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Research Article

Linear Mixed-Model Analysis to Examine Longitudinal Trajectories in Vocabulary Depth and Breadth in Children Who Are Hard of Hearing

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Purpose: Children who are hard of hearing (CHH) tend to have reduced vocabularies compared to children with normal hearing (CNH). Prior research on vocabulary skills in children with hearing loss has focused primarily on their breadth of knowledge (how many words are known). Depth of vocabulary knowledge (how well words are known) is not well documented for CHH. The current study used linear mixed models (LMMs) to investigate growth trajectories of vocabulary depth and breadth in CHH relative to age-matched CNH.
Method: Participants for this study included 155 children (93 CHH, 62 CNH) enrolled in a longitudinal study. Examiners administered a standardized measure of vocabulary knowledge at ages 7, 8, and 9 years. We constructed multiple LMMs with fixed effects for group and age. The models included various combinations of random intercepts for subject and item and random slope for age.
Results: For depth, CHH showed significant and stable deficits compared to CNH over time. For breadth, CNH showed greater vocabulary breadth, but the group differences diminished with age. For CHH, higher aided audibility, age, and maternal educational level were associated with greater vocabulary breadth and depth. Age at hearing aid fitting was not.
Conclusions: A major advantage of using LMM is that it allowed us to cope with missing data points while still accounting for variability within and across participants. Assessment of both vocabulary breadth and depth may be useful in identifying school-age CHH who are at risk of delays in language outcomes.

Vocabulary knowledge is a critical component of language and literacy (Duncan et al., 2007; Hart & Risley, 1995; Marchman & Fernald, 2008). Children who are typically developing show large individual differences in vocabulary size and rate of growth (Bates, Bretherton, & Snyder, 1988). Children who are deaf or hard of hearing demonstrate similar patterns of large variation in vocabulary size (Mayne, Yoshinaga-Itano, & Sedey, 1999; Mayne, Yoshinaga-Itano, Sedey, & Carey, 1998). They also demonstrate significant deficits in vocabulary knowledge relative to same-age hearing peers (Convertino, Borgna, Marschark, & Durkin, 2014; Moeller, 2000; Tomblin, Harrison, et al., 2015), as well as slower rates of vocabulary acquisition (Blamey et al., 2001; Connor, Hieber, Arts, & Zwolan, 2000; Moeller, Osberger, & Eccarius, 1986).

Much of the prior work on vocabulary development in children with hearing loss has focused on how many words an individual knows (i.e., vocabulary breadth). Evaluation of vocabulary breadth typically involves standardized tests in which the child points to a picture in a closed set when provided with a target word or labels a picture (Prezbindowski & Lederberg, 2003). Although these measures provide an efficient method for estimating lexicon size, they do not fully capture how much individuals know about words (i.e., vocabulary depth). The question of whether children who are hard of hearing (CHH) exhibit deficits in both quantity and quality of vocabulary knowledge is intriguing, as breadth and depth have been proposed to contribute to functional outcomes in different

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ways and thus have important implications for clinical practice.

Vocabulary breadth and depth have been shown to be associated with different outcomes. Vocabulary breadth is linked to skills such as peer acceptance (Gertner, Rice, & Hadley, 1994), as well as reading decoding, because phonological representations map onto orthographic representations (Ouellette, 2006; Wise, Sevcik, Morris, Lovett, & Wolf, 2007). At the same time, deeper vocabulary knowledge facilitates efficient word retrieval and faster word identification (Wise et al., 2007). Stronger depth of vocabulary is associated with stronger lexical–semantic representations, which leads to more efficient semantic access and better reading comprehension (Nation & Snowling, 1999; Ouellette, 2006; Paul & Gustafson, 1991). Intensive training in depth of vocabulary knowledge also leads to significant improvements in reading comprehension (Clarke, Snowling, Truelove, & Hulme, 2010).

The goal of the current study is to examine longitudinal changes in vocabulary breadth and depth in CHH compared to age-matched children with normal hearing (CNH). To address this goal, we used a linear mixed model (LMM) to analyze data from a longitudinal study on outcomes of children with mild to severe hearing loss. A major hurdle with our longitudinal data set is that it is characterized by multiple missing data points, a common challenge in human subjects research (Krueger & Tian, 2004). Traditional statistical approaches (e.g., repeated-measures analysis of variance [ANOVA]) lack the flexibility to handle such complex data sets, making it difficult to interpret results. In contrast, LMMs offer a number of advantages when examining change over time in language development. Prior to describing the benefits of LMMs, we will review the literature on vocabulary development in CNH and CHH.

Vocabulary Development in CNH

Lexical acquisition is often measured by how many words a child knows (Gray, Plante, Vance, & Henrichsen, 1999; Moeller, Tomblin, Yoshinaga-Itano, Connor, & Jerger, 2007). Common assessments include the MacArthur–Bates Communicative Development Inventories (MBCDI; Fenson et al., 1994), the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2007), or the Expressive One-Word Picture Vocabulary Test (Martin & Brownell, 2011). Vocabulary tasks that involve word recognition or naming assess surface-level lexical knowledge, but not the deeper semantic knowledge that is required to use language flexibly and meaningfully (Best, Dockrell, & Braisby, 2006). To fully understand an individual's vocabulary knowledge, we also want to consider vocabulary depth or how well we know words. The concept of vocabulary depth is multifaceted. Vocabulary depth can reflect the richness of semantic representations and the degree of lexical–semantic activation, which can be measured using lexical–semantic decision tasks, semantic categorization tasks, or eye tracking (Huang & Snedeker, 2011; Pexman, Hargreaves, Siakaluk, Bodner, & Pope, 2008). Vocabulary depth also comprises the strength of connections between words and their attributes. These connections may be organized at the phonological or semantic level of representation in the mental lexicon, with evidence to suggest that phonological organization develops more gradually than semantic organization (Riva, Nichelli, & Devoti, 2000; Wechsler-Kashi, Schwartz, & Cleary, 2014). Regardless of the linguistic subsystem being examined, however, weaker connections between words and immature lexical–semantic organization lead to deficiencies in the quality of vocabulary knowledge (Nation, 2014).

In addition to lexical decision or semantic categorization tasks, word definitions offer one strategy for tapping into the depth of children's vocabulary knowledge (Dockrell, Messer, George, & Ralli, 2003). The ability to produce word definitions improves with development (Nippold, 1995). Starting around 7 years of age, typically developing children can provide definitions that are both specific and contain multiple characteristics about a word (Benelli, Arcuri, & Marchesini, 1988; Litowitz, 1977; Wehren, De Lisi, & Arnold, 1981).

Deficits in vocabulary depth have been well established in hearing children with developmental language disorders (DLDs; Botting & Adams, 2005; McGregor, Oleson, Bahnsen, & Duff, 2013; Sheng & McGregor, 2010). McGregor et al. (2013) examined whether delays in depth and breadth of vocabulary knowledge persist or resolve over time. They obtained oral definitions from children with and without DLD at Grades 2, 4, 8, and 10. The researchers measured breadth based on the number of correct definitions the children produced and depth based on the amount of information within each definition. LMMs were utilized to investigate changes in vocabulary depth and breadth over time. McGregor et al. demonstrated that the nature of the vocabulary deficits in the DLD group were characterized by limited depth and breadth. Deficits in both dimensions of vocabulary knowledge persisted across development.

Vocabulary Development in Children With Hearing Loss

The vocabulary domain is often assessed in children with hearing loss to develop goals for individualized education programs, monitor educational progress, and determine whether interventions are effective (Prezbindowski & Lederberg, 2003). However, there are few prospective longitudinal studies that are representative of the current generation of children with mild to severe hearing loss who use hearing aids (HAs; Eisenberg et al., 2007). Most research has focused on describing the factors that are associated with individual differences in vocabulary outcomes for children who are deaf (Blamey et al., 2001; Boons et al., 2013; Lund, Werfel, & Schuele, 2015; Mayne et al., 1998, 1999; Moeller, 2000; Wake, Poulakis, Hughes, Carey-Sargeant, & Rickards, 2005), including children with cochlear implants (CIs; for reviews, see Luckner & Cooke, 2010; Lund, 2015). Thus, there is a gap in the literature regarding how vocabulary breadth and depth develop over time in CHH compared to their same-age hearing peers, as well as what factors influence vocabulary breadth and depth.

Prior to universal newborn hearing screening in the 2000s (Thompson et al., 2001), CHH showed delays in vocabulary size throughout early childhood and into adolescence (Davis, Elfenbein, Schum, & Bentler, 1986; Gilbertson & Kamhi, 1995). These studies consisted of cross-sectional research with a wide age range and small number of participants. Davis et al. (1986) assessed vocabulary skills in 40 school-age CHH ranging in age from 5 to 18 years. Degree of hearing loss had no significant impact on vocabulary size (measured with the PPVT-R), but standard scores for the whole group were significantly lower than the normative data for the test norms. Gilbertson and Kamhi (1995) examined 20 school-age children with mild–moderate hearing loss. Ten of these children received scores in the low average range on the PPVT, whereas another 10 children scored below average. The authors suggested that the CHH who scored below average may have had additional learning disabilities that were unrelated to their hearing loss.

The current generation of CHH have the advantage of being identified and receiving intervention at much earlier ages compared to children born prior to the 2000s (Spivak, Sokol, Auerbach, & Gershkovich, 2009). Because of the earlier identification of hearing loss, researchers can now prospectively measure vocabulary knowledge over time, starting early in development. Moeller, Hoover, et al. (2007) obtained 30-min video and audio recordings of parent–child interactions every 6–8 weeks, starting at 10 months and ending at 24 months of age. The participants all had bilateral mild to profound hearing loss and were early identified. Child utterances were transcribed and coded as either a recognizable word or unrecognizable utterance. Coders used both the phonetic details of the children's utterances and the communicative context to make this distinction. Parents completed the MBCDI (Fenson et al., 1994) at the same visits to assess vocabulary comprehension and production. Vocabulary growth, measured as the proportion of recognizable words from the parent–child interactions and vocabulary scores on the MBCDI at each visit, was analyzed using repeated-measures ANOVA. Infants with mild to severe hearing loss tended to exhibit delays in expressive vocabulary skills starting around 10 months of age, but parallel rates of development up to 24 months, relative to same-age hearing children.

Moeller, Hoover, et al. (2007) showed that, even in the presence of early identification and intervention, CHH exhibit vocabulary delays starting at the onset of first words. The CHH also appeared to maintain their rate of vocabulary growth but did not catch up to same-age hearing peers. Because Moeller et al. ended data collection at 24 months of age, it is unclear whether these vocabulary delays would persist or resolve over time. It is important to identify whether delays in vocabulary will persist, as longstanding deficits have cascading effects on academic achievement and literacy outcomes (Conti-Ramsden, Durkin, Simkin, & Knox, 2009; Cunningham & Stanovich, 1997; Snowling, Bishop, Stothard, Chipchase, & Kaplan, 2006; Tabors, Snow, & Dickinson, 2001).

Stiles, McGregor, and Bentler (2012) provide some evidence regarding the persistence of vocabulary delays in older CHH. They examined receptive vocabulary in 16 school-age CHH. The CHH performed significantly worse on the PPVT compared to an age-matched group of CNH. Maternal education level, chronological age, and aided audibility accounted for a significant proportion of the variance in the CHH. Results from a recent multicenter project, the Outcomes of Children With Hearing Loss (OCHL) study (Moeller & Tomblin, 2015; Tomblin, Harrison, et al., 2015), replicated Stiles, McGregor, et al.'s findings with a large cohort of early-identified, preschool-age CHH and CNH. Because Stiles, McGregor, et al. and Tomblin, Harrison, et al. (2015) used cross-sectional data, these studies cannot inform us about growth trajectories. Furthermore, the conclusions from Moeller, Hoover, et al. (2007); Stiles, McGregor, et al.; and Tomblin, Harrison, et al. are limited because they are isolated to quantitative dimensions of vocabulary knowledge, which are arguably not sensitive to individual differences in how children represent meanings and use words within their lexicon (Gray et al., 1999; Löfkvist, Almkvist, Lyxell, & Tallberg, 2014).

We would expect that children who experience delays in vocabulary breadth might also show deficits in vocabulary depth, given previous findings of deficits in both breadth and depth of vocabulary in children with DLD (Marinellie & Johnson, 2002; McGregor et al., 2013). One underlying cause of quantitative and qualitative vocabulary deficits in children with DLD has been attributed to fragile lexical–semantic organization (Nation, 2014). Atypical lexical–semantic organization has also been seen in children with hearing loss (Wechsler-Kashi et al., 2014), lending further support to the notion that CHH may show deficits in vocabulary depth and breadth. Nevertheless, the question of qualitative delays in vocabulary has not been fully explored, even though it has been stated in the literature that CHH will show delays in depth in addition to delays in breadth (Luckner & Cooke, 2010).

Challenges in Interpreting Longitudinal Data

A major difficulty in conducting longitudinal studies and interpreting growth in outcomes is missing data points. As Moeller, Hoover, et al. (2007) noted, missing data are almost unavoidable in longitudinal research because participants start late, drop out, or miss intervening test visits. Moeller et al. used repeated-measures ANOVA to analyze their data, which excludes any individual with any amount of missing data from the analysis. In repeated-measures ANOVA, the statistical terminology for missing data is *missing completely at random* (MCAR). MCAR specifies that the reason the data are missing is independent of the observed and missing data (Little & Rubin, 2002). This means that the statistical analysis being performed uses the assumption that the reason the data value is missing is not due to any observable measure and is due only to random chance. Therefore, the observations that are missing can be thought of as a random sample among all of the values, and individuals can be dropped from the analysis without biasing the parameter estimates.

As an example, in a given data set, participants were tested between 6 and 10 years of age, but not every child was tested at all of the ages in that range. For a participant that was tested at ages 8 and 9 years, but not at the age of 7 years, we would need to remove all observations for that participant from the analysis if we were using repeated-measures ANOVA. Unfortunately, even though the parameter estimates will be unbiased, dropping the observed observations from a participant that has some missing data from the entire analysis results in reduced sample size and power. LMMs, in contrast, assume *missing at random* (MAR)—a term that sounds similar to MCAR but conceptually means something quite different. MAR means that the missing value does depend on observed values from that individual, but the reason for being missing does not depend on covariates that were not observed. In practice, this means that we can still use the individual participant's data points that were observed for the analysis. For our example of the participant that was tested at ages 8 and 9 years, but not at 7 years, an LMM uses the observed data to approximately fit a regression line through the observed values. We would then assume that any scores from missed visits would approximately follow the same regression trend. This results in increased sample size and power for the study.

The current article will highlight the use of LMMs to conduct longitudinal analyses, rather than a more traditional repeated-measures ANOVA. The LMM approach has a number of advantages, particularly when researchers are working with dynamic longitudinal data sets (Krueger & Tian, 2004). We present a brief tutorial on repeated-measures ANOVA versus LMMs to demonstrate these advantages.

Repeated-Measures ANOVAs Versus LMM in Longitudinal Research

Repeated-measures ANOVA is a traditional approach to the analysis of normally distributed longitudinal or clustered data. They are an extension of paired *t* tests, but with more than two groups. They are included in most statistical software, making them easy to conduct and interpret. A repeated-measures ANOVA involves comparing the outcome measure across multiple measurement points and between independent groups. The independent variables must be categorical (e.g., CNH vs. CHH). The goal is typically to assess change across the measurement items between the independent groups by accounting for within-subject correlation because subjects are measured multiple times. The model is designed by using a random subject effect to separate out the variance in the outcome score into between-subjects variance, σ_s^2, and within-subject residual variance, σ_e^2. The model estimated correlation, also known as intraclass correlation, is computed as $\rho = \frac{\sigma_s^2}{\sigma_s^2+\sigma_e^2}$.

In order for the *F* test to be valid from repeated-measures ANOVA, the assumption of sphericity must hold. One definition of sphericity is that all variances of all pairwise differences between variables are equal (Hedeker & Gibbons, 2006). If sphericity does not hold, then the *F* tests are too liberal. Practically speaking, among the repeated measures, we must assume that all time points have the same correlation with each other as imposed by the model. If the correlations differ from each other, often evaluated using Mauchly's test (Mauchly, 1940), then an adjustment to approximate an *F*-distribution test can be conducted by reducing the degrees of freedom appropriately via Greenhouse–Geisser epsilon (Greenhouse & Geisser, 1959) or Huynh–Feldt epsilon (Huynh & Feldt, 1976).

Repeated-measures ANOVA is an effective testing procedure that is easy to implement in standard statistical software when (a) all of the above assumptions are met, (b) we have complete data on all subjects, and (c) we have relatively equal variances between the repeated measures. However, if at least one of those assumptions is not perfectly met, then LMMs are an alternative that should be considered.

LMMs are extensions of linear regression models that include random effects and correlated errors. LMMs may also be referred to as multilevel models (Duff, Tomblin, & Catts, 2015; Vagenas & Totsika, 2018). An LMM begins with a linear regression model. Consistent with ANOVA methods, we can include group effects known as fixed effects (variables that can be directly observed and are constant across individuals, such as hearing status). The simplest LMM will include a normally distributed subject random effect, also known as a random intercept. *Random effects* are variables whose levels represent a random sample from a population, such as subjects, where we want to capture additional variance or correlation. A *mixed model*, by definition, contains a mix of both fixed effects and random effects. A *random intercept* denotes how far above or below the population group mean an individual will be, on average. If that person is above average on one data point, then we expect that individual to be above average on the other data points as well. Additional random effects can be included in LMMs by incorporating random slope models or hierarchical (nested) repeated structures. These options allow for greater flexibility in the correlations between the measures that are repeated.

It is important to note that both repeated-measures ANOVA and LMMs have their own strengths and weaknesses. Repeated-measures ANOVA is simple to conduct, and interpretation is straightforward. It is easy to calculate relative effect sizes such as eta squared or partial eta squared, which informs us about the practical significance of the results. On the other hand, repeated-measures ANOVA presents us with obstacles that make it difficult to analyze longitudinal data from clinical populations, such as individuals with hearing loss (Horn, Fagan, Dillon, Pisoni, & Miyamoto, 2007). ANOVA is based on the rationale that the data set is complete (no missing data), the participants are randomized in separate groups, and the timing between data points is constant across participants (Krueger & Tian, 2004). Behavioral studies often have difficulty in meeting these assumptions because human variables (illness, weather, fatigue, etc.) or study design factors make it a challenge to obtain all data points for every participant and maintain a fixed schedule across data points. When data points are missing, the analysis can still be conducted, but the participants who are missing any data are removed from the analysis completely, which reduces power and creates bias in the data set. In contrast, because LMMs assume MAR (as described in the earlier section), individuals that have multiple missing data points are still included in the analysis, because the observed values are used to determine the longitudinal trajectory through the use of random effects. Another advantage of LMMs is that they not only allow for modeling linear changes over time in the dependent variable but also nonlinear growth across visits. In a repeated-measures ANOVA, time must be treated categorically, whereas with LMM, time can be treated as a continuous variable or a categorical variable. This flexibility allows participants to enter the study at different time points, as in the case of accelerated longitudinal designs, which combines cross-sectional and longitudinal data into one design (Holte et al., 2012).

The Current Study

CHH experience inconsistent access to auditory–linguistic input and are at risk of vocabulary delays (Tomblin, Harrison, et al., 2015). However, we know little about how vocabulary breadth and depth change with age in CHH, beyond the preschool years. Furthermore, research on depth of vocabulary knowledge in CHH has been overlooked in favor of vocabulary breadth. It is unclear if these risks in the quantity of vocabulary knowledge extend to the quality of vocabulary knowledge and whether these deficits are maintained over time. There is a need for longitudinal research on vocabulary depth and breadth in a contemporary group of CHH with access to early identification and intervention, but this research is often hampered by the challenges inherent in conducting longitudinal research, including small sample sizes, missing data, and variable timing between data points. The current study uses LMM to address these challenges in order to answer the following research questions:

1. How does breadth and depth of vocabulary knowledge change over time for CHH relative to CNH?
2. What factors influence breadth and depth of vocabulary knowledge in CHH?

Method

Participants

Participants included 93 CHH and 62 CNH who were enrolled in a multicenter, longitudinal study on outcomes of children with mild to severe hearing loss—the OCHL study. The primary recruitment sites were The University of Iowa, Boys Town National Research Hospital, and The University of North Carolina at Chapel Hill. CHH had a bilateral hearing loss with a better ear four-frequency pure-tone average in the mild to moderately severe range. Both CHH and CNH had to meet several criteria to participate: (a) spoken English as the primary communication mode, (b) vision within normal limits (with correction), and (c) no major motor or cognitive impairments. Nonverbal cognition was assessed using the Block Design and Matrix Reasoning subtests of the Wechsler Preschool and Primary Scale of Intelligence–Third Edition (Wechsler, 2002) at the age of 4 years and the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler & Hsiao-pin, 2011) at the age of 6 years. Children who were within 1.5 *SD*s of the norm-referenced mean on at least one of the two subtests at 4 or 6 years of age qualified for participation. CNH and CHH were matched by age and socioeconomic status. Demographic information, including audiologic data for the CHH, is provided in Table 1.

Data reported in the current analyses occurred when the children were approximately 7, 8, or 9 years of age. Some of the children from the Iowa and Boys Town test sites also participated in a second longitudinal project that was conducted after the completion of the OCHL study. This second project was called *Complex Listening in School-Age Hard-of-Hearing Children* (hereinafter Complex Listening), and children contributed data at first and/or third grade

Table 1. Demographic characteristics for children who are hard of hearing (CHH) and children with normal hearing (CNH).

	CHH (*n* = 93)		CNH (*n* = 62)	
Variable	***M* (*SD*)**	**Range**	***M* (*SD*)**	**Range**
BEPTA (dB HL)[a]	43.14 (16.06)	7.5–75	< 20	
Aided BESII	0.78 (.14)	0.38–.99		
Age at confirmation (months)	20.90 (22.62)	0.25–84.00		
Age at HA fitting (months)	21.81 (21.83)	1.50–68.00		
Maternal education level (years)	15.09 (2.50)	8.00–22.00	15.94 (3.05)	8.00–22.00

Note. BEPTA = better ear pure-tone average in dB HL; BESII = better ear speech intelligibility index; HA = hearing aid.

[a]The criteria for study enrollment for children who were hard of hearing was a BEPTA of no better than 25 dB HL and no poorer than 75 dB HL. Exceptions were made to include children with mild high-frequency hearing level (three-frequency pure-tone average less than 25 dB HL in the better ear, but thresholds greater than 25 dB HL at 3, 4, or 6 kHz).

(around 7 or 9 years of age, respectively). All participants had completed the WASI Vocabulary subtest during at least one visit over the course of the studies.

Procedure

The OCHL study used a prospective accelerated longitudinal design. Between 2009 and 2013, participants enrolled in the study between the ages of 6 months and 7 years of age and were followed over the length of the study or until 9 years of age. Because participants entered the study at different time points, the number of participants varies at each age level. Starting in 2013, children who had completed the OCHL study from the Iowa or Boys Town National Research Hospital test sites were enrolled in the Complex Listening study. The Complex Listening study used a longitudinal design, in which children were tested during or the summer after first and third grade. The average age of the first graders in the Complex Listening study was 7.62 (SD = 0.44), and the average age of the third graders was 9.33 (SD = 0.42).

For the current analysis, participants from the OCHL and Complex Listening studies contributed data from the WASI Vocabulary at up to three ages: 7 years (CHH, n = 74; CNH, n = 44), 8 years (CHH, n = 37; CNH, n = 19), and 9 years (CHH, n = 39, CNH, n = 28). The average length of time between visits was 1.4 years (SD = 0.65, range: 0.4–3.04). Because participants entered the study at different time points, they varied in terms of the number of visits or "repeats." Furthermore, some participants were seen at the 7-year-old visit, missed the 8-year-old visit, and were seen again at the 9-year-old visit. We had 93 children with only one visit, 38 with two visits, and 24 with three visits. In a repeated-measures ANOVA, the missing data points would result in listwise deletion, allowing the analysis on only 24 subjects.

Audiologic Assessment and HA Verification

An audiologist completed a hearing assessment at each test visit. The audiologist obtained air- and bone-conduction thresholds at 500, 1000, 2000, and 4000 Hz at a minimum. The four-frequency better ear pure-tone average was then calculated. CNH were screened in both ears at 20 dB HL at these four frequencies.

For CHH, the audiologist determined that HAs were functioning within manufacturer specifications using ANSI (ANSI S3.22-2003) conformity measures of HA function. The aided speech intelligibility index (SII; ANSI S3.5-1997) was calculated for both ears to estimate the audibility of speech with the HA based on the child's age, ear canal acoustics (measured real-ear-to-coupler difference or age-average real-ear-to-coupler difference) and hearing thresholds. SII represents access of the audible speech spectrum at a conversational speech level (65 dB SPL) from a distance of 1 m.

Vocabulary Assessment

Children's breadth and depth of vocabulary were assessed using an adaptation of the WASI Vocabulary subtest. The WASI Vocabulary subtest is a standardized measure of expressive vocabulary. The examiner asks the participant to define an item. There is only one version of the WASI Vocabulary, so the same words were presented to the participants at each visit. Children ages 6–8 years have the potential to answer 30 items, and children ages 9–11 years have the potential to answer 34 items. In the standardized version of the WASI Vocabulary, responses receive 0, 1, or 2 points based on accuracy. Examiners prompted children for additional information, as necessary, when indicated by the WASI Vocabulary manual. Testing ceased when participants reached ceiling (five consecutive scores of 0) or the highest item possible for their age, whichever occurs first. Participants' responses were audio-recorded and transcribed in their entirety.

For the purposes of the current study, we adapted the scoring on the WASI Vocabulary to capture subtle differences in depth of vocabulary knowledge. The adapted scoring system was developed from previously described protocols (Duff, 2015; McGregor et al., 2013). Depth of knowledge was assessed using a 5-point quality scale. To develop the 5-point scale, we identified semantic elements and elaborative details for the first 30 target words. Definitions received a score of 0 if the child presented (a) only incorrect information, (b) produced a morphological derivative of the target (e.g., shirt*s* for shirt or mapp*ed* for map) without providing additional explanation, or (c) produced an unconventional definition or an idiom. Definitions received a score of 1 if the child produced (a) only one semantic element and either used the incorrect part of speech or an unconventional definition, (b) used the word correctly in a novel sentence, or (c) included only elaborative details. Definitions received a score of 2 if the child produced one semantic element and used the correct part of speech. Definitions received a score of 3 if the child used two semantic elements. Definitions received the highest possible score of 4 if the child produced two semantic elements and elaborative details or three semantic elements. The minimum depth score a child could receive was 0, and the maximum score was 120 (4 × 30). Examples of semantic elements and elaborative details for each word are included in the Appendix.

Vocabulary breadth was also assessed using the WASI Vocabulary measure. For a given item, children received credit for vocabulary size if they received a score of 1 or better on the quality scale. Consistent with McGregor et al. (2013), vocabulary breadth is operationally defined here as being able to recognize and provide some accurate information about a word. The minimum breadth score a child could receive was 0, and the maximum score was 30.

Two research assistants coded all of the definitions independently for all children. Disagreements of greater than 1 point were resolved via consensus. Disagreements that were within 1 point were averaged together. Reliability was calculated as total agreement within 1 point divided by total words. Reliability between coders was 96%.

Statistical Analyses

The first research question evaluated how breadth and depth of vocabulary changes across age. To address this research question, we constructed an LMM for breadth and another LMM for depth to test for mean differences between groups (CHH vs. CNH). The model for breadth was an LMM with group, age, and a Group × Age interaction for fixed effects. Here, there was only one observation per time point where the outcome score was the number of words identified correctly. We used the Akaike information criterion (AIC) to assist with selecting the appropriate statistical model. A lower AIC value indicates better quality of fit; thus, we chose the model that demonstrated the minimum AIC. The random intercept model yielded the lowest AIC (AIC = 1,243), whereas a random intercept and slope model was slightly higher (AIC = 1,245).

The model for depth included group and age as fixed effects, whereas a random intercept for subject was included to account for within-subject correlations (Model 1). Other models under consideration had the same fixed effects, but a random intercept for subject and a random slope for age (Model 2) and a random intercept for subject plus a random intercept for word (Model 3) to account for subject-specific slopes over age and variance between words, respectively. The AIC was again used to select which random effects to include in the final depth model. Model 3 was the best fitting model (AIC = 17,252, 17,254, 13,224, respectively). An interaction term between group and age was investigated, but including the term resulted in a larger AIC value and was thus not included in the final model.

For all models, a Satterthwaite adjustment was used to compute the degrees of freedom. Relative effect sizes were computed following Brysbaert and Stevens (2018). Analyses were performed using the lmer4 package in R.

The second research question examined what factors were associated with individual differences in vocabulary breadth and depth for only CHH. To conduct this analysis, we constructed two separate LMMs with a random intercept to account for within-subject correlation on the breadth and depth measures. The dependent variables for the two models were total breadth score and total depth score. The independent predictor variables were maternal education level, aided SII, age at HA fitting, and chronological age. Dummy variables represented the categorical variables in the statistical models. Maternal education level was coded as ordinal levels (1 = *high school or less,* 2 = *some college,* 3 = *bachelor's degree,* 4 = *postgraduate,* with 1 as the reference level). Age at HA fitting was coded as a dichotomous variable (1 = *HA fitting < 6 months,* 2 = *HA fitting > 6 months,* with < 6 months as the reference level).

Results

Research Question 1: Changes in Breadth and Depth of Vocabulary Knowledge Over Time

For vocabulary breadth, the estimated subject variance was 6.91, whereas the estimated residual variance was 4.70, indicating a substantial amount of between-subjects variability, $\hat{\rho} = 0.595$. Table 2 summarizes the results of the LMM for breadth. We found a significant main effect for group ($\hat{\beta} = 8.65$, $p = .0059$, $d = 2.54$), a significant main effect for age ($\hat{\beta} = 1.46$, $p < .0001$, $d = 0.43$), and a nearly significant interaction between group and age ($\hat{\beta} = -0.76$, $p = .0547$, $d = 0.13$). CNH had breadth scores that were on average 8.65 words more than CHH, with both groups increasing with age by about 1.45 words per year. However, the difference between the groups diminished over time as determined from the negative interaction term (see Figure 1). Although it is not strictly statistically significant at the .05 level of significance, it is important to note that the narrowing over time is clinically relevant. We found significant mean differences in favor of the CNH at ages 7 years (diff = 3.32, $p < .0001$), 8 years (diff = 2.56, $p < .0001$), and 9 years (diff = 1.79, $p = .01$), but with diminishing differences between groups across age. Figure 1 shows the changes in the breadth of vocabulary for the two groups across age.

The estimated random effects for depth were 0.12 for between-subjects variance, 0.52 for between-words variance, and 0.48 for residual variability, indicating substantial between-subjects variance. Table 3 summarizes the results of the LMM for depth. We found a statistically significant group effect ($\hat{\beta} = 0.24$, $p < .0001$, $d = 0.22$) and age effect ($\hat{\beta} = 0.26$, $p < .0001$, $d = 0.25$). CNH had, on average, a depth score that was 0.24 points higher than CHH. Older children had scores 0.26 higher per year on average. Unlike the vocabulary breadth measures, we did not see a significant interaction between group and age. Figure 2 shows the changes in depth of vocabulary for the CHH and CNH, with parallel rates of development across age.

Research Question 2: Factors Associated With Vocabulary Breadth and Depth in CHH

To understand what factors were related to breadth and depth scores for the CHH, we used LMM (see Tables 4 and 5). As described in the Statistical Analysis section, the independent predictor variables were maternal education level, aided SII, age at HA fitting, and chronological age. For breadth, a random intercept model was used to account for within-subject correlation. Results indicate that chronological age ($\hat{\beta} = 1.39$, $p < .0001$, $d = 0.41$), maternal education level ($\hat{\beta}_2 = 2.57$, $\hat{\beta}_3 = 0.15$, $\hat{\beta}_4 = -0.24$, $d_2 = 0.76$, $d_3 = 0.04$, $d_4 = 0.07$, $F(3, 71.58) = 4.54$, $p = .0225$), and SII ($\hat{\beta} = 13.50$, $p < .0001$, $d = 4.00$), were all significantly related to breadth, but not age at HA fitting ($\hat{\beta} = -0.65$, $p = .4111$, $d = 0.19$). Older age, higher maternal education level, and greater audibility were related to increased breadth of vocabulary.

For depth, a random intercept and random word effect were included to account for within-subject correlation and between-words variation. Chronological age ($\hat{\beta} = 0.27$, $p < .0001$, $d = 0.25$), maternal education level ($\hat{\beta}_2 = 0.32$, $\hat{\beta}_3 = 0.02$, $\hat{\beta}_4 = -0.10$, $d_2 = 0.30$, $d_3 = 0.02$, $d_4 = 0.09$, $F(3, 72.78)$, $p = .0040$), and SII ($\hat{\beta} = 0.53$, $p = .0074$, $d = 0.50$) were significantly related to depth. Older age, higher maternal education level, and greater audibility were related to increased depth of vocabulary. Age at HA fitting ($\hat{\beta} = -0.10$, $p = .2541$, $d = 0.09$) was not.

Table 2. Linear mixed model with hearing status and age as the fixed effects and vocabulary breadth as the dependent variable (pairwise contrasts are indented).

Parameter	Estimate	Test (*df*)	*p*	Effect size
Hearing status (reference = NH)	8.65	*t* = 2.80 (146.03)	.0059	*d* = 2.54
Age	1.46	*t* = 6.02 (129.60)	< .0001	*d* = 0.43
Hearing status × Age	−0.76	*t* = −1.94 (140.89)	.0547	*d* = 0.13
Age 7 (HH vs. NH)	3.32	*t* = −5.46 (215.24)	< .001	*d* = 0.97
Age 8 (HH vs. NH)	−2.56	*t* = −4.75 (164.16)	< .001	*d* = 0.75
Age 9 (HH vs. NH)	−1.79	*t* = −2.49 (236.84)	.0134	*d* = 0.53

Note. *df* = degrees of freedom; NH = normal hearing; HH = hard of hearing.

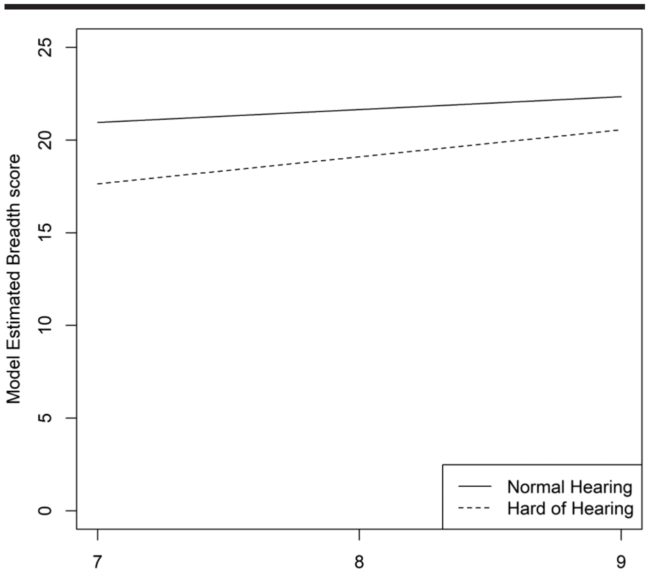
Discussion

The goal of this study was to compare the trajectories of vocabulary depth and breadth in school-age CHH and CNH. In addition to examining the developmental trajectories of vocabulary knowledge, we also examined factors that may support vocabulary depth and breadth in CHH. Identifying sources of individual variability in vocabulary knowledge will provide insight into effective, evidence-based interventions with this population of children (Moeller, Tomblin, et al., 2007).

Repeated-Measures ANOVA and LMMs

One analytic approach for addressing the question of how vocabulary breadth and depth change over time would be to use a repeated-measures ANOVA and compare related means as a function of visit (Moeller, Hoover, et al., 2007). Another approach would be to use an extension of linear regression models, LMM. The complexity of the current data set made it challenging to meet the assumptions of a repeated-measures ANOVA; therefore, we constructed LMMs to analyze the data. As described in the Introduction section, LMMs offer a number of advantages over repeated-measures ANOVA. First and foremost, LMMs are more flexible at handling missing data and dropout than ANOVA. Repeated-measures ANOVA also reduces the degrees of freedom in the *F* test to approximate an *F* distribution due to violations of the sphericity assumption. Although there is no widespread agreement in the degrees of freedom to use in an LMM, the degrees of freedom is at least as large in an LMM compared to the ANOVA model. As a result, LMMs are more statistically powerful than ANOVA because participants with missing data are not removed entirely. Second, LMM can readily account for important continuous and categorical covariates. Third, LMM is more flexible in handling the correlation between the repeated measurements, which is critical in longitudinal studies.

Figure 1. Breadth scores by group and age.



Although LMM is more appropriate than repeated-measures ANOVA for analyzing dynamic, longitudinal data, undergraduates and postgraduates in communication sciences and disorders and related fields are more familiar with the repeated-measures ANOVA approach (Krueger & Tian, 2004; Vagenas & Totsika, 2018). One of the aims of this article was to describe the utility of LMMs in behavioral research. Although we cannot contribute a full description of LMMs due to space limitations, our hope is that we can provide clinicians and researchers with enough information to recognize when an LMM would be more beneficial to use than a repeated-measures ANOVA.

Developmental Trajectories of Vocabulary Breadth and Depth in CHH and CNH

The present findings indicated that school-age CHH showed deficits in both vocabulary breadth and vocabulary depth compared to CNH. The reduced vocabulary size in the CHH is consistent with prior cross-sectional research in children who are deaf or hard of hearing (Blamey et al., 2001; Davis et al., 1986; Gilbertson & Kamhi, 1995; Moeller, 2000; Sarchet et al., 2014; Stiles, Bentler, & McGregor, 2012; Stiles, McGregor, et al., 2012; Tomblin, Harrison, et al., 2015). The results on vocabulary depth are also in line with previous work on children who are deaf (Coppens, Tellings, Verhoeven, & Schreuder, 2011,

Table 3. Linear mixed model with hearing status and age as the fixed effects and vocabulary depth as the dependent variable.

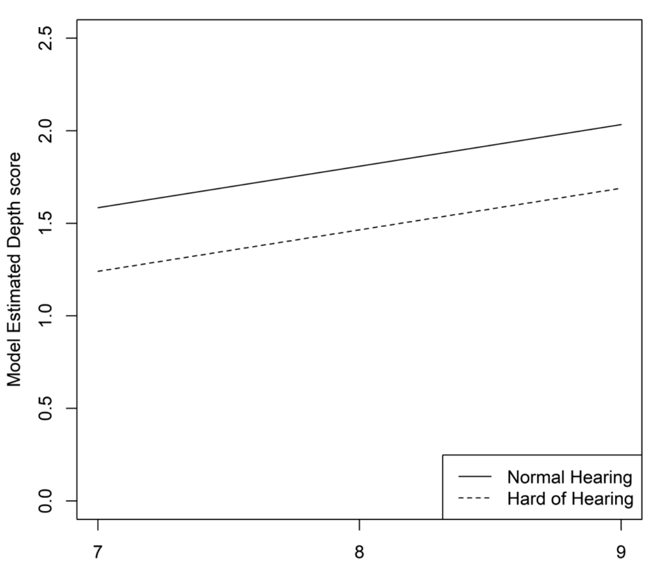
Parameter	Estimate	Test (*df*)	*p*	Effect size
Hearing status (reference = NH)	0.24	$t = 3.93$ (153.34)	.0001	$d = 0.22$
Age	0.26	$t = 19.53$ (5,301.27)	< .0001	$d = 0.25$

Note. *df* = degrees of freedom; NH = normal hearing.

2013; Paul & Gustafson, 1991). To the best of our knowledge, however, this is the first study to examine vocabulary depth in CHH with access to early identification and intervention.

Developmental trajectories in vocabulary depth and breadth are not well documented in school-age CHH. Therefore, we compare the present results to studies on children with DLD. McGregor et al. (2013) examined how breadth and depth of vocabulary knowledge develops over time in a large group of children with DLD and children who were typically developing. Unlike the current study, which examined changes between 7 and 9 years of age, McGregor et al. explored a longer time span of second to 10 grade. Results between the two studies were consistent in several ways: (a) Vocabulary depth and breadth improved over time, (b) typically developing children outperformed children in the diagnostic groups (DLD or CHH), and (c) the magnitude of the deficits between diagnostic groups in vocabulary depth remained constant over time. The two data sets differed with respect to vocabulary breadth. McGregor et al. did not find a significant Visit × Group interaction, indicating that children with DLDs demonstrated consistent delays in vocabulary size over time. In contrast, we saw a nearly significant interaction with vocabulary breadth between visit and group in the current results, and the mean difference between groups grew progressively smaller. Figure 1 demonstrates how CHH gradually narrowed the gap in their vocabulary size, relative to same-age hearing peers, whereas Figure 2 shows the stable growth trajectories in vocabulary depth for the two groups. We also note, however, that the mean difference in CHH had not caught up to the CNH by the age of 9 years. To establish that the gap in vocabulary size actually is diminishing over time, we intend to continue testing this cohort of children into secondary grades.

Figure 2. Depth scores by group and age.



The results from the current study support the view that CHH have less in-depth knowledge of words. In the DLD literature, researchers have suggested that reduced depth of vocabulary knowledge is associated with differences in lexical–semantic connections (Nation, 2014), as well as impoverished lexical–semantic representations (Dockrell et al., 2003). At this point, it would be speculative to state that the deficits in vocabulary depth for CHH are the result of fragile lexical–semantic representations. Our word definition task is limited because it is an end-point metric that does not lend itself to evaluating how CHH activate and process lexical information. To understand how children represent lexical–semantic knowledge in long-term memory, we could use online tasks that evaluate lexical access and word recognition. For example, eye-tracking in the visual world paradigm explores activation at both the phonological and semantic levels in real time (Allopenna, Magnuson, & Tanenhaus, 1998; Huang & Snedeker, 2011). The visual world paradigm has been used in children with CIs, with evidence to suggest that they show atypical lexical competition effects (McMurray, Farris-Trimble, & Rigler, 2017), but the paradigm has not been applied to CHH. Another example of an online measure is event-related potentials such as N400 responses. The typical N400 response is elicited in the presence of semantically incongruent stimuli, which provides information about the time course of lexical–semantic processing. To date, one study has used an N400 paradigm to evaluate lexical–semantic organization in 15 CHH, ages 5–7 years old (Kallioinen et al., 2016). CHH showed reduced effects on the event-related potential responses compared to age-matched CNH, which is a possible indicator of a less well-developed lexical–semantic organization. Overall, online lexical–semantic processing in CHH is an unexplored area, but such research may better inform us about how children activate and use words in the presence of degraded auditory–linguistic input.

Table 4. Linear mixed model with age, aided audibility, age at hearing aid fitting, and maternal education levels as fixed effects and vocabulary breadth as the dependent variable (pairwise contrasts are indented).

Parameter	Estimate	Test (*df*)	*p*	Effect size
Age	1.39	*t* = 4.73 (68.37)	< .0001	*d* = 0.41
SII	13.50	*t* = 5.31 (70.52)	< .0001	*d* = 4.00
Age at HA fitting (reference < 6 months)	−0.65	*t* = −0.83 (76.68)	.4111	*d* = 0.19
Maternal education		*F* = 3.39 (3, 71.58)	.0225	
1 vs. 2	2.57	*t* = 2.52 (71.28)	.0143	*d* = 0.76
1 vs. 3	0.15	*t* = 0.15 (69.13)	.8958	*d* = 0.04
1 vs. 4	−0.24	*t* = −0.22 (70.01)	.9155	*d* = 0.07
2 vs. 3	−2.42	*t* = −2.46 (71.64)	.0163	*d* = 0.72
2 vs. 4	−2.81	*t* = −2.69 (74.70)	.0108	*d* = 0.83
3 vs. 4	−0.39	*t* = −0.37 (73.07)	.8120	*d* = 0.12

Note. *df* = degrees of freedom; SII = speech intelligibility index; HA = hearing aid.

Factors Associated With Vocabulary Breadth and Depth in CHH

In addition to group differences in vocabulary depth and breadth, we also noted large variation in both metrics for the CHH. This variation in language outcomes is typical in children with hearing loss (Moeller, Tomblin, et al., 2007). One of the central hypotheses of the OCHL study is that the consistency of auditory access accounts for individual differences (Moeller & Tomblin, 2015). Effective interventions, including earlier fitting of HAs, better audibility from HAs, and high-quality linguistic input from caregivers, are expected to have a positive influence on the child's cumulative auditory–linguistic experience. Increased experience with linguistic input will result in more efficient language processing skills, whereas reduced auditory access will exacerbate risk for language delays. We have evidence to support this inconsistent access hypothesis in the areas of speech perception (McCreery, Walker, Spratford, Oleson, et al., 2015), global language development (Ambrose, Walker, Unflat-Berry, Oleson, & Moeller, 2015), morphosyntactic development (Koehlinger, Van Horne, & Moeller, 2013), and understanding of false belief (Walker, Ambrose, Oleson, & Moeller, 2017). This article was the first from the OCHL study to specifically examine whether auditory access impacts vocabulary knowledge.

Not surprisingly, vocabulary breadth increased with age (Duff et al., 2015). Maternal education level also contributed to variation in vocabulary breadth. Studies have demonstrated that maternal education level has a significant effect on vocabulary knowledge in CNH (Fernald, Marchman, & Weisleder, 2013; Hirsh-Pasek et al., 2015; Hoff, 2013; Weisleder & Fernald, 2013). The majority of work on children with hearing loss also shows a significant association between maternal education level and language outcomes (Ching et al., 2013; Fitzpatrick, Crawford, Ni, & Durieux-Smith, 2011). Although not directly measured in the current study, we also note that the quality and quantity of language input from adult caregivers and clinicians has a strong impact on vocabulary development in children with hearing loss (Lund & Douglas, 2016; Szagun & Stumper, 2012). Taken together, these results highlight the crucial role of environmental input on outcomes in children with hearing loss, in addition to consistent auditory access.

After accounting for age and maternal education level, children with higher aided audibility demonstrated greater vocabulary breadth. In a separate study with 16 CHH,

Table 5. Linear mixed model with age, aided audibility, age at hearing aid fitting, and maternal education levels as fixed effects and vocabulary depth as the dependent variable (pairwise contrasts are indented).

Parameter	Estimate	Test (*df*)	*p*	Effect size
Age	0.27	*t* = 13.49 (2600.58)	< .0001	*d* = 0.25
SII	0.53	*t* = 2.70 (298.84)	.0074	*d* = 0.50
Age at HA fitting (reference < 6 months)	−0.10	*t* = −1.15 (73.58)	.2541	*d* = 0.09
Maternal education		*F* = 7.28 (3, 72.78)	.0040	
1 vs. 2	0.32	*t* = 2.75 (73.01)	.0075	*d* = 0.30
1 vs. 3	0.02	*t* = 0.20 (72.14)	.8412	*d* = 0.02
1 vs. 4	−0.10	*t* = −0.80 (72.05)	.4260	*d* = 0.09
2 vs. 3	−0.29	*t* = −2.66 (73.11)	.0095	*d* = 0.27
2 vs. 4	−0.41	*t* = −3.54 (73.45)	.0007	*d* = 0.38
3 vs. 4	−0.12	*t* = −1.02 (72.92)	.3091	*d* = 0.11

Note. *df* = degrees of freedom; SII = speech intelligibility index; HA = hearing aid.

Stiles, Bentler, et al. (2012) also found that aided audibility accounted for a significant proportion of variance in vocabulary size. Although not specific to vocabulary outcomes, Tomblin, Harrison, et al. (2015) showed that children with higher aided audibility had steeper growth trajectories in global language skills compared to children with lower aided SII. Thus, these studies provide further evidence for one of the sources of vocabulary delays in CHH. Specifically, auditory access via well-fit HAs has a substantial impact on vocabulary knowledge. These results have important implications for clinical services for young CHH. Results from our research team and others support the importance of using best practices to manage pediatric amplification, specifically using real-ear or simulated real-ear measures to ensure HAs are optimally fit (Bagatto et al., 2016; McCreery, Bentler, & Roush, 2013; McCreery, Walker, Spratford, Bentler, et al., 2015; Moodie, The Network of Pediatric Audiologists of Canada, Scollie, Bagatto, & Keene, 2017).

Although aided SII was a significant predictor of vocabulary breadth, we did not find an association with age at HA fitting. Previous literature in this area has been mixed. Sininger, Grimes, and Christensen (2010) reported that age at HA fitting was the largest single predictor of spoken language skills. On the other hand, Ching et al. (2013) did not find a significant impact of age at HA fitting on language outcomes in 3-year-olds with mild to profound hearing loss. Tomblin, Harrison, et al. (2015) reported that age at HA fitting had a significant impact on global language skills at the age of 2 years, but the effect diminished by the age of 6 years. Furthermore, children who were later fit displayed accelerated language growth once they started wearing HAs. Although we did not see a significant impact of age at HA fitting on vocabulary breadth, we still advocate for providing amplification soon after diagnosis for all degrees of hearing loss, in line with the recommendations of the Joint Committee on Infant Hearing (2007). Earlier, consistent access to sound provides a strong foundation for oral language development, reduces the likelihood that CHH will have to “catch up” over time, and may act as a moderator of later functional abilities once children enter school.

Consistent with the vocabulary breadth data, age, maternal education level, and higher aided SII were associated with deeper vocabulary knowledge, and age at HA fitting did not predict individual differences in vocabulary depth. Hoff and Naigles (2002) proposed that children who are exposed to greater variety of words in different contexts have deeper semantic knowledge. Higher aided audibility may increase opportunities to participate in and overhear conversations among adults and peers, leading to increased depth of vocabulary. An additional, unexplored mechanism is metalinguistic knowledge or the understanding of what information would be useful and relevant when describing words. Marinellie and Johnson (2002) reported that difficulties with metalinguistic knowledge contributed to poorer performance on vocabulary depth measures in children with DLD. It is possible that CHH would show a similar association, but further investigation is needed to test this hypothesis.

Limitations and Future Directions

This study represents an important contribution to the literature on CHH because it is the first to compare developmental trajectories in vocabulary knowledge for age-matched CHH and CNH. Nevertheless, we note that there are several limitations. One major limitation of this study is that we were constrained to a word definition task as our index of vocabulary breadth and depth. Word definitions are a valid means to examine vocabulary knowledge (Duff et al., 2015; McGregor et al., 2013; Nippold, 1995), but they also tap into working memory and metalinguistic knowledge of how to define words (Marinellie & Johnson, 2002). We did not control for either of these factors in this study. Stiles, McGregor, et al. (2012) reported that verbal working memory skills were not delayed in CHH compared to CNH but also noted large individual differences in working memory and an association with vocabulary size. Future directions should include adjusting for metalinguistic knowledge, working memory, and executive function in the analysis. These two factors can be easily included as fixed effects in an LMM analysis.

Word definition tasks, particularly the WASI Vocabulary test, are somewhat restricted in that they are contrived and decontextualized. We also acknowledge that longitudinal results may have been impacted by practice effects because there is only one version of the WASI Vocabulary words. Children would have been exposed to the same list of words on an annual basis. As stated earlier in the Discussion section, we encourage researchers to utilize more creative means to assess lexical–semantic representations and activation in real time for CHH. This information will provide us with insight into the mechanisms underlying reduced vocabulary breadth and depth for children who are acquiring language via a degraded and inconsistent signal.

We were also limited in our age range for the current study. The longitudinal sample only included data up to 9 years of age. Vocabulary development is influenced by reading ability in later grades (Duff et al., 2015); however, there is still a lack of knowledge about reading skills in CHH (Moeller, Tomblin, et al., 2007) and the interaction between reading and vocabulary knowledge. We see a critical need to investigate language and literacy development in adolescents and teens who have mild to severe hearing loss and use HAs, as much of our literature focuses on children who are deaf and/or use CIs or preschool-age CHH.

Finally, we acknowledge that both the CHH and the CNH in the OCHL study represent an economically advantaged group of children, on average. The maternal education levels of the cohort as a whole are higher than the U.S. population (Tomblin, Walker, et al., 2015), and participants also used spoken English as their primary mode of communication. Therefore, it is unclear whether these findings would extend to children from lower socioeconomic or culturally/linguistically diverse backgrounds. Furthermore, the current findings may not generalize to children with additional disabilities, as the OCHL sample excludes children with visual, cognitive, or motor impairments. Results should be interpreted with caution, given the strict inclusionary and exclusionary criteria for the participants in this study. It is possible that the current findings overestimate the vocabulary skills of CHH.

Conclusions

Although repeated-measures ANOVA has a long history as a useful statistical method, many of today's research questions can be better addressed using mixed models. The current study used robust statistical techniques that take into account both longitudinal growth and repeated items per time point. As a group, school-age CHH demonstrate deficits in both breadth and depth of vocabulary knowledge at the age of 7 years. Vocabulary depth deficits appeared to remain stable up to the age of 9 years, with parallel growth rates for the CHH and CNH. Vocabulary breadth deficits for the CHH decreased with age, as they showed accelerated growth rates compared to the CNH. It is unclear whether CHH will be able to completely close the gap with their hearing peers later in development. These findings also expanded our understanding of the factors that support growth in vocabulary breadth and depth in CHH, with higher aided audibility and maternal education level supporting both dimensions of vocabulary skills. Further research is needed to understand the nature and developmental time course of vocabulary depth and breadth in later adolescence for CHH.

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Scoring System, Semantic Elements, and Elaborative Details for the Wechsler Abbreviated Scale of Intelligence Vocabulary Words

0 = *No real grasp of the word*	**1 = *Very surface-level understanding***	**2 = *Very basic/partial definition***	**3 = *Sufficient understanding of the word***	**4 = *Very deep understanding and well elaborated definition***

• Incorrect information/no semantic relationship
• "Don't know"
• Morphological derivative without correct information
• Phonologically similar word
• Very idiosyncratic semantic relationship (unconventional definition) without semantic elements/ with incorrect information
  • Note! Includes idioms/colloquial phrases (if only information given)
	• One semantic element AND EITHER:
	  • Incorrect part of speech
	  • Unconventional definition/idiosyncratic semantic relationship
	• Correct use of word in novel sentence
	  • Note! NOT correct use in an idiom or colloquial phrase
	• Correct elaborative details only, with NO semantic elements
		• One semantic element AND correct part of speech
		  • Note! At this point, an unconventional definition brings the score down to a 1
			• Two semantic elements
			• Note! At this point, an unconventional definition DOES NOT bring the score down
				• Two semantic elements AND elaborative detail(s)
				• Three semantic elements (with or without details)

Word Definitions (* = not acceptable; POS = part of speech)

Word	POS	Semantic elements	Elaborative details
Fish	Noun/verb	• Lives in water • Animal • Swims • Catch/caught • Eat/eaten • Cold blooded	• Scales • Gills • Breathe water • Bubbles
Shovel	Noun/verb	• Tool • Used to dig/throw • Scoop and handle	• Dirt/sand/snow/food • Sandbox toy
Map	Noun/verb	• Represent/shows an area • Streets • States/countries • Directions • GPS	• Atlas • Google Maps • "Map it out"/plan • Paper map • Maps on devices

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Scoring System, Semantic Elements, and Elaborative Details (ED) for the Wechsler Abbreviated Scale of Intelligence Vocabulary Words

Word	POS	Semantic elements	Elaborative details
Shell	Noun/verb	• Hard covering of animal/insect/nut/egg • Protects • Supports • Found on beach	• Peanuts/eggs/examples • Fragile/breakable (egg shells)
Shirt	Noun	• Clothing • Worn • Upper body • Covers	• Sleeves • Collar/buttons/zipper • Types/examples • Put on/goes on • Fabric types (cloth, cotton, yarn*) • Laundry
Flashlight	Noun	• Use in dark • Small light • Helps you see • Turn on/off • Search/find	• Batteries • Phone flashlights • Light bulb • Bright/other physical elements
Shoe	Noun	• Foot • Protection • Worn	• Types/examples • Laces/buckle/straps/Velcro • Sole/heel • Put on/goes on • Purpose (walk, run, etc.)
Car	Noun	• Vehicle • 4 Wheels (steering wheel is ED) • Carries people • Engine • Drive them/ride in them • Helps get from place to place/go places	• Types/examples/automobile • 4 Doors • Windows/seatbelts/car seats • Roads/stoplights • Gas • One part of a train • Alternative to walking
Bird	Noun	• Animal • Flies • Lays eggs • Beak/wings/feathers • Warm blooded • Chirps/sings/tweets • Eats worms	• Migration • Can be hunted/eaten • Nests in trees • Types/examples • NOTE: *to go birding, *badminton birdie • We eat it
Calendar	Noun	• Schedule/ chart • Days/weeks/months • Shows important days/holidays • Show/record activities/shows activities for the day	• Wall calendar/planners • Birthdays • School calendars/events • Mark off/cross off days • Used for reminders
Number	Noun/verb	• Word/symbol to assign how much/how many/quantity • Used to count • Used for math	• Adding/subtracting/multiply/divide • Number 1 = best (ranking) • Counting (out loud: 1, 2, 3, 4, …) • Age, date, other examples of things numbers are used for
Bell	Noun	• Metal • Musical instrument • Rings/high pitched/ding/makes noise • Church/clock towers • End of wind instrument • School bells • Hollow/cup shaped	• Gets people's attention • Bell choirs • Pet collars • Sleigh bells • Any other examples of bells
Lunch	Noun/verb	• Food/meal • Middle of the day/noon/12 o'clock • Eat • After breakfast/ before dinner/second meal of the day	• Lunch break/recess • Sandwiches • School lunches (hot/cold) • Not dinner or breakfast • Hungry
Police	Noun/verb	• Officers/group/squad/cops • Enforce laws/arrest • Investigate crimes • Keep people safe/protect • Control/keep order • Guns (other weapons used) • Give speeding tickets/car accident help	• Badges • Sirens • Cars/lights • Police station • Donuts and coffee • Crossing guard • Uniform

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Scoring System, Semantic Elements, and Elaborative Details for the Wechsler Abbreviated Scale of Intelligence Vocabulary Words

Word	POS	Semantic elements	Elaborative details
Vacation	Noun/verb	• Time away/off from school/work (or a break from…/get away) • Relax • Travel/go somewhere/go somewhere else • Visit someone [in another place]	• Missing school • Airplanes/hotels • Florida/locations • Beach/tropics • Warm • Holiday • Go with family • Have fun
Pet	Noun/verb	• Animal in the home • Family owned (animal you have) • Friend/keeps you company/companion • Stroke gently • Take care of/play with	• Spoiled/love • Walks/train • Feeding • Leash/collar/bowl • Types/examples • Just say "animal" • From a "pet" store • Not wild • Protection (somewhat)
Balloon	Noun/verb	• Filled with air/gas (helium/oxygen) • Expands when filled • Floats (flies) • Blow it up	• Clowns have them • Float away/get lost/pop • Circus/fairs • Loud noise when popped • Can make animals with them • String attached to it • Circle/oval • Hold it/hit it/play with it • Parties • Can be filled with water
Transform	Verb	• To *change* completely in form or appearance • To *become* something different	• The Frog princess/examples • Explaining transformation process • NOTE: *Transformers without explanation
Alligator	Noun	• Reptile • Big/sharp teeth • Big jaws/bite/chomp • Live in water and land/swamp • Long body/long tail • Green • Eat animals/carnivore/predator • Cold blooded	• Crocodile • Short legs • Scales/armored body • Swim with eyes out of water • Everglades/Florida • Lagoons • Sewers • Could be dangerous • Can see at zoo • Lay eggs (related to being a reptile)
Cart	Noun/verb	• Small-wheeled vehicle • Usually pushed/pulled around • Move things with it/carry things in it	• Horse-drawn vehicle • Grocery cart • Food vendors (ice cream cart) • Farm equipment • Minecart • Can ride in it • Metal/plastic/basket-like Not train car
Blame	Noun/verb	• Say/think that a person/thing is responsible for something (to place responsibility on someone else) • Fault/responsible • The supposed responsibility	• Guilty/innocent • Trouble/punishment • Bad/naughty/breaking rules • Tell on someone/tattle • Lie • Do it to avoid getting in trouble
Dance	Noun/verb	• Move with the music • Rhythm • Something you go to (to see or to perform) • A sport	• Dance class/recital • Types/examples • Ballet shoes/tutus/dresses • Balls • Exercise • Self-expression
Purpose	Noun	• The reason for doing something • The goal of an action • Inspiration/meaning/intention	• Doing something on purpose • Not accidentally

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Scoring System, Semantic Elements, and Elaborative Details for the Wechsler Abbreviated Scale of Intelligence Vocabulary Words

Word	POS	Semantic elements	Elaborative details
Entertain	Verb	• To hold someone's attention • To make happy/excited • Fun to watch/do • Have guests/people over • Perform/to put on a show (could include dancing or singing)	• Shows/performances • Games/play • TV/Netflix/movies • Sporting events • Museums • Clowns
Famous	Adjective	• Well known (details about life are known) • Popular • Widely recognized	• In the news/magazines • Have paparazzi • Examples/names—gives examples of jobs (athlete, singer, actor, dancer, author, government official, etc.) or drops names • Celebrities/"star"/Hollywood • Could be rich • "Cool"/"awesome" • Good looking/handsome/beautiful • Exceptionally skilled in something/ talented/charitable/ memorable/role model • Fans/followers
Reveal	Verb	• To uncover/expose/unveil • Remove the barrier • Show/tell • To make known/seen • Secrets (explicitly tell a secret)/expose a secret/find out	• Surprise • Makeovers • Gender reveal parties • Magicians/magic
Decade	Noun	• Period of time • 10 years	• Especially beginning with a 0 year • Long • Characteristics of decades (70s, 80s) • Multiple of 10
Tradition	Noun	• Done repeatedly/strictly/same way every time • Part of the group of people/family/culture • Has been done a long time/passed down	• Holiday traditions • Cultural traditions • Ceremonies • Church traditions • Personal examples
Rejoice	Verb	• Celebrate • Sing • Feel excited about something • Joy	• Celebrating religious events • Songs in church/school
Enthusiastic	Adjective	• Excited about something • Full of energy • Active	• Hyperactivity/hyper • Examples of things that make them enthusiastic