups significantly differed in performance. For Digit Span, completed at age 4 by 91 participants (38 with TH, 26 with CI, 27 with HA; $F(2, 90) = 3.42$, $p = 0.037$)), children with CI performed significantly lower than children with TH ($p = 0.034$) but not children with HA ($p = 0.771$) and children with HA did not perform differently than children with TH ($p = 0.518$). For Nonword Repetition, completed at age 4 by 89 participants (37 with TH, 26 with CI, 26 with HA; $F(2, 88) = 13.99$, $p < 0.001$)), children with CI and children with HA performed more poorly than children with TH ($p < 0.001$ for both comparisons) but did not perform differently from each other ($p = 1.00$). A correlation was run to evaluate the strength of relation between the two phonological memory measures and indicated a correlation of 0.66 ($p < 0.01$), but the strength of the correlation did not indicate that the two variables were equivalent. For EOWPVT-4 scores, completed at age 4 by 117 participants (47 with TH, 34 with CI, and 36 with TH; $F(2, 116) = 11.523$, $p < 0.001$), children with CI and children with HA performed lower than children with TH ($p < 0.001$ and $p = 0.002$, respectively) but did not perform differently from each other ($p = 1.00$).

Results of the regression models are displayed in Table 3.

In models predicting performance on low density- low probability words, the only significant predictor was EOWPVT-4 for children with HA and children with TH, and none of the predictors were significant for children with CI. In models predicting performance on high density—high probability words, no predictors were significant across groups. For low density—high probability words, none of the predictors were significant for children with HA or TH, and the EOWPVT-4 predicted performance for children with CI. For high density—low probability words, none of the predictors were significant for children across groups.

4 | Discussion

The overall purpose of the present study was to evaluate how auditory device, age, time listening with a device, phonological memory and omnibus vocabulary knowledge interact with the lexical characteristics of neighborhood density and phonotactic probability to influence of vocabulary knowledge for children who are DHH. Broadly, and consistent with prior literature (Lund 2016; Yoshinaga-Itano et al. 2017; Walker et al. 2019), children with CI and with HA knew fewer words than CTH. Additionally, both phonotactic probability and neighborhood density influenced which words children were likely to know at ages 4 and 6; however, phonotactic probability and neighborhood density did not differentially influence children who were DHH as compared to CTH. These findings extend prior findings related to the influence of lexical characteristics on word knowledge in DHH children to the 4- to 6-year-age range.

The first research question addressed whether level of vocabulary knowledge and growth trajectories differed for children by device type, controlling for the effects of lexical characteristics on words. Analysis revealed a main effect of device type on knowledge: both children with CI and children with HA knew fewer words than children with TH across lexical categories after controlling for the effects of age. Additionally, the significant interaction effect between age and device type indicated that children who are DHH were growing in vocabulary knowledge faster than their peers with TH, who served as a reference in those effects. A faster growth rate for children who are DHH may indicate that children are beginning to close gaps in word knowledge between ages 4 and 6. However, the overall main effect and primarily medium-to-large effect sizes (overall effect size difference between CI and TH groups of 0.81 and between HA and TH groups of 0.48 at age 6) would indicate that, by age 6, children who are DHH and using HA and CI still know, on average, fewer words than peers with TH. This finding is consistent with prior work identifying gaps in vocabulary knowledge between children who are DHH and their peers with TH at school entry (e.g., Lund 2016; Werfel et al. 2022). That vocabulary growth is rapid in the preschool/early elementary school years between ages 4 and 6 is promising, and future work should explore the influences of academic instruction on that growth beyond age 6.

The second research question asked whether there is an effect of the lexical characteristic probability on vocabulary knowledge, and whether those effects differ by device. The main effect of neighborhood density indicated that children were, between ages 4 and 6, more likely to know words with low density than high density when the effects of phonotactic probability are controlled. The main effect of phonotactic probability similarly indicated that children were more likely to know words with low phonotactic probability (i.e., rare sequences of words) than with high probability when the effects of neighborhood density are controlled. The interaction effect between neighborhood density and phonotactic probability matched the findings from Lund (2019): children were more likely to know words with matched density and probability than with mismatched density and probability. In other words, children were more likely to know low density, low probability words than low density, high probability words.

TABLE 3 | Results of regression models for each amplification group according to lexical characteristics.

Group	Lexical characteristic	Parameter	Estimate	Standard error	*t*	*p*
Cochlear implant	Low density-low probability	Intercept	4.436	2.685	1.652	0.127
		Time with device in months	0.008	0.015	0.524	0.61
		Digit span	−0.333	0.362	−0.921	0.377
		Nonword repetition	0.202	0.13	1.554	0.148
		EOWPVT-4	0.023	0.026	0.901	0.387
	High density-high probability	Intercept	−3.33	3.444	−0.967	0.354
		Time with device in months	−0.008	0.019	−0.437	0.67
		Digit span	0.137	0.464	0.296	0.773
		Nonword repetition	0.039	0.166	0.233	0.82
		EOWPVT-4	0.089	0.033	2.71	0.02
	Low density-high probability	Intercept	−12.683	4.99	−2.542	0.027
		Time with device in months	−0.012	0.028	−0.435	0.672
		Digit span	0.457	0.672	0.679	0.511
		Nonword repetition	−0.241	0.241	−0.999	0.339
		EOWPVT-4	0.177	0.048	3.71	0.003
	High density-low probability	Intercept	−5.008	4.124	−1.214	0.25
		Time with device in months	−0.011	0.023	−0.47	0.647
		Digit span	0.262	0.555	0.472	0.646
		Nonword repetition	−0.456	0.199	−2.287	0.043
		EOWPVT-4	0.105	0.039	2.673	0.022
Hearing aid	Low density-low probability	Intercept	−1.486	2.174	−0.684	0.505
		Time with device in months	−0.002	0.017	−0.113	0.911
		Digit span	−0.11	0.208	−0.527	0.606
		Nonword repetition	0.002	0.078	0.026	0.979
		EOWPVT-4	0.089	0.023	3.932	0.001
	High density-high probability	Intercept	3.012	1.798	1.675	0.115
		Time with device in months	0.018	0.014	1.264	0.226
		Digit span	0.409	0.172	2.374	0.031
		Nonword repetition	0.012	0.064	0.187	0.854
		EOWPVT-4	0.006	0.019	0.312	0.759
	Low density-high probability	Intercept	2.616	3.499	0.747	0.466

(Continues)

TABLE 3 | (Continued)

Group	Lexical characteristic	Parameter	Estimate	Standard error	*t*	*p*
		Time with device in months	−0.016	0.027	−0.607	0.553
		Digit span	0.24	0.335	0.716	0.485
		Nonword repetition	−0.033	0.125	−0.266	0.794
		EOWPVT-4	0.036	0.036	0.988	0.339
	High density-low probability	Intercept	2.419	2.137	1.132	0.275
		Time with device in months	−0.017	0.016	−1.016	0.326
		Digit span	0.399	0.205	1.951	0.07
		Nonword repetition	0.142	0.076	1.859	0.083
		EOWPVT-4	0.01	0.022	0.437	0.668
Typical hearing	Low density-low probability	Intercept	4.187	1.303	3.214	0.003
		Digit span	0.131	0.236	0.557	0.582
		Nonword repetition	−0.043	0.04	−1.071	0.292
		EOWPVT-4	0.033	0.012	2.693	0.011
	High density-high probability	Intercept	1.551	1.908	0.813	0.422
		Digit span	0.109	0.345	0.316	0.754
		Nonword repetition	0.021	0.059	0.359	0.722
		EOWPVT-4	0.039	0.018	2.162	0.038
	Low density-high probability	Intercept	1.826	2.275	0.803	0.428
		Digit span	−0.227	0.412	−0.552	0.585
		Nonword repetition	0.063	0.07	0.9	0.375
		EOWPVT-4	0.039	0.021	1.833	0.076
	High density-low probability	Intercept	2.643	1.882	1.404	0.17
		Digit span	0.041	0.341	0.121	0.905
		Nonword repetition	−0.015	0.058	−0.258	0.798
		EOWPVT-4	0.02	0.018	1.149	0.259

The effects of density and probability in this study did not differ by device type; that is, children who are DHH did not know different patterns of words, based on lexical characteristics, than CTH. However, this may be related to the age ranges studied in the present work. The Lund (2019) study evaluated word knowledge for children between the ages of six and eight years old, and children with CI were more likely to know words with low neighborhood density than high neighborhood density, whereas CTH were more likely to know words with high, rather than low density. That study included a vocabulary-matched, younger, group of CTH, who also tended to know more low-density words (like children with CI). The present study evaluated the knowledge of children at ages 4 and 6, and all groups of children were more likely to know low density rather than high density words. Thus, these results may not be contradictory; rather, they may indicate that CTH take advantage of high-density cues to increase high-density word knowledge after age 6 in a way that children with CI (and possibly hearing aids) do not after age 6.

Recall that phonotactic probability and neighborhood density are thought to support word learning in different ways. Phonotactic probability likely supports triggering of word learning; that is, low probability words help children to recognize that a word is different and needs to be acquired. In the present study, that children tend to know more words with low phonotactic probability may indicate that they take advantage of this cue. That the interaction effect indicates that children also tend to know more words with matched lexical characteristics also suggests that low-probability, low-density words are most likely to be known (as is the case, see Figure 1). This is consistent with prior work (Lund 2019; Hoover et al. 2010) that these words may be the easiest to acquire. Neighborhood density, on the other hand, is likely to support configuration and engagement of new words. That is, it may be easier to learn a word that sounds like lots of words that a child already knows because the sequence of phonemes in the word is already close to words stored in phonological memory (and thus, are easy to access). It is possible that children begin to take advantage of density cues more as they age. Additionally, as children build their overall vocabularies as they age, it is also possible that they are better able to build dense networks: if children have more words in their lexicon, high density words may have more neighbors to continue supporting engagement and configuration during word learning. Future work should continue to explore whether differences in ability to access the support of high neighborhood density in learning might change, according to device type, after age 6.

The third research question, then, asked whether length of device use, phonological memory, and omnibus vocabulary knowledge predicted word knowledge across the different combinations of lexical characteristics according to device type. For low density, low probability words, none of these predictors were significant for the word knowledge of children with CI. However, for children with HA and children with TH, overall knowledge as measured by the EOWPVT test at age 4 influenced words known at age 6. For high density, high probability words and high density, low probability words, no predictors were significant across groups. For low density, high probability words, EOWPVT score was a significant predictor for children with CI, but not for children with HA or children with TH.

Vocabulary knowledge, as indexed by score on the EOWPVT at age 4, was the only factor predicted word knowledge across lexical categories at age 6, predicting one set of lexical characteristics for children with CI, and another for children with TH and HA. At the level of vocabulary acquisition, omnibus existing vocabulary knowledge likely contributes to multiple parts of the word learning process. During the triggering stage, existing vocabulary knowledge must (subconsciously) be compared to the word to be learned; the new word can only be recognized as novel relative to words that are already in the lexicon. During the configuration stage, existing vocabulary knowledge can support retention of new words, as words that sound like known words may be easier to hold in memory. During the engagement stage, existing vocabulary knowledge can be used to integrate the new word into an existing lexical-semantic network for efficient, later retrieval. For children with TH and with HA, none of the other factors explored significantly predicted knowledge, and vocabulary size only predicted knowledge of matched low-density, low probability words. It is possible that, for children with TH and HA (in the case of low density, low probability words), existing vocabulary knowledge has the most influence on learning in lexical conditions ideal for learning new words (Hoover et al. 2010). For children with CI, general vocabulary size predicted learning in low density, high probability words (unmatched probabilities). Thus, children with CI may be relying on lexical characteristics in a different way than children with TH or HA.

This study included two measures of phonological memory: the Digit Span and Nonword Repetition tasks. Both measures are thought to measure short-term phonological memory (Gray 2003). Digit span tasks, theoretically, allow children to rely on their knowledge of number names to complete the task (and thus, tap already-established lexical knowledge; Gathercole et al. 1997). Nonword repetition does not directly rely on already-established knowledge of particular words; however, it may also interact with lexical knowledge because nonwords that resemble words in a child's lexicon are easier to repeat (e.g., Dollaghan et al. 1995). In the present study, the tasks were analyzed separately because their correlation, though significant, was 0.66, indicating the two variables may have different predictive values. Both have been used in prior studies of children with language disorders and with diagnoses like hearing loss (e.g., Werfel et al. 2023). None of these measures were significant predictors of performance across word types.

Interestingly, time listening was not a significant factor predicting words known by either children with HA or children with CI. Although time listening, or "listening age" has been examined in the literature as a predictor of outcomes (e.g., Davidson, Geers, Uchanski et al. 2019), it does not appear to have substantial impact above and beyond other important predictors in this study. As demonstrated in Table 1, children generally received their listening devices (hearing aids or cochlear implants) prior to age 3. Even though previous work has demonstrated an effect of age at implant or age at hearing aid fitting, it is possible that the influence of those variables (as part of experience with listening) have diminishing returns: that is, after a certain point, a 6 month difference in listening experience is less influential in vocabulary outcomes than other variables, particularly if children received access to sound at a relatively young age.

Children with CIs, then, may have different underlying skills that are interacting with the lexical characteristics of words to produce word knowledge. Omnibus vocabulary knowledge appears to be the strongest predictor of vocabulary outcomes for children with Cis, but for different types of words than for children with HA and TH. It is possible that this contributes to our understanding of how children with different devices may process words differently. Nittrouer et al. (2022) have suggested that children with CIs have poorer sensitivity to the phonological structure of language than CTH and that they may approach processing of words more holistically or based on lexicosemantic (vocabulary) knowledge than children with typical hearing. The 2022 study did not include children with HA, but for children with CI, it would make sense that in the present study, existing vocabulary knowledge influenced the words children knew, rather than phonological memory. Differences in processing and later learning in children with CI and HA must be further explored.

Overall, there appears to be an effect of hearing loss and device use on learning of words with varying lexical characteristics: both children with CIs and with HAs did not know as many words as CTH. The third research question from this study leads to a next question: Is it possible that children with CI and children with HA fall behind their typical peers for different reasons? Both may have delayed knowledge, but their strategies for acquiring new words, if different, may set up children listening acoustically versus electronically for different outcomes.

4.1 | Limitations and Future Directions

Limitations of the work provide avenues for future directions. First, this study evaluated the influence lexical characteristics on word knowledge. However, much of the literature that predicts lexical characteristic influence focuses on the process of word learning, rather than on a more distal outcome. A logical next step in this line of inquiry is to study how lexical characteristics influence learning novel words for DHH children, particularly in ecologically valid scenarios. Word-learning work would provide additional basis for future recommendations for learning for children who listen through HA or CI.

The role of existing expressive vocabulary knowledge and of phonological memory in word knowledge were observed, but these roles must further explored with particular emphasis on how the predictors may relate to incremental versus whole-word processing and how that process influences the word-learning process. From a clinical perspective: if these predictors are likely to tell us which words kids are likely to know, then a next step is to ask if there are ways to supplement or overcome a child's particular struggle. For example, if a child struggles with phonological memory, is there a way to supplement that memory to lead to word retention?

The present study was also limited in the age range it explored. Future work may consider tracing children beyond age 6, particularly given some of the contradictory results in patterns of words known between children in this study and in the Lund (2019) study. It is possible that patterns of learning shift with age, and that this shift was not captured in the age range selected for this study.

Finally, this study looked only at specific, single-word knowledge outcomes. To extend the contributions of the work, another logical next step is to evaluate how knowing specific types of words (e.g., high density words) is likely to influence other linguistic outcomes. The relation between word knowledge and other linguistic activities is clearly bi-directional. It is possible that as children build more dense networks of words, for example, that they also become better at manipulating those words at the phoneme level (which is influential in the development of later skills like reading). Future works can build on this model to better indicate how hearing loss and listening through a device is likely to influence word learning, which is then likely to influence other outcomes as well.

Author Contributions

Emily Lund: conceptualization, data curation, formal analysis, writing – original draft, methodology, project administration, funding acquisition, writing – review and editing, investigation. **Krystal L. Werfel**: writing – review and editing, conceptualization, funding acquisition, methodology, investigation, project administration.

Ethics Statement

The University of South Carolina (Institutional Review Board of record) and Texas Christian University Institutional Review Boards approved procedures for this study. Participants were part of the longitudinal ELLA study of a national sample of children who are DHH (Emergent Language and Literacy Development in Children with Hearing Loss; NIH/NIDCD R01DC017173 to Krystal L. Werfel and Emily Lund).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are not publicly available due to concerns about identifiability but are available from the corresponding author on reasonable request. Data collection on this longitudinal study began prior to changes in Federal guidelines about data sharing, so participants did not sign a consent form stating their data would be shared. Additionally, audiological profiles are sufficiently unique that sharing complete individual data may render some participants identifiable.

References

Adlof, S. M., and H. Patten. 2017. "Nonword Repetition and Vocabulary Knowledge as Predictors of Children's Phonological and Semantic Word Learning." *Journal of Speech, Language, and Hearing Research* 60, no. 3: 682–693.

Anderson, S. F. 2023. "Multiplicity in Multiple Regression: Defining the Issue, Evaluating Solutions, and Integrating Perspectives." *Psychological Methods* 28, no. 6: 1223–1241.

AuBuchon, A. M., D. B. Pisoni, and W. G. Kronenberger. 2015. "Short-Term and Working Memory Impairments in Early-Implanted, Long-Term Cochlear Implant Users Are Independent of Audibility and Speech Production." *Ear and Hearing* 36, no. 6: 733–737.

Ching, T. Y., H. Dillon, V. Marnane, et al. 2013. "Outcomes of Early- and Late-Identified Children at 3 Years of Age: Findings From a Prospective Population-Based Study." *Ear and Hearing* 34, no. 5: 535–552.

Cochlear. 2021. Cochlear Implants for Children. https://www.cochlear.com/us/en/home/diagnosis-and-treatment/how-cochlearsolutionswork/cochlear-implants/cochlear-implants-children/cochlear-implants-children.

Davidson, L. S., A. E. Geers, S. Hale, M. M. Sommers, C. Brenner, and B. Spehar. 2019. "Effects of Early Auditory Deprivation on Working Memory and Reasoning Abilities in Verbal and Visuo-Spatial Domains for Pediatric CI Recipients." *Ear and Hearing* 40, no. 3: 517.

Davidson, L. S., A. E. Geers, R. M. Uchanski, and J. B. Firszt. 2019. "Effects of Early Acoustic Hearing on Speech Perception and Language for Pediatric Cochlear Implant Recipients." *Journal of Speech, Language, and Hearing Research* 62: 3620–3637.

Dirks, D. D., S. Takayanagi, and A. Moshfegh. 2001. "Effects of Lexical Factors on Word Recognition Among Normal-Hearing and Hearing-Impaired Listeners." *Journal of the American Academy of Audiology* 12, no. 5: 233–244. CLOCKSS. https://doi.org/10.1055/s-0042-1745602.

Dollaghan, C. A., M. E. Biber, and T. F. Campbell. 1995. "Lexical Influences on Nonword Repetition." *Applied Psycholinguistics* 16, no. 2: 211–222. https://doi.org/10.1017/s0142716400007098.

Duchesne, L., and M. Marschark. 2019. "Effects of Age at Cochlear Implantation on Vocabulary and Grammar: A Review of the Evidence." *American Journal of Speech-Language Pathology* 28, no. 4: 1673–1691.

Eisenberg, L. S., A. S. Martinez, S. R. Holowecky, and S. Pogorelsky. 2002. "Recognition of Lexically Controlled Words and Sentences by Children With Normal Hearing and Children With Cochlear Implants." *Ear and Hearing* 23, no. 5: 450–462. https://doi.org/10.1097/00003446-200210000-00007

Expressive One-Word Picture Vocabulary Test. (2011). SpringerReference. https://doi.org/10.1007/springerreference_184242.

Gathercole, S. E., and A.-M. Adams. 1993. "Phonological Working Memory in Very Young Children." *Developmental Psychology* 29, no. 4: 770–778. https://doi.org/10.1037/0012-1649.29.4.770

Gathercole, S. E., G. J. Hitch, E. Service, and A. J. Martin. 1997. "Phonological Short-Term Memory and New Word Learning in Children." *Developmental Psychology* 33, no. 6: 966–979. https://doi.org/10.1037/0012-1649.33.6.966.

Gray, S. 2003. "Diagnostic Accuracy and Test–Retest Reliability of Nonword Repetition and Digit Span Tasks Administered to Preschool Children With Specific Language Impairment." *Journal of Communication Disorders* 36, no. 2: 129–151. https://doi.org/10.1016/s0021-9924(03)00003-0.

Gray, S. I., R. Levy, M. Alt, T. P. Hogan, and N. Cowan. 2022. "Working Memory Predicts New Word Learning Over and Above Existing Vocabulary and Nonverbal IQ." *Journal of Speech, Language, and Hearing Research* 65, no. 3: 1044–1069.

Guo, L.-Y., K. K. McGregor, and L. J. Spencer. 2015. "Are Young Children With Cochlear Implants Sensitive to the Statistics of Words in the Ambient Spoken Language?" *Journal of Speech, Language, and Hearing Research* 58, no. 3: 987–1000. https://doi.org/10.1044/2015_jslhr-h-14-0135

Hall, M. L., I. M. Eigsti, H. Bortfeld, and D. Lillo-Martin. 2017. "Auditory Deprivation Does Not Impair Executive Function, but Language Deprivation Might: Evidence From a Parent-Report Measure in Deaf Native Signing Children." *Journal of Deaf Studies and Deaf Education* 22, no. 1: 9–21.

Han, M. K., H. L. Storkel, J. Lee, and C. Yoshinaga-Itano. 2015. "The Influence of Word Characteristics on the Vocabulary of Children With Cochlear Implants." *The Journal of Deaf Studies and Deaf Education* 20, no. 3: 242–251. https://doi.org/10.1093/deafed/env006

Harding, J. F., P. A. Morris, and D. Hughes. 2015. "The Relationship Between Maternal Education and Children's Academic Outcomes: A Theoretical Framework." *Journal of Marriage and Family* 77, no. 1: 60–76.

Hoover, J. R., H. L. Storkel, and T. P. Hogan. 2010. "A Crosssectional Comparison of the Effects of Phonotactic Probability and Neighborhood Density on Word Learning by Preschool Children." *Journal of Memory and Language* 63: 100–116.

Jones, S. D. 2019. "Accuracy and Variability in Early Spontaneous Word Production: The Effects of Age, Frequency and Neighbourhood Density." *First Language* 40, no. 2: 128–150. https://doi.org/10.1177/0142723719894768.

Kirk, K. I., D. B. Pisoni, and M. J. Osberger. 1995. "Lexical Effects on Spoken Word Recognition by Pediatric Cochlear Implant Users." *Ear and Hearing* 16, no. 5: 470–481. https://doi.org/10.1097/00003446-199510000-00004.

Kuperman, V., H. Stadthagen-Gonzalez, and M. Brysbaert. 2012. "Age-of-Acquisition Ratings for 30,000 English Words." *Behavior Research Methods* 44, no. 4: 978–990. https://doi.org/10.3758/s13428-012-0210-4.

Leach, L., and A. G. Samuel. 2007. "Lexical Configuration and Lexical Engagement: When Adults Learn New Words." *Cognitive Psychology* 55: 306–353.

Lederberg, A. R., A. K. Prezbindowski, and P. E. Spencer. 2000. "Word-Learning Skills of Deaf Preschoolers: The Development of Novel Mapping and Rapid Word-Learning Strategies." *Child Development* 71, no. 6: 1571–1585.

Lund, E. 2016. "Vocabulary Knowledge of Children With Cochlear Implants: A Meta-Analysis." *Journal of Deaf Studies and Deaf Education* 21, no. 2: 107–121.

Lund, E. 2019. "Comparing Word Characteristic Effects on Vocabulary of Children With Cochlear Implants." *The Journal of Deaf Studies and Deaf Education* 24, no. 4: 424–434. https://doi.org/10.1093/deafed/enz015

Lund, E., N. Brock, and K. L. Werfel. 2022. "Location Effects on Spoken Language and Literacy for Children Who Are DHH." *Journal of Deaf Studies and Deaf Education* 27, no. 1: 48–61.

Lund, E., C. Miller, W. M. Douglas, and K. Werfel. 2020. "Teaching Vocabulary to Improve Print Knowledge in Preschool Children With Hearing Loss." *Perspectives of the ASHA Special Interest Groups* 5, no. 6: 1366–1379.

Martin, N. A., and R. Brownell. 2011. *Expressive One-Word Picture Vocabulary Test-4 (EOWPVT-4)*. Academic Therapy Publications.

McCreery, R. W., E. A. Walker, M. Spratford, D. Lewis, and M. Brennan. 2019. "Auditory, Cognitive, and Linguistic Factors Predict Speech Recognition in Adverse Listening Conditions for Children With Hearing Loss." *Frontiers in Neuroscience* 13: 1093. https://doi.org/10.3389/fnins.2019.01093.

Mitchell, R. E., and M. A. Karchmer. 2004. "Chasing the Mythical Ten Percent: Parental Hearing Status of Deaf and Hard of Hearing Students in the United States." *Sign Language Studies* 4, no. 2: 138–163.

Moore, J. K., and F. H. Linthicum Jr. 2007. "The Human Auditory System: A Timeline of Development." *International Journal of Audiology* 46, no. 9: 460–478.

Nakeva von Mentzer, C., S. Wallfelt, E. Engström, et al. 2020. "Reading Ability and Working Memory in School-Age Children Who Are Deaf and Hard of Hearing Using Cochlear Implants and/or Hearing Aids: A 3-Year Follow-Up on Computer-Based Phonics Training." *Perspectives of the ASHA Special Interest Groups* 5, no. 6: 1388–1399.

Nassiri, A. M., J. P. Marinelli, C. M. Lohse, and M. L. Carlson. 2023. "Age and Incidence of Cochlear Implantation in the Pediatric Population With Congenital Bilateral Profound Hearing Loss." *Otology and Neurotology* 44: e492–3496.

Nittrouer, S., J. Antonelli, and J. Lowenstein. 2022. "The Emergence of Bifurcated Structure in Children's Language." *Journal of Experimental Psychology* 151: 3045–3059.

Nittrouer, S., J. H. Lowenstein, and D. G. Sinex. 2021. "The Contribution of Spectural Processing to the Acquisition of Phonological Sensitivity by Adolescent Cochlear Implant Users and Normal-Hearing Controls." *Journal of the Acoustical Society of America* 150: 2116–2130.

Pisoni, D. B., and A. Geers. 2000. "Working Memory in Deaf Children With Cochlear Implants: Correlations Between Digit Span and Measures of Spoken Language Processing." *Annals of Otology, Rhinology & Laryngology* 109: 92–93.

Rajan, V., H. Konishi, K. Ridge, et al. 2019. "Novel Word Learning at 21 Months Predicts Receptive Vocabulary Outcomes in Later Childhood." *Journal of Child Language* 46, no. 4: 617–631.

Rush, O., K. L. Werfel, and E. Lund. 2023. "Lexical–Semantic Organization as Measured by Repeated Word Association in Children Who Are Deaf and Hard of Hearing Who Use Spoken Language." *Journal of Speech, Language, and Hearing Research* 66, no. 10: 3925–3939.

Sharma, S., S. Cushing, B. Papsin, and K. Gordon. 2020. "Hearing and Speech Benefits of Cochlear Implantation in Children: A Review of the Literature." *International Journal of Pediatric Otorhinolaryngology* 133: 109984.

Stiles, D. J., R. A. Bentler, and K. K. McGregor. 2012. "The Speech Intelligibility Index and the Pure-Tone Average as Predictors of Lexical Ability in Children Fit With Hearing Aids." *Journal of Speech, Language, and Hearing Research* 55: 764–778.

Storkel, H. 2013. "A Corpus of Consonant-Vowel-Consonant Real Words and Nonwords: Comparison of Phonotactic Probability, Neighborhood Density, and Consonant Age of Acquisition." *Behavioral Research Methods* 45: 1159–1167.

Storkel, H. L., J. Armbruster, and T. P. Hogan. 2006. "Differentiating Phonotactic Probability and Neighborhood Density in Adult Word Learning." *Journal of Speech Language, and Hearing Research* 49: 1175–1192.

Storkel, H. L., and J. R. Hoover. 2010. "Word Learning by Children With Phonological Delays: Differentiating Effects of Phonotactic Probability and Neighborhood Density." *Journal of Communication Disorders* 43, no. 2: 105–119. https://doi.org/10.1016/j.jcomdis.2009.11.001.

Storkel, H. L., and S. Y. Lee. 2011. "The Independent Effects of Phonotactic Probability and Neighbourhood Density on Lexical Acquisition by Preschool Children." *Language and Cognitive Processes* 26: 191–211.

Tan, D., R. J. Fujiwara, and K. H. Lee. 2024. "Current Issues With Pediatric Cochlear Implantation." *Journal of Audiology & Otology* 28, no. 2: 79.

Tomblin, J. B., M. Harrison, S. E. Ambrose, E. A. Walker, J. J. Oleson, and M. P. Moeller. 2015. "Language Outcomes in Young Children With Mild to Severe Hearing Loss." *Ear and Hearing* 36: 76S–91S.

Walker, E., M. Spratford, S. E. Ambrose, L. Holte, and J. Oleson. 2017. "Service Delivery to Children With Mild Hearing Loss: Current Practice Patterns and Parent Perceptions." *American Journal of Audiology* 26, no. 1: 38–52. https://doi.org/10.1044/2016_AJA-16-0063.

Walker, E. A., A. Redfern, and J. J. Oleson. 2019. "Linear Mixed-Model Analysis to Examine Longitudinal Trajectories in Vocabulary Depth and Breadth in Children Who Are Hard of Hearing." *Journal of Speech, Language, and Hearing Research* 62, no. 3: 525–542.

Werfel, K. L., G. Reynolds, L. Fitton. 2022. "Oral Language Acquisition in Preschool Children Who are Deaf and Hard-of-Hearing." *The Journal of Deaf Studies and Deaf Education* 27, no. 2: 166–178. https://doi.org/10.1093/deafed/enab043

Werfel, K. L., G. Reynolds, and L. Fitton. 2023. "A Longitudinal Investigation of Code-Related Emergent Literacy Skills in Children Who Are Deaf and Hard of Hearing Across the Preschool Years." *American Journal of Speech-Language Pathology* 32: 629–644. https://doi.org/10.1044/2022_AJSLP-22-00169.

Yoshinaga-Itano, C., A. L. Sedey, M. Wiggin, and W. Chung. 2017. "Early Hearing Detection and Vocabulary of Children With Hearing Loss." *Pediatrics* 140, no. 2: e20162964.