Home Auditory Environments of Children With Cochlear Implants and Children With Normal Hearing

Yuanyuan Wang,[1] Molly Cooke,[1] Jessa Reed,[1] Laura Dilley,[2] and Derek M. Houston[1,3]

Objectives: Early home auditory environment plays an important role in children's spoken language development and overall well-being. This study explored differences in the home auditory environment experienced by children with cochlear implants (CIs) relative to children with normal hearing (NH).

Design: Measures of the child's home auditory environment, including adult word count (AWC), conversational turns (CTs), child vocalizations (CVs), television and media (TVN), overlapping sound (OLN), and noise (NON), were gathered using the Language Environment Analysis System. The study included 16 children with CIs (M = 22.06 mo) and 25 children with NH (M = 18.71 mo). Families contributed 1 to 3 daylong recordings quarterly over the course of approximately 1 year. Additional parent and infant characteristics including maternal education, amount of residual hearing, and age at activation were also collected.

Results: The results showed that whereas CTs and CVs increased with child age for children with NH, they did not change as a function of age for children with CIs; NON was significantly higher for the NH group. No significant group differences were found for the measures of AWC, TVN, or OLN. Moreover, measures of CTs, CVs, TVN, and NON from children with CIs were associated with demographic and child factors, including maternal education, age at CI activation, and amount of residual hearing.

Conclusions: These findings suggest that there are similarities and differences in the home auditory environment experienced by children with CIs and children with NH. These findings have implications for early intervention programs to promote spoken language development for children with CIs.

Key words: Auditory environment, Children, Cochlear implants.

(Ear & Hearing 2022;43;592–604)

INTRODUCTION

Universal newborn hearing screening and early cochlear implantation provide unique opportunities for deaf children to gain early access to auditory and linguistic input. Despite the advances in the cochlear implant (CI) technology to improve hearing experience, many children with CIs who learn spoken language still lag behind their peers with normal hearing (NH) in many domains, including linguistic skills, cognitive abilities, and social competence (e.g., Niparko et al. 2010; Conway et al. 2011; Geers et al. 2011; Holt et al. 2012; Houston & Bergeson 2014; Lund 2016; Bharadwaj & Mehta 2016; Monroy et al. 2019). For example, a meta-analysis showed that children with CIs had a smaller spoken vocabulary size as compared with their peers with NH (Lund 2016). This raises significant concerns as underdeveloped linguistic and cognitive skills during early development may lead to later behavioral problems and academic underachievement, resulting in significant personal and societal burdens (Mohr et al. 2000; Meinzen-Derr et al. 2020). Nevertheless, much of the variability in child developmental outcomes is not explained by conventional factors associated with demographic, CI device, and medical variables (Peterson et al. 2010; Geers et al. 2011). Understanding the sources of variability will provide important information for effective early intervention services. Therefore, it is critical to identify other factors that may shape consequential differences in the developmental outcomes of children with CIs. The primary purpose of this study was to explore characteristics of the home auditory environment—an important factor influencing child spoken language development—experienced by children with CIs relative to their peers with NH.

Home Auditory Environment and Developmental Outcomes of Children With NH

According to the social interactionist theory, language acquisition depends critically on the interaction between the developing child and their social environment (Vygotsky 1996). Children learn language out of a desire to communicate with their ambient environment. Language emerges from, and is dependent on, exposure to environmental input from which the child is being reared. Note that this theory recognizes the importance of both environmental and biological factors in language development (Piaget 2002). There is no doubt that home environment constitutes one of the most important early social environments for developing children. It is well documented that early home auditory environment, including both linguistic and nonlinguistic input, influences children's overall development and well-being (Zimmerman et al. 2009; Greenwood et al. 2011; Weisleder & Fernald 2013; Gilkerson et al. 2018; Romeo et al. 2018).

In their landmark study, Hart and Risley (1995) recorded and transcribed monthly hour-long interactions between caregivers and their children who were between 10 and 36 mo. The number of words the caregivers spoke to children significantly predicted the child's later language and cognitive development. Similarly, Huttenlocher et al. (1991) examined the relationship between exposure to caregiver speech and children's early vocabulary growth from children between 14 and 26 mo of age. They found that the amount of maternal speech to their children was positively correlated with the child's vocabulary growth rate.

In the past decades, limited by technology, researchers approached this question by mainly examining a small amount of sample due to the time and efforts it required for data collection, coding, and processing. However, with the development of automatic speech processing technology, new tools became available which allow for automated collection and analysis of daylong speech samples from the home environment. Among these tools, the Language Environment Analysis (LENA) System (Christakis et al. 2009; Xu et al. 2009;

[1]Department of Otolaryngology—Head and Neck Surgery, The Ohio State University, Columbus, Ohio, USA; [2]Department of Communicative Sciences and Disorders, Michigan State University, East Lansing, Michigan, USA; and [3]Nationwide Children's Hospital, Columbus, Columbus, Ohio, USA.

<zdoi; 10.1097/AUD.0000000000001124>

Zimmerman et al. 2009) is probably the most widely-used tool. The LENA system consists of a digital recorder and software package that automatically processes the audio. It allows for up to 16 hr of continuous recording of speech data collected close to the target child who wears the LENA recorder. Once the data collection is completed, the LENA software automatically uploads and analyzes the auditory data and generates measures of different aspects of the child's auditory environment. These measures include adult word count (AWC; the total number of adult words spoken near the target child who wears the device), CTs count (the total number of conversational interactions the child engages in with an adult in which one speaker initiates and the other responses within 5 seconds), and child vocalization count (CVs; the total number of speech-like utterances produced by the child). In addition to the human speech signal, the LENA software also generates other classifications, including TV and media (TVN; audio from a television or other electronic sources), noise (NON; rattles, bumps, and other nonhuman signals), and overlapping speech (OLN; segments with overlapping speech). Previous research has consistently shown that LENA's automated measures are associated with child language and cognitive outcomes (Wang, Williams et al. 2020).

Since its introduction in 2009, the LENA system has been used for measuring various aspects of the child's home auditory environment. For example, in a large-scale longitudinal study, Gilkerson et al. (2017) collected monthly daylong recordings from 329 children with NH between 2 and 48 mo of age using the LENA system. The language and cognitive skills of these children were assessed every 2 or 6 mo. They showed that AWC, CTs, and CVs calculated by LENA's automated algorithm were significantly positively correlated with language and cognitive measures. Moreover, neural evidence indicated that children with NH who experienced a larger number of CTs showed greater brain activation during speech processing, which mediated the relationship between CTs and language outcomes (Romeo et al. 2018). Recent meta-analytical work examining the ability of the automated measures from the LENA System to predict language outcomes has also demonstrated a small-to-medium size positive association between AWC ($r = 0.21$) and child language, and medium-size positive associations between CTs ($r = 0.31$) and CVs ($r = 0.32$) and measures of language, regardless of the child's developmental status (Wang, Williams et al. 2020).

Nevertheless, not all factors in the child home auditory environment are beneficial for child development; some auditory signals, including television and electronic media, noise, and overlapping sound may negatively impact information processing and developmental outcomes (Zimmerman et al. 2009; Tomopoulos et al. 2010; Klatte et al. 2013). For example, each hour of television exposure to children measured by LENA was associated with a 2.68 decrease in the Preschool Language Scale (Zimmerman et al. 2009). It has been hypothesized that in the presence of electronic media, caregivers may provide a reduced amount of linguistic input and engage in fewer high-quality interactions with their children, leading to reduced learning opportunities (Zimmerman et al. 2009; Ambrose et al. 2014). There has also been much discussion on the adverse effects of auditory noise on many aspects of child development (Haines et al. 2001; Klatte et al. 2013; Erickson & Newman 2017). Although there is limited research on the direct impact of auditory noise at home on the developmental outcomes in young children, previous research has shown that chronic noise exposure both at home and at school negatively impacts reading and long-term cognitive processes in school-age children (Evans 2006). Wachs (1978) also demonstrated that 12- to 14-mo-old boys in noisier homes had deficits in intellectual functioning measured at 31 mo of age as compared with the boys of the same age in quieter homes. The noise may impair children's ability to learn, either by providing less information for learning, or making listening particularly challenging. For example, noise may cover up target speech, causing an incomplete representation of the information carried by the target speech. Moreover, understanding speech in noise may be cognitively demanding, as it requires listeners to focus their attention on a particular stimulus while filtering out other stimuli. This is particularly challenging for young children, whose ability to filter out unattended stimuli is still under development during childhood (Conway et al. 2001; McMillan & Saffran 2016).

Taken together, the results of these studies suggest that the home auditory environment consists of both linguistic and nonlinguistic factors that may positively or negatively impact child development outcomes. Note the properties of the child's auditory environment are not static, rather, they may change across development, and may be influenced by factors including family socioeconomic status (SES) (Huttenlocher et al. 1991; Hart & Risley 1995; Gilkerson et al. 2008). For example, in the Natural Language Study including 334 children with typical development between 2 and 48 mo, the LENA Foundation showed that whereas the AWC did not change as a function of child age, the CTs between caregivers and the child and the CVs increased significantly with child age (Gilkerson et al. 2008). Family SES has also been shown to be correlated with language input (Huttenlocher et al. 1991; Hart & Risley 1995; Pace et al. 2017). For example, less educated parents or parents in low-income homes, proxies for low SES, talk and interact with their children less frequently, compared with parents from higher SES families (Hart & Risley 1995), although see Sperry et al. (2019) for different findings. Therefore, research examining children's home auditory environment should also take into account these and other factors that may influence the characteristics of the home auditory environment.

Home Auditory Environment and Developmental Outcomes of Children With Hearing Loss

In addition to child age and family SES, the home auditory environment may also be affected by the child's hearing status, as there is likely a bidirectional relationship between child characteristics and their environment. For example, children who are more proficient language users possess better skills at initiating or participating in conversations, resulting in caregivers providing more linguistic input within conversational interactions (Hoff-Ginsberg 1986; Hoff-Ginsberg 1994). Children with hearing loss, in general, demonstrate reduced linguistic and communicative abilities (Niparko et al. 2010; Geers et al. 2011; Houston & Bergeson 2014; Lund 2016), which may interrupt the natural communication or joint attention between the caregiver and their child (Cejas et al. 2014; Wang et al. 2018). Indeed, empirical evidence has demonstrated differences in the amount and quality of speech directed to children with

CIs as compared with children with NH in laboratory settings (Bergeson et al. 2006).

While much information about the home auditory environment of children with NH and its relationship with developmental outcomes is available, researchers have only recently begun to explore the role of the home auditory environment on the development outcomes in children with hearing loss (Ambrose et al. 2014; Vohr et al. 2014; Ambrose et al. 2015; Arora et al. 2020; Yoshinaga-Itano et al. 2020). In one such study, Vohr et al. (2014) used the LENA system to examine the language environment of 23 children with hearing loss who were between 32 and 46 mo. They showed that a larger number of CVs, higher percentage of language (including adult and CVs and distant speech and unclear speech, CTs, and monologs), and higher percentage of meaningful language (including adult and CVs) were associated with higher expressive language scores, even after adjusting for nonverbal intelligence. Using the LENA system, Ambrose et al. (2014) collected daylong recordings of auditory environments of 28 children with mild to severe hearing loss. The findings showed that the quantity of CTs was positively associated with children's communication outcomes at 2 and 3 years of age; however, the amount of electronic media exposure (TVN) generated by the LENA system was negatively associated with receptive language abilities at 2 years of age. Similarly, Busch et al. (2020) showed that increased music exposure obtained from the data logs of CI processors was correlated with poorer receptive vocabulary. Children with hearing loss may also be particularly vulnerable to noises in the ambient environment, due to the less optimal speech signals received by the hearing devices. Although there is no direct evidence showing a relationship between noise exposure at home and developmental outcomes in children with hearing loss, research has shown that noise may disproportionately affect speech processing in children with hearing loss. For example, kindergarteners with CIs showed poorer speech recognition in noise as compared with their peers with NH (Caldwell & Nittrouer 2013); furthermore, both children with CIs and children with HAs required a high signal-to-noise ratio to achieve a similar level of performance as their peers with NH (Lewis et al. 2016).

Despite these findings, very little is known about the properties of the real-world auditory environment experienced by young children with CIs as compared with children with NH. Therefore, knowledge of the properties of the auditory environment experienced by children with CIs, amenable factors that can be adjusted by empowering and involving parents, is much needed to inform new strategies for early intervention (Moeller et al. 2013). Previous studies on the home auditory environment experienced by children with hearing loss tend to combine children with CIs and children HAs in the same group largely due to small sample size (Rufsvold et al. 2018); the heterogeneity of the participants could introduce potential confounds that complicate the interpretations. Moreover, previous study focused on the linguistic signals in the environment, and research examining potentially adverse signals, including TV and media sounds, noise, and overlapping sounds, is relatively rare. It is most important to note that, previous study with children with CIs did not examine the developmental changes of the characteristics of auditory environment. Note that children's auditory environment and their access to the auditory information may change from time to time (Busch et al. 2017; Wiseman & Warner-Czyz 2018); therefore, only a longitudinal design could provide unique insight and capture differences in the changes during development that may have significant implications for developmental outcomes for children with CIs.

Research Questions and Predictions

The goal of this present study was to examine the characteristics of the home auditory environments experienced by children with CIs relative to children with NH. Specifically, we asked two questions:

1. What are the characteristics of the home auditory environment experienced by children with CIs, relative to children with NH?
2. Which child and family factors are associated with the variability in the home auditory environments of children with CIs?

To answer these questions, we collected longitudinal daylong recordings of the home auditory environments of children with NH and children with CIs using the LENA system. Moreover, we collected a variety of child and parent characteristics, including maternal education, family income, child hearing and medical history. We predicted that children with CIs may experience a different home auditory environment as compared with children with NH. Moreover, some child and family characteristics may explain variability in the home auditory environment experienced by children with CIs.

MATERIALS AND METHODS

Participants

A total of 41 children and their caregivers participated in the study. Families lived in Midwestern towns in the United States and spoke English as the primary language. The CI group consisted of 16 children (10 male and 6 female). They were recruited from a CI program in a university medical center and advertisements posted on social media. The children with CIs all had bilateral severe to profound hearing loss (M = 103 dB HL measured by unaided pure tone average in the better ear); had at least one CI activated by age 2 years; and their families had chosen spoken language as the primary communication goal (7 families were spoken only; 4 families were primarily spoken with ASL support, and 5 families were primarily spoken with some sign support). The control group consisted of 25 children with NH (11 male and 14 female), recruited from ads posted on social media. The children with NH had NH per family report and no known history of language or hearing impairment. Experimenters informed caregivers of the broad interests and potential (minimal) risks of the study during the consenting process. The recruitment strategy and materials, and the study protocol were approved by an Institutional Review Board. Additional group characteristics for the children with CIs and the children with NH are shown in Table 1.

Procedure

We used the LENA system to collect daylong recordings of children's auditory environment during a typical day at home. We chose to use the LENA system for the following reasons: (1) data collection using LENA was less obtrusive than in-person data collection thus ensuring that samples were relatively more authentic; (2) it allowed for automatic processes

TABLE 1. Demographic and child characteristics for children with cochlear implants (CIs) and children with normal hearing (NH)

Variable	CI (n = 16)	NH (n = 25)
Child gender (female)	6 (37.5%)	14 (56%)
Child age	22.06 ± 5.20	18.71± 7.58
Maternal education (years)	15.46 ± 2.81	15.52 ± 1.76
≥17 (Graduate school)	4 (25%)	7 (28%)
16 (College degree)	5 (31.25%)	9 (36%)
13–16 (Some college)	5 (21.25%)	7 (28%)
≤12 (High school or less)	2 (12.5%)	2 (8%)
Household income		
≥100 k	4 (25%)	6 (24%)
75–99 k	6 (37.5%)	6 (24%)
50–75 k	2 (12.5%)	7 (28%)
<50 k	3 (18.75%)	4 (16%)
Not reported	1 (6.25%)	2 (8%)
Audiological information		
Age at CI fitting (mo)	14.03 ± 3.73	NA
Duration of CI use (mo)	8.01 ± 4.42	NA
Better ear PTA (dB HL)	103.23 ± 19	NA
Communication Mode (Spoken Only)	7 (46.7%)	NA

Child and maternal characteristics are presented as percentage or mean ± SD. Better ear PTA: better ear unaided pure-tone average measured before implantation (across the frequencies of 250, 500, 1000, 2000, and 4000 Hz).
CI indicates cochlear implant; NH, normal hearing.

and analysis of massive-scale naturalistic sounds occurring in the home environment; and (3) LENA's automated measures have been shown to predict measures of child language (Wang, Williams et al. 2020).

All families received a LENA DLP and a LENA vest and were given a demonstration of their use. Paperwork, including questionnaires and full instructions on device use, were included in the packets that were sent home along with return packaging. Parents were asked to begin recording as soon as the child got up and to have the child wear the device in the vest for a full day. Parents were encouraged to keep the vest close to the child if the child took it off and at bath or sleep times. To protect their privacy, families were given the option to pause and resume recordings or to have their recordings deleted and not included in the study after the fact.

Two questionnaires were completed with each LENA recording for use in human interpretation of the data, not included here: one daily log and one weekly log. Parents used the daily logs to note recording start and end times, bedtime, as well as any pauses and a general list of the recording day's activities and their locations. The weekly logs asked parents to list, by day of the week, any weekly activities (e.g., play groups, speech therapy, and religious services) that their child regularly participated in at the time of the recording. Families were compensated $25 per LENA recording and an additional $5 for both questionnaires.

Measures

We extracted measures that characterize different aspects of the child's auditory environment from the LENA software for each recording. The measures included in the analyses were as follows: (1) AWC: the total number of adult words spoken near the target child; (2) CTs: the total number of conversational interactions between the target child and the caregivers in which one speaker initiates and the other response within five seconds; (3) CVs: the total number of speech-like segments produced by the target child; we included CVs because child vocal development reflects the adult language model and is driven by interactions with their social partners (Moeller et al. 2007). In addition, according to auditory feedback models, hearing one's own voice allows the child to evaluate their production relative to the adult production, and is required for vocal learning (Brainard & Doupe 2000). (4) TVN: the duration of all segments classified by the LENA software as electronic media; (5) NON: the duration of all segments classified as nonspeech noise; (6) OLN: the duration of all segments with overlapping sounds. Because the duration of recordings varied, we normalized the measures of interest by the recording duration, resulting in AWC per hour, CTs per hour, CVs per hour, and percent of each recording classified as TVN, NON, and OLN.

Families contributed 1 to 3 recordings quarterly over the course of approximately 1 year, with a total of 137 recordings. Three recordings were excluded because the duration of these recordings was shorter than 4 hr, the minimum duration for LENA's algorithm to provide reliable measures. In addition, four recordings were excluded because the recordings were conducted in the child's daycare. To keep the age ranges comparable between the NH and the CI group, we only included recordings collected when the children were between 11 and 33 mo of age. Therefore, we excluded 22 recordings and included 108 recordings in the final analysis. The number of recordings ranged from 1 to 11 per family (M = 2.63, SD = 1.92). The age at recording ranged between 11.13 and 31.96 mo (M = 20.45, SD = 5.54); the duration of the recordings ranged from 4.31 to 16 hr (M = 14.31, SD = 2.85). Children with NH were slightly younger than children with CIs, $t(36.75) = 1.91$, $p = 0.064$; maternal education did not differ between the two groups, $t(39) = 0.004$, $p = 0.997$. Descriptive characteristics of the recordings and measures of auditory environment for the children with CIs and children with NH are shown in Table 2.

Statistics

All analyses were conducted in the *R* environment (R Core Team 2014). Before any analysis, we applied logarithm transformation (Bartlett & Kendall 1946; Adikaram et al. 2015) to all measures of child auditory environment for the following reasons. First, it is possible that the relationship between the independent and dependent variables may not be linear; using the

TABLE 2. Measures of child auditory environment

Group	CI (n = 16)	NH (n = 25)
Average recording number/child	3.50	2.08
Number of recordings	56	52
Duration of recordings (hr)	15.02 ± 2.04	13.54 ± 3.37
AWC	962.0 ± 542.98	1193.6 ± 579.28
CTs	34.70 ± 18.74	44.49 ± 29.52
CVs	158.07 ± 74.89	138.97 ± 78.12
TVN	11.76% ± 12.73	5.36% ± 4.75
NON	2.41% ± 1.10	9.34% ± 12.32
OLN	12.21% ± 5.79	14.62% ± 7.12

Measures of the auditory environment are presented as mean ± SD.
AWC indicates number of adult word count per hour; CI, cochlear implant; CTs, number of conversational turns per hour; CVs, number of child vocalizations per hour; NH, normal hearing; NON, percentage of noise; OLN, percentage of overlapping sounds; TVN, percentage of TV and media.

logarithm transformed data form makes the effective relationship nonlinear, while still preserving the linear model. Second, graphing results in terms of percentage (for TVN, NON, and OLN) distorted the shapes of curves. Specifically, we inspected the distributions of each LENA automated measure using histograms and QQ plots. The distributions of TVN and NON were not normally distributed. Logarithm transformation improved the shape and yielded approximately normal distributions for all measures. Finally, logarithm transformation can reduce the range of values caused by outliers and deemphasize the influence of outliers. After data transformation, we also conducted an outlier diagnosis for each measure by visually inspecting the distributions and using the rosnerTest() function from the EnvStats package to identify potential outliers (Millard et al. 2020). Outliers were removed before further analysis.

First, to compare the auditory environment experienced by children with CIs and children with NH, for each measure, we constructed stepwise linear mixed-effects models using the lme4 package (Bates et al. 2015). The models assumed fixed effects from Hearing Status (NH and CI) and Age. We also included a combination of Age and Participant as random intercept and random slope. We first tested whether the fixed factors and the interactions between fixed effects (Hearing Status × Age) improved the model over the unconditional model which only included Participant as a random intercept, followed by similar tests including Age as a random slope over the random effect. Next, we tested whether the inclusion of control variables improved the fit. Control variables included maternal education as an index for family SES and child gender. Another potential index for family SES was family income. However, bivariate correlation showed that maternal education and family income were highly correlated, ($p < 0.001$), therefore, we only included maternal education as an index for family SES because there is evidence that maternal education is the most robust predictor for child developmental outcomes and family income has no effect independent of maternal education (Erola et al. 2016). The full model, fitted with the complete structure, was lmer(measure ~ Maternal education + Child Gender + Age × Hearing Status + (1+Age|Participant). These steps were repeated either until a step suggested significant effects from the intercept, or until none of the available control variables could contribute to the model anymore. Thus, the step immediately before adding a new variable was selected as the final model. To assist with selecting the appropriate statistical model, we compared each increasingly complex model and formally tested whether a particular model provides a better model fit to the data over another using the Akaike information criterion (AIC) and Chi-square test. For all models, statistical results were generated using the summary() function from the lmerTest package (Kuznetsova et al. 2015). We also explored the relationship between the measures of the auditory environment by conducting repeated measures correlation analysis separated by hearing status using the rmcorr package (Bakdash & Marusich 2017). Second, to explore child and family factors that might influence properties of the auditory environment experienced by children with CIs, we ran mixed-effects models including maternal education, amount of residual hearing (as measured by unaided pure-tone average in the better ear before receiving CIs), age (if a significant factor for the CI group from the above analyses), age at activation, and communication mode as fixed factors, because these factors were found to be associated with many aspects of language input and child skills. We also included Participant as a random intercept for each measure using the lme4 package (Bates et al. 2015). Similarly, models with the lowest AIC, which indicated the best fitting, were selected and reported.

RESULTS

Comparison of Measures of Auditory Environment Between the CI and the NH Groups

AWC • No outliers were identified and thus all data points were included in the analysis. The model including Age and Hearing Status as the fixed factors and Participant as a random intercept was the best fitting model. Neither Age nor Hearing Status was significant, ts < 1.03, ps > 0.269, suggesting that AWC did not change as a function of child age or child hearing status. Table 3 summarizes the results from the best-fitting models for each measure.

CTs • No outliers were identified and thus all data points were included in the analysis. The model including Age, Hearing Status, and their interaction term as the fixed factors and Participant as a random intercept was the best fitting model. Analysis revealed that the interaction of Age and Hearing Status was significant, $\beta = 0.06$, $t(79.77) = 2.40$, $p = 0.016$. The CTs increased as a function of age for children with NH, $\beta = 0.043$, $t(31.51) = 2.42$, $p = 0.032$; in contrast, the CTs did not change as a function of age for children with CIs, $\beta = -0.018$, $t(47.31) = -1.16$, $p = 0.271$, see Figure 1.

CVs • No outliers were identified and thus all data points were included in the analysis. The model including Age, Hearing Status, and their interaction term as the fixed factors, Participant as a random intercept, and Maternal Education as a covariate was the best fitting model. The interaction of Age and Hearing Status was significant, $\beta = 0.06$, $t(76.13) = 2.55$, $p = 0.011$. The CVs increased as a function of age for children with NH, $\beta = 0.04$, $t(29.95) = 2.53$, $p = 0.017$; in contrast, CTs did not change as a function of age for children with CIs, $\beta = -0.02$, $t(47.28) = -0.96$, $p = 0.344$, see Figure 2.

TVN • The outlier test identified one outlier which was thus excluded from the analysis. The model including Age and Hearing Status as the fixed factors and Participant as a random intercept was the best fitting model. Age was significant, $\beta = 0.04$, $t(81.16) = 1.99$, $p = 0.047$, because the amount of TVN exposure increased with child age, see Figure 3.

NON • No outliers were identified and thus all data points were included in the analysis. The model including Age and Hearing Status as the fixed factors, Participant as a random intercept, and age as a random slope was the best fitting model. Hearing Status was significant, $\beta = 0.82$, $t(32.50) = 2.93$, $p = 0.004$, because children with NH were exposed to a larger amount of NON than children with CIs, see Figure 4.

OLN • No outliers were identified and thus all data points were included in the analysis. The model including Age and Hearing Status as the fixed factors and Participant as a random intercept was the best fitting model. No significant main effects were found for the fixed factors, ts < 1.25, ps > 0.211, suggesting that OLN did not change as a function of child age or child hearing status.

TABLE 3. Best fitting mixed-effects models comparing the measures of the auditory environment experienced by children with cochlear implants (CIs) and children with normal hearing (NH)

	AWC				CTs				CV			
Coefficient	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*
Intercept	6.80	0.24	6.33 to 7.27	**<0.001**	3.91	0.39	3.15 to 4.67	**<0.001**	4.53	0.55	3.44 to 5.61	**<0.001**
Age	0.00	0.01	−0.02 to 0.02	0.882	−0.02	0.02	−0.05 to 0.02	0.286	−0.02	0.02	−0.05 to 0.01	0.248
Hearing Status (NH)	0.15	0.14	−0.12 to 0.42	0.269	−1.13	0.52	−2.16 to −0.11	**0.030**	−1.37	0.47	−2.28 to −0.46	**0.003**
Age* Hearing Status(NH)					0.06	0.03	0.01 to 0.11	**0.016**	0.06	0.02	0.01 to 0.10	**0.011**
Maternal Education									0.06	0.03	−0.01 to 0.12	0.084
Random Effects												
σ^2	0.15				0.23				0.21			
τ_{00}	0.11_{ID}				0.16_{ID}				0.09_{ID}			
ICC	0.41				0.41				0.30			
N	41_{ID}				41_{ID}				41_{ID}			
Observations	108				108				108			
Marginal R^2/ Conditional R^2	0.021/0.426				0.072/0.456				0.154/0.410			

	TVN				NON				OLN			
Coefficient	Estimates	SE	Confidence Interval (95%)	*P*	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*
Intercept	−3.67	0.50	−4.65 to −2.70	**<0.001**	−3.99	0.42	−4.81 to −3.16	**<0.001**	−2.40	0.23	−2.85 to −1.95	**<0.001**
Age	0.04	0.02	0.00 to 0.08	**0.047**	0.01	0.02	−0.03 to 0.04	0.612	0.01	0.01	−0.01 to 0.03	0.211
Hearing Status (NH)	−0.36	0.28	−0.90 to 0.18	0.193	0.82	0.28	0.27 to 1.37	**0.004**	0.13	0.13	−0.12 to 0.38	0.301
Age* Hearing Status(NH)												
Maternal Education												
Random Effects												
σ^2	0.75				0.30				0.16			
τ_{00}	0.37_{ID}				0.59_{ID}				0.08_{ID}			
ICC	0.33				0.66				0.31			
N	41_{ID}				41_{ID}				41_{ID}			
Observations	107				108				108			
Marginal R^2/ Conditional R^2	0.092/0.395				0.151/0.712				0.025/0.332			

The analyses were conducted based on the logarithm transformed data. Significance of bold at p = 0.05.

AWC indicates number of adult word count per hour; CI, cochlear implant; CTs, number of conversational turns per hour; CVs, number of child vocalizations per hour; NH, normal hearing; NON, percentage of noise; OLN, percentage of overlapping sounds; TVN, percentage of TV and media.

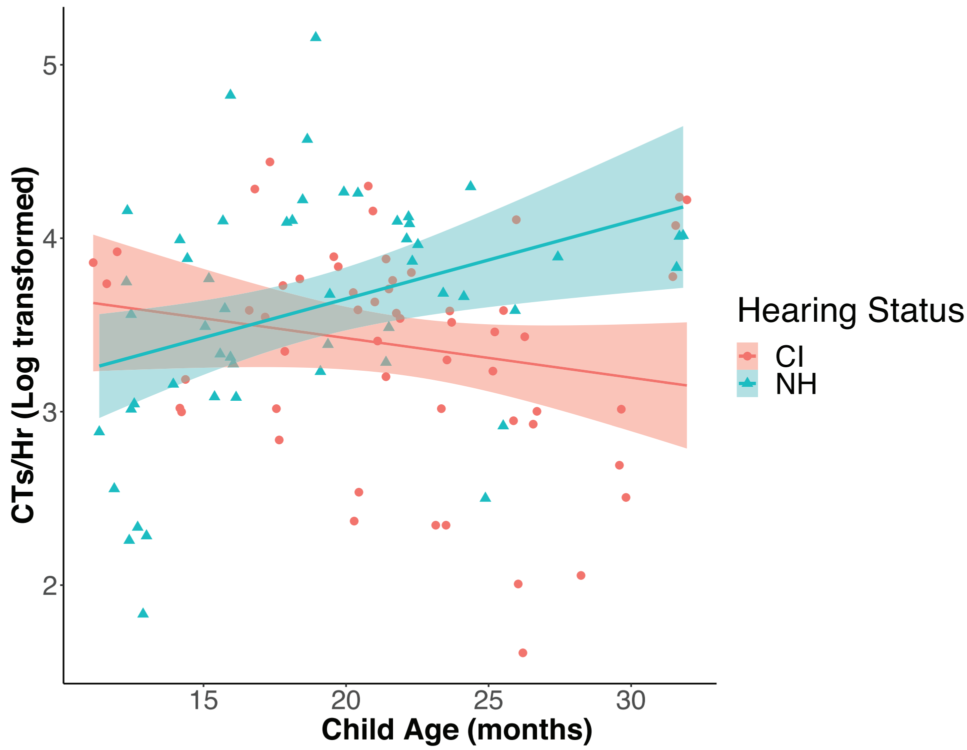

Fig. 1. Conversational turns (CTs) per hour as a function of child hearing status (CI and NH) and child age (mo). Each data point represents one recording. The shaded area represents 95% confidence interval for each group. CI indicates cochlear implant; NH, normal hearing.

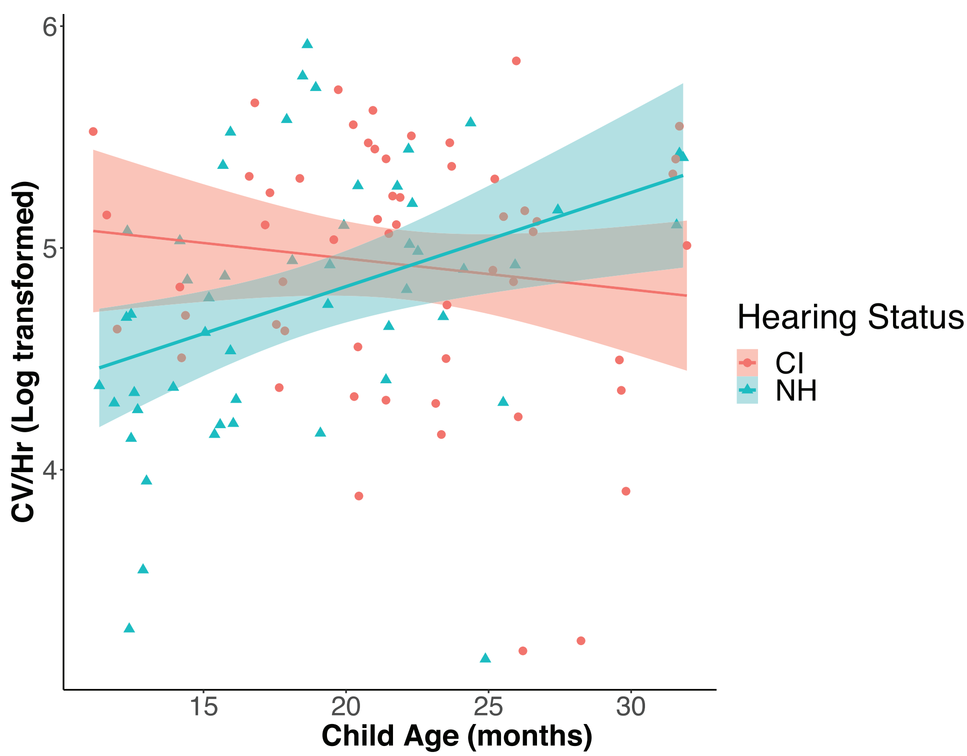

Fig. 2. Child vocalizations (CVs) per hour as a function of child hearing status (CI and NH) and child age (mo). Each data point represents one recording. The shaded area represents 95% confidence interval for each group. CI indicates cochlear implant; NH, normal hearing.

Correlations Among the Properties of the Auditory Environment

Repeated measures correlations for the measures of child home auditory environment are shown in Table 4. Results showed that for children with CIs, higher AWC was associated with increased CTs, CVs, and OLN, *r*s > 0.317, *p*s < 0.043, and decreased TVN and NON, *r*s >.−378, *ps*< 0.015; higher CTs was associated with increased CVs and OLN, *r*s > 0.573, *ps* < 0.001, and decreased TVN and NON, *rs* > −0.311, *ps* < 0.048; and higher CVs was associated with increased OLN, *r* = 0.417, *p* = 0.007. Moreover, higher NON was correlated with decreased OLN, *r* = −0.34, *p* = 0.029. For children with NH, higher AWC was associated with increased CTs, NON, and OLN, *rs* > 0.401, *ps* < 0.035; higher CTs was associated with increased CVs and OLN, *rs* > 0.499, *ps* < 0.007; higher CVs was associated with increased OLN, *r* = 0.435, *p* = 0.021. Furthermore, higher NON was corelated with increased OLN, *r* = 0.361, *p* = 0.059, see Table 4.

Factors Associated With the Properties of the Auditory Environment of Children With CIs

The mixed-effects models on children with CIs showed that maternal education significantly positively predicted CTs, β = 0.13, *t*(0.91) =3.90, *p* < 0.001, and CVs, β = 0.13, *t*(1.84) = 2.85, *p* = 0.004, suggesting that higher maternal education was associated with increased CTs and CVs. Age at activation significantly negatively predicted CTs, β = −0.13, *t*(2.42) = −3.68, *p* = 0.004, and tended toward the same direction for CVs, β = −0.07, *t*(3.57) = −1.81, *p* = 0.07, suggesting that earlier activation was associated with increased CTs and possibly CVs. Furthermore, PTA (measured by unaided pure-tone average in the better ear) significantly negatively predicted TVN, β = −0.04, *t*(4.43) = −3.09, *p* = 0.002, suggesting that a larger amount of residual hearing was associated with increased TVN, see Table 5.

DISCUSSION

The home auditory environment of a child includes a range of acoustic information that scaffolds the child's linguistic and cognitive development. This study aimed to investigate the properties of the home auditory environment experienced by children with CIs relative to children with NH in a longitudinal design. To achieve this goal, we used the LENA system to obtain daylong audio recordings of the children's home environment and conducted automated analysis to compare the properties of the home auditory environment, including AWC, CTs, CVs, TVN, NON, and OLN, experienced by children with CIs and children with NH. This study complements previous research on this topic to provide an overall picture of the characteristics of the home auditory environment experienced by children with hearing loss (VanDam et al. 2012; Vohr et al. 2014; Busch et al. 2017; Wiseman & Warner-Czyz 2018; Busch et al. 2020).

Home Auditory Environment Experienced by Children With CIs and Children With NH

Taken together, our findings indicated that hearing status influenced CTs, CVs, and NON. Specifically, CTs and CVs increased with child age for children with NH; in contrast, CTs and CVs did not change with age for children with CIs. Moreover, children with NH were exposed to a larger amount of NON than children with CIs. Child hearing status, on the other hand, did not significantly influence the measures of AWC, TVN, and OLN; furthermore, TVN increased as child age for both groups. These findings are consistent with and extend previous findings in many ways, which we discuss below.

First, these findings replicated the findings from the Natural Language Study conducted by the LENA foundation (Gilkerson et al. 2008) with a smaller cohort of children with NH from a geographically more restricted location. Specifically, our findings and the Natural Language Study consistently demonstrated that whereas CTs and CVs increase with child age, AWC did not

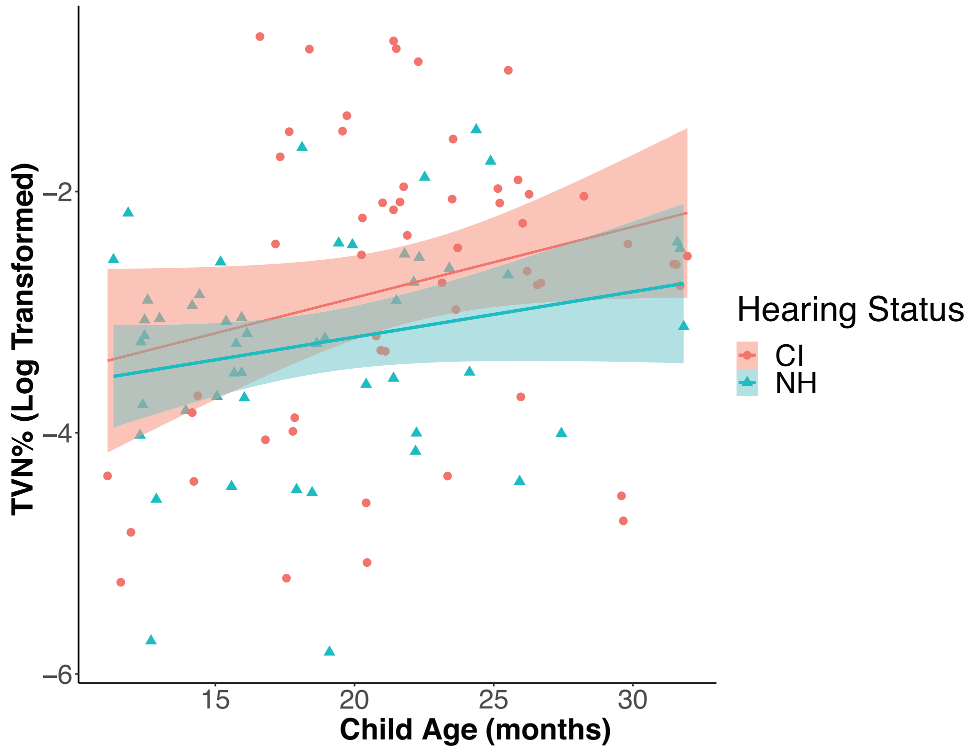

Fig. 3. Percent of TV and media (TVN), grouped by child hearing status (CI and NH). Each data point represents one recording. CI indicates cochlear implant; NH, normal hearing.

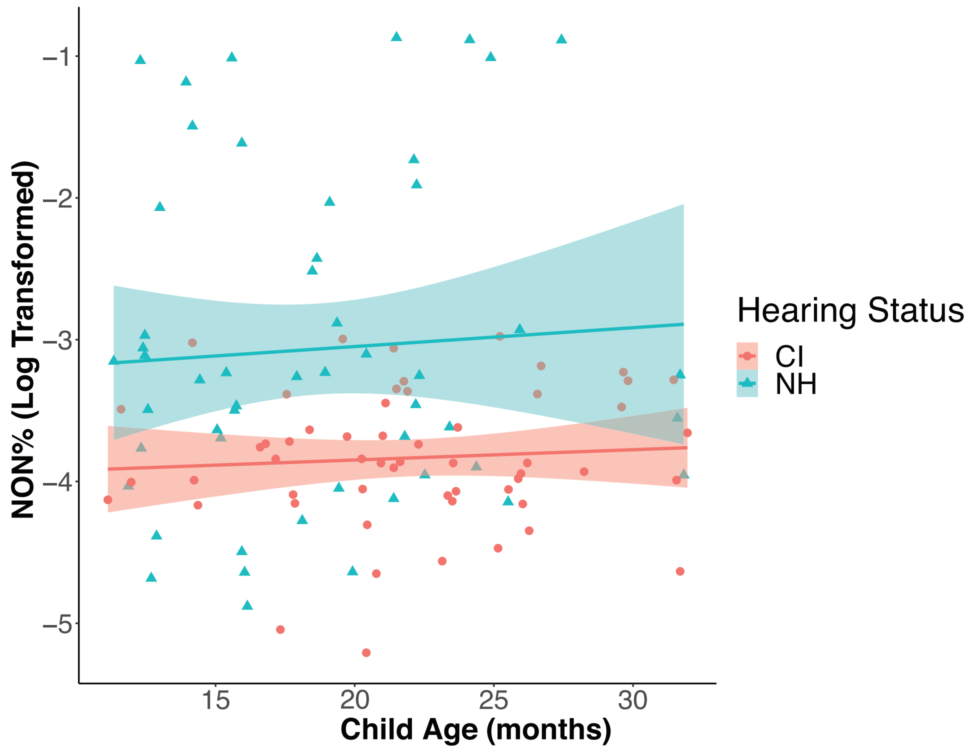

Fig. 4. Percent of noise (NON) as a function of child hearing status (CI and NH) and child age (mo). Each data point represents one recording. CI indicates cochlear implant; NH, normal hearing.

change with age for children with NH. These findings promote our understanding of the developmental characteristics of the linguistic input to young children with NH, providing important knowledge to the field of developmental research.

Second, we found that CTs and CVs did not show age-appropriate increases for children with CIs. The reduced growth rates of CTs in children with CIs relative to children with NH could be due to inconsistent CI device use, as previous research showed that children with CIs did not wear their devices consistently (Busch et al. 2017; Busch et al. 2020; Wiseman & Warner-Czyz 2018). For example, Busch et al. (2017) analyzed data logs of 510 children and found that the median daily CI use was 8.5 hr per day in the first 6 years of life. Similarly, Wiseman and Warner-Czyz (2018) showed that the average daily CI use was 7.6 hr/day for children who were 7 years of age. The inconsistent CI use may lead to reduced opportunity for language exposure, because caregivers may interact less frequently with children when the devices were not used. These findings suggest that early intervention programs that encourage consistent device use may allow children with CIs better opportunities for receiving greater exposure to language input.

The findings regarding CTs are concerning, as previous research has shown that more frequent caregiver-child interactions were associated with improved child developmental outcomes from the earliest stages in development (Ambrose et al. 2014; Caskey et al. 2014). The reduced rates of CTs may have potentially far-reaching implications for developmental outcomes for children with CIs. Note that the reduced growth rates of CTs and child linguistic skills may be interdependent, and the significant association between CTs and CVs supports this notion. During early development, infants experience several universal vocal stages, beginning with crying, vegetative sounds, and transitioning into more complex vocalizations including consonant-vowel combinations (Oller 2000). Both theoretical and empirical evidence has shown that child vocal development is, at least in part, driven by social interactions. For example, according to the social feedback theory, caregiver's responses to CVs encourage more complex CVs over time (Goldstein & Schwade 2008). On the other hand, CVs could

TABLE 4. Correlations among the properties of the auditory environment

	AWC	CTs	CVs	TVN	NON	OLN
CI						
AWC	1	0.702**	0.317*	−0.419*	−0.378*	0.676**
CTs		1	0.823**	−0.311*	−0.346*	0.573**
CVs			1	−0.159	−0.164	0.417*
TVN				1	−0.04	−0.161
NON					1	−0.34*
OLN						1
NH						
AWC	1	0.438*	0.173	0.177	0.401*	0.521*
CTs		1	0.920**	−0.086	0.163	0.499*
CVs			1	−0.210	0.076	0.435*
TVN				1	−0.039	−0.098
NON					1	0.361+
OLN						1

The analyses were conducted based on the logarithm transformed data.
AWC indicates number of adult word count per hour; CI, cochlear implant; CTs, number of conversational turns per hour; CVs, number of child vocalizations per hour; NH, normal hearing; NON, percentage of noise; OLN, percentage of overlapping sounds; TVN, percentage of TV and media.
***p < 0.001.*
**0.001 < p < 0.05.*
+0.05 < p < 0.10.

TABLE 5. Best fitting mixed-effects models examining the potential predictors for the variability in the measures of the child auditory environment experienced by children with cochlear implants (CIs)

	AWC				CTs				CV				TVN				NON				OLN			
Coefficient	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*	Estimates	SE	Confidence Interval (95%)	*p*
Intercept	6.83	0.10	6.62 to 7.03	**<0.001**	4.00	0.58	2.87 to 5.12	**<0.001**	4.65	0.73	3.23 to 6.08	**<0.001**	−1.32	1.77	−4.79 to 2.14	0.455	− 3.34	0.55	−4.42 to −2.27	**<0.001**	−2.13	0.10	−2.32 to −1.93	**<0.001**
Age at Activation					−0.13	0.04	−0.20 to −0.06	**<0.001**	−0.07	0.04	−0.15 to 0.01	0.071	0.08	0.11	−0.13 to.0.30	0.456	−0.06	0.03	−0.12 to 0.01	0.084				
Maternal Education					0.13	0.03	0.06 to 0.20	**<0.001**	0.13	0.04	0.04 to 0.21	**0.004**	0.11	0.11	−0.10 to 0.32	0.318	0.03	0.03	−0.03 to 0.09	0.346				
Communication Mode					0.17	0.18	−0.19 to 0.53	0.365					−0.04	0.50	−1.03 to 0.95	0.934	−0.10	0.18	−0.45 to 0.24	0.561				
PTA					−0.01	0.00	−0.02 to 0.00	0.076	−0.01	0.01	−0.02 to 0.00	0.283	−0.04	0.01	−0.06 to −0.01	**0.002**	0.00	0.00	−0.01 to 0.01	0.915				
Age													−0.01	0.05	−0.11 to 0.09	0.874								
Random effects																								
σ^2	0.17				0.24				0.23				1.01				0.22				0.12			
τ_{00}	0.11_{ID}				0.00_{ID}				0.04_{ID}				0.23_{ID}				0.00_{ID}				0.11_{ID}			
ICC	0.38				0.01				0.14				0.18				0.00				0.48			
N	16_{ID}				11_{ID}				12_{ID}				11_{ID}				11_{ID}				16_{ID}			
Observations	56				44				45				44				44				56			
Marginal R^2/Conditional R^2	0.000/0.379				0.452//0.457				0.326/0.420				0.309/0.437				0.124/0.127				0.000/0.477			

The analyses were conducted based on the logarithm transformed data. Significance of bold at p = 0.05.

AWC indicates number of adult word count per hour; CTs, number of conversational turns per hour; CVs, number of child vocalizations per hour; ICC, intraclass correlation coefficient; NON, percentage of noise; OLN, percentage of overlapping sounds; TVN, percentage of TV and mediaID, participant ID.

elicit developmentally appropriate and contingent responses from the caregiver, which will lead to better child vocal skills that subsequently receive more high-quality input from the caregiver. For children with CIs, communicative characteristics such as reduced audibility, atypical vocalization patterns, and reduced joint attention may make it challenging for their parents to establish or maintain interactions with their children with hearing loss (Vohr et al. 2014). For example, children with hearing loss show delayed onset of canonical babbling and smaller consonant inventories (Stoel-Gammon & Otomo 1986). There is also evidence that mothers respond differently to different types of CVs (Gros-Louis et al. 2014). Therefore, atypical vocalizations by children with hearing loss may elicit fewer contingent responses from the caregivers that subsequently influence CVs, affecting the development of CTs between the child and the caregivers. This notion was supported by recent findings showing that both the adult response rate to CVs and the child response rate to adult responses were significantly higher in the NH group than in the CI group, suggesting that child hearing status affects the contingency between CVs and adult responses (Wang, Chen et al. 2020).

Third, our results also demonstrated that approximately 9.34% of the recordings from children with NH were classified as NON, which was significantly higher than that of 2.41% from children with CIs. The reduced NON for children with CIs may be the results of caregivers trying to create a less noisy environment for their children with CIs, because listening in the presence of noise is especially challenging for children with CIs (Caldwell & Nittrouer 2013). However, the reduced NON for children with CIs may not necessarily suggest that the speech signals children with CIs received are sufficiently clear/loud. In a recent study, Benítez-Barrera et al. (2020) found that that the average signal-to-noise ratio (SNR) in the home environments of children with hearing loss was approximately +7.9 dB SNR, and approximately 84% of these SNRs were below the +15 dB SNR recommended by the American Speech-Language Hearing Association. In addition, although not statistically significant, our findings suggest that children with CIs were exposed to a larger amount of TVN than children with NH (11.76% vs. 5.36%). One possible explanation is that children with CIs may use music training programs/apps that are designed as a habilitation tool to improve their speech perception. Another possibility is that the higher amount of TVN may be associated with reduced caregiver-child interaction. We return to this issue when discussing the associations among the measures of the auditory environment in the next section. The nonspeech aspects of the home auditory environment are not well documented in children with CIs; therefore, we hope the present study would encourage future research to assess noise and TV and media exposure experienced by children with NH and children with hearing loss, and to identify factors that may contribute to or explain variability in the amount of such exposure.

Correlations Among the Properties of the Auditory Environment

The major findings from the repeated measures correlation analyses were that the increased caregiver speech and interactions between adults and children, specifically AWC and CTs, were significantly correlated with the reduced amount of TVN and NON for children with CIs, and this relationship was less strong for children with NH. These findings are consistent with the findings that background television reduces parent responsiveness to their children with hearing aids and affects the quantity and quality of interactions between caregivers and young children (Ambrose et al. 2014). These findings suggest that the language input to children with CIs may be more vulnerable to the noisier environment compared with children with NH; an alternative interpretation is that the reduced language input may lead to increased TV and noise exposure for children with CIs. These findings have significant clinical implications for early intervention programs to provide appropriate services to improve language input and reduce the amount of TV, media, and noise exposure to children with CIs.

Factors Associated With the Properties of the Auditory Environment of Children With CIs

Our analyses showed that maternal education level contributed to variation in the measures of CTs and CVs in children with CIs. Specifically, higher maternal education was associated with increased CTs and CVs. These results are consistent with previous research showing that children from higher SES families received a larger amount of linguistic input and engaged in more interactions with their caregivers (Hart & Risley 1995; Pace et al. 2017). Moreover, earlier activation was associated with increased CTs and showed a similar trend for CVs. Specifically, children with CIs whose CIs were activated earlier engaged in more parent-child interactions and produced more vocalizations. These findings are consistent with prior evidence that early hearing experience has a measurable effect on language input to children with hearing loss and children's linguistic skills (Bergeson & McCune 2004; Geers & Moog 1987; Wieland et al. 2015). It is worthy of note that our mixed model indicated that maternal education and earlier activation independently contribute to explaining variabilities in CTs and CVs. These findings suggest that more intensive intervention on providing an optimal auditory environment to children with CIs may be beneficial for both children from low SES families and children who receive implantation at a later age. Surprisingly, we found that lower PTA was associated with increased TVN. Due to the paucity of research, we do not have a clear answer for the nature of these relationships, and thus would like to invite future research to shed light on this topic.

Study Strengths and Limitations

This study examined the naturalistic auditory environment experienced by children with CIs relative to children with NH. A major strength of the present research was the collecting and analyzing of daylong naturalistic auditory samples from the home environment in a longitudinal design. This methodology allowed us to provide important knowledge about the properties of the auditory environment experienced by children with CIs, and more importantly, the change of these properties with child development. The present study also extended previous work to investigate the nonlinguistic aspects of the auditory input, including TVN, NON, and OLN, which have been less studied in the literature.

The limitations of this study were related to methodological characteristics and LENA automated analysis. First, our small sample size, although not uncommon in studies including young children with CIs, may limit the generalization of our findings to other groups of children with CIs. Moreover, although LENA measures the total number of words spoken by adults (AWC), it does not distinguish between the speech directed to children and the speech overheard by children. Therefore, we do not know if children with CIs and children with NH hear a similar amount of speech directed to them; this is important because previous studies have shown that child-directed speech, but not overheard speech, is associated with later language skills (Weisleder & Fernald 2013). In addition, LENA only collects auditory information; therefore, other non-auditory information was not captured. Note that in our study, although families have chosen spoken English as the primary communication goal, some families used ASL and sign as support to the spoken language; the lack of the nonauditory linguistic input, as well as other social cues, including the facial and gesture communication, prevented us from analyzing the overall quality of the language input and the multimodal communications between the child and the caregivers. Finally, we did not analyze information on many factors that may influence the home auditory environment, including the early intervention services received by the children and their families and child language skills. Future studies are encouraged to explore this topic further to promote our understanding of which factors may improve children's home auditory environment.

Summary

In summary, the findings from this study suggest that children with CIs experience a less optimal auditory environment, especially because the CTs and CVs did not show age-appropriate increases in children with CIs, as compared with children with NH. Reduced CTs and CVs may be interdependent, leading to long-term negative consequences on the developmental outcomes in children with CIs. These findings support the need for early intervention programs for children with CIs that encourage and coach parents to provide contingent responses to their CVs and improve CVs. Our findings also suggest the importance of consistent device use and early device activation, which may increase the opportunity for children with CIs to receive greater language exposure.

ACKNOWLEDGMENTS

We thank Rondeline Williams and Anna Roy for their assistance with data collection, and Jongmin Jung for organizing and compiling audiological data.

This research was supported by the National Institute on Deafness and Other Communication Disorders Grant (R01 DC008581) to D.M.H. and L.D. There are no conflicts of interest, financial, or otherwise.

Y.W. conceptualized and designed the study, supervised data collection, conducted the statistical analysis, and drafted the initial article. M.C. coordinated and supervised data collection, participated in data interpretation, assisted with article preparation, and reviewed and revised the article. J.R. coordinated and supervised data collection, reviewed and revised the article. L.D. conceptualized the study, reviewed and revised the article. D.M.H. conceptualized and designed the study, coordinated and supervised data collection, participated in data interpretation, reviewed and revised the article. All authors approved the article as submitted.

Address for correspondence: Yuanyuan Wang, PhD, Department of Otolaryngology—Head and Neck Surgery, The Ohio State University, 915 Olentangy River Rd., Columbus, OH 43212, USA. E-mail: yywang118@gmail.com.

Received July 15, 2020; accepted July 21, 2021; published online ahead of print September 22, 2021.

REFERENCES

Adikaram, K. L. B., Hussein, M. A., Effenberger, M., Becker, T. (2015). Data transformation technique to improve the outlier detection power of Grubbs' test for data expected to follow linear relation. *J Appl Mathematics*, *2015*, 1–9.

Ambrose, S. E., VanDam, M., Moeller, M. P. (2014). Linguistic input, electronic media, and communication outcomes of toddlers with hearing loss. *Ear Hear, 35*, 139–147.

Ambrose, S. E., Walker, E. A., Unflat-Berry, L. M., Oleson, J. J., Moeller, M. P. (2015). Quantity and quality of caregivers' linguistic input to 18-month and 3-year-old children who are hard of hearing. *Ear Hear, 36 Suppl 1*, 48S–59S.

Arora, S., Smolen, E. R., Wang, Y., Hartman, M., Howerton-Fox, A., Rufsvold, R. (2020). Language environments and spoken language development of children with hearing loss. *J Deaf Stud Deaf Educ, 25*, 457–468.

Bakdash, J. Z., & Marusich, L. R. (2017). Repeated measures correlation. *Front Psychol, 8*, 456.

Bartlett, M. S., & Kendall, D. (1946). The statistical analysis of variance-heterogeneity and the logarithmic transformation. *Suppl J R Stat Soc*, *8*, 128–138.

Bates, D., Mächler, M., Bolker, B., Walker, S. (2015). Fitting linear mixed-effects models using lme4. *J Stat Softw*, *67*, 1–48.

Benítez-Barrera, C. R., Grantham, D. W., Hornsby, B. W. Y. (2020). The challenge of listening at home: Speech and noise levels in homes of young children with hearing loss. *Ear Hear, 41*, 1575–1585.

Bergeson, T. R., & McCune, K. (2004). Mothers speech to hearing-impaired infants with cochlear implants: Some preliminary findings. *Res Spoken Language Process*, *26*, 235–244.

Bergeson, T. R., Miller, R. J., McCune, K. (2006). Mothers' speech to hearing-impaired infants and children with cochlear implants. *Infancy*, *10*, 221–240.

Bharadwaj, S. V., & Mehta, J. A. (2016). An exploratory study of visual sequential processing in children with cochlear implants. *Int J Pediatr Otorhinolaryngol, 85*, 158–165.

Brainard, M. S., & Doupe, A. J. (2000). Auditory feedback in learning and maintenance of vocal behaviour. *Nat Rev Neurosci, 1*, 31–40.

Busch, T., Vanpoucke, F., van Wieringen, A. (2017). Auditory environment across the life span of cochlear implant users: Insights from data logging. *J Speech Lang Hear Res, 60*, 1362–1377.

Busch, T., Vermeulen, A., Langereis, M., Vanpoucke, F., van Wieringen, A. (2020). Cochlear implant data logs predict children's receptive vocabulary. *Ear Hear, 41*, 733–746.

Caldwell, A., & Nittrouer, S. (2013). Speech perception in noise by children with cochlear implants. *J Speech Lang Hear Res, 56*, 13–30.

Caskey, M., Stephens, B., Tucker, R., Vohr, B. (2014). Adult talk in the NICU with preterm infants and developmental outcomes. *Pediatrics, 133*, e578–e584.

Cejas, I., Barker, D. H., Quittner, A. L., Niparko, J. K. (2014). Development of joint engagement in young deaf and hearing children: Effects of chronological age and language skills. *J Speech Lang Hear Res, 57*, 1831–1841.

Christakis, D. A., Gilkerson, J., Richards, J. A., Zimmerman, F. J., Garrison, M. M., Xu, D., Gray, S., Yapanel, U. (2009). Audible television and decreased adult words, infant vocalizations, and conversational turns: A population-based study. *Arch Pediatr Adolesc Med, 163*, 554–558.

Conway, A. R., Cowan, N., Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychon Bull Rev, 8*, 331–335.

Conway, C. M., Pisoni, D. B., Anaya, E. M., Karpicke, J., Henning, S. C. (2011). Implicit sequence learning in deaf children with cochlear implants. *Dev Sci, 14*, 69–82.

Erickson, L. C., & Newman, R. S. (2017). Influences of background noise on infants and children. *Curr Dir Psychol Sci, 26*, 451–457.

Erola, J., Jalonen, S., Lehti, H. (2016). Parental education, class and income over early life course and children's achievement. *Res Soc Stratif Mob*, *44*, 33–43.

Evans, G. W. (2006). Child development and the physical environment. *Annu Rev Psychol, 57*, 423–451.

Geers, A. E., & Moog, J. S. (1987). Predicting spoken language acquisition of profoundly hearing-impaired children. *J Speech Hear Disord, 52*, 84–94.

Geers, A. E., Strube, M. J., Tobey, E. A., Pisoni, D. B., Moog, J. S. (2011). Epilogue: Factors contributing to long-term outcomes of cochlear implantation in early childhood. *Ear Hear, 32*(1 Suppl), 84S–92S.

Gilkerson, J., Coulter, K., Richards, J. (2008). Transcriptional analyses of the LENA Foundation natural language corpus (LENA Foundation Technical Report LTR-06-2). *Retrieved from LENA Foundation:* http://www. lenafoundation. org/TechReport. aspx/Transcription/LTR-06-2.

Gilkerson, J., Richards, J. A., Warren, S. F., Montgomery, J. K., Greenwood, C. R., Kimbrough Oller, D., Hansen, J. H. L., Paul, T. D. (2017). Mapping the early language environment using all-day recordings and automated analysis. *Am J Speech Lang Pathol, 26*, 248–265.

Gilkerson, J., Richards, J. A., Warren, S. F., Oller, D. K., Russo, R., Vohr, B. (2018). Language experience in the second year of life and language outcomes in late childhood. *Pediatrics, 142*, e20174276.

Goldstein, M. H., & Schwade, J. A. (2008). Social feedback to infants' babbling facilitates rapid phonological learning. *Psychol Sci, 19*, 515–523.

Greenwood, C. R., Thiemann-Bourque, K., Walker, D., Buzhardt, J., Gilkerson, J. (2011). Assessing children's home language environments using automatic speech recognition technology. *Commun Disord Quar*, *32*, 83–92.

Gros-Louis, J., West, M. J., King, A. P. (2014). Maternal responsiveness and the development of directed vocalizing in social interactions. *Infancy*, *19*, 385–408.

Haines, M. M., Stansfeld, S. A., Job, R. F., Berglund, B., Head, J. (2001). Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children. *Psychol Med, 31*, 265–277.

Hart, B., & Risley, T. R. (1995). *Meaningful Differences in the Everyday Experience of Young American Children*. Paul H Brookes Publishing.

Hoff-Ginsberg, E. (1986). Function and structure in maternal speech: Their relation to the child's development of syntax. *Develop Psychol*, *22*, 155–163.

Hoff-Ginsberg, E. (1994). Influences of mother and child on maternal talkativeness. *Discourse Processes*, *18*, 105–117.

Holt, R. F., Beer, J., Kronenberger, W. G., Pisoni, D. B., Lalonde, K. (2012). Contribution of family environment to pediatric cochlear implant users' speech and language outcomes: Some preliminary findings. *J Speech Lang Hear Res, 55*, 848–864.

Houston, D. M., & Bergeson, T. R. (2014). Hearing versus listening: Attention to speech and its role in language acquisition in deaf infants with cochlear implants. *Lingua, 139*, 10–25.

Huttenlocher, J., Haight, W., Bryk, A., Seltzer, M., Lyons, T. (1991). Early vocabulary growth: Relation to language input and gender. *Develop Psychol*, *27*, 236–248.

Klatte, M., Bergström, K., Lachmann, T. (2013). Does noise affect learning? A short review on noise effects on cognitive performance in children. *Front Psychol, 4*, 578.

Kuznetsova, A., Brockhoff, P. B., Christensen, R. H. B. (2015). lmerTest: tests in linear mixed effects models. R package version 2.0-20. https://cran. rproject. org/web/packages/lmerTest. Accessed, 15, 2016.

Lewis, D., Schmid, K., O'Leary, S., Spalding, J., Heinrichs-Graham, E., High, R. (2016). Effects of noise on speech recognition and listening effort in children with normal hearing and children with mild bilateral or unilateral hearing loss. *J Speech Lang Hear Res, 59*, 1218–1232.

Lund, E. (2016). Vocabulary knowledge of children with cochlear implants: A meta-analysis. *J Deaf Stud Deaf Educ, 21*, 107–121.

McMillan, B. T., & Saffran, J. R. (2016). Learning in complex environments: The effects of background speech on early word learning. *Child Dev, 87*, 1841–1855.

Meinzen-Derr, J., Wiley, S., Grove, W., Altaye, M., Gaffney, M., Satterfield-Nash, A., Folger, A. T., Peacock, G., Boyle, C. (2020). Kindergarten readiness in children who are deaf or hard of hearing who received early intervention. *Pediatrics, 146*, e20200557.

Millard, S. P., Kowarik, A., Kowarik, M. A. (2020). Package 'EnvStats'. https://cran.r-project.org/web/packages/EnvStats/EnvStats.pdf.

Moeller, M. P., Carr, G., Seaver, L., Stredler-Brown, A., Holzinger, D. (2013). Best practices in family-centered early intervention for children who are deaf or hard of hearing: An international consensus statement. *J Deaf Stud Deaf Educ, 18*, 429–445.

Moeller, M. P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B., Lewis, D., Estee, S., Pittman, A., Stelmachowicz, P. (2007). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part II–transition to words. *Ear Hear, 28*, 628–642.

Mohr, P. E., Feldman, J. J., Dunbar, J. L., McConkey-Robbins, A., Niparko, J. K., Rittenhouse, R. K., Skinner, M. W. (2000). The societal costs of severe to profound hearing loss in the United States. *Int J Technol Assess Health Care, 16*, 1120–1135.

Monroy, C., Shafto, C., Castellanos, I., Bergeson, T., Houston, D. (2019). Visual habituation in deaf and hearing infants. *PLoS One, 14*, e0209265.

Niparko, J. K., Tobey, E. A., Thal, D. J., Eisenberg, L. S., Wang, N. Y., Quittner, A. L., Fink, N. E.; CDaCI Investigative Team. (2010). Spoken language development in children following cochlear implantation. *JAMA, 303*, 1498–1506.

Oller, D. K. (2000). *The Emergence of the Speech Capacity*. Psychology Press.

Pace, A., Luo, R., Hirsh-Pasek, K., Golinkoff, R. M. (2017). Identifying pathways between socioeconomic status and language development. *Ann Rev Linguistics*, *3*, 285–308.

Peterson, N. R., Pisoni, D. B., Miyamoto, R. T. (2010). Cochlear implants and spoken language processing abilities: Review and assessment of the literature. *Restor Neurol Neurosci, 28*, 237–250.

Piaget, J. (2002). *The Language and Thought of The Child* (Vol. *10*). Psychology Press.

R Core Team. (2014). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. In.

Romeo, R. R., Leonard, J. A., Robinson, S. T., West, M. R., Mackey, A. P., Rowe, M. L., Gabrieli, J. D. E. (2018). Beyond the 30-million-word gap: Children's conversational exposure is associated with language-related brain function. *Psychol Sci, 29*, 700–710.

Rufsvold, R., Wang, Y., Hartman, M. C., Arora, S. B., Smolen, E. R. (2018). The impact of language input on deaf and hard of hearing preschool children who use listening and spoken language. *Am Ann Deaf, 163*, 35–60.

Sperry, D. E., Sperry, L. L., Miller, P. J. (2019). Reexamining the verbal environments of children from different socioeconomic backgrounds. *Child Dev, 90*, 1303–1318.

Stoel-Gammon, C., & Otomo, K. (1986). Babbling development of hearing impaired and normally hearing subjects. *J Speech Hear Disord*, *51*, 33–41.

Tomopoulos, S., Dreyer, B. P., Berkule, S., Fierman, A. H., Brockmeyer, C., Mendelsohn, A. L. (2010). Infant media exposure and toddler development. *Arch Pediatr Adolesc Med, 164*, 1105–1111.

VanDam, M., Ambrose, S. E., Moeller, M. P. (2012). Quantity of parental language in the home environments of hard-of-hearing 2-year-olds. *J Deaf Stud Deaf Educ, 17*, 402–420.

Vohr, B. R., Topol, D., Watson, V., St Pierre, L., Tucker, R. (2014). The importance of language in the home for school-age children with permanent hearing loss. *Acta Paediatr, 103*, 62–69.

Vygotsky, P. (1996). The problems of Plato. *Swiss J Psychol*, *55*, 84–92.

Wachs, T. D. (1978). The relationship of infants' physical environment to their Binet performance at 21/2 years. *Int J Behav Development*, *1*, 51–65.

Wang, Y., Chen, C.-h., Reed, J., Dilley, L., Houston, D. (2020). The effects of hearing loss on the social feedback loop in infants with cochlear implants. The 2020 International Conference on Infant Studies (ICIS) Biennial Meeting, Glasgow, Scotland.

Wang, Y., Shafto, C. L., Houston, D. M. (2018). Attention to speech and spoken language development in deaf children with cochlear implants: A 10-year longitudinal study. *Dev Sci, 21*, e12677.

Wang, Y., Williams, R., Dilley, L., Houston, D. M. (2020). A meta-analysis of the predictability of LENA™ automated measures for child language development. *Dev Rev, 57*, 100921.

Weisleder, A., & Fernald, A. (2013). Talking to children matters: Early language experience strengthens processing and builds vocabulary. *Psychol Sci, 24*, 2143–2152.

Wieland, E. A., Burnham, E. B., Kondaurova, M., Bergeson, T. R., Dilley, L. C. (2015). Vowel space characteristics of speech directed to children with and without hearing loss. *J Speech Lang Hear Res, 58*, 254–267.

Wiseman, K. B., & Warner-Czyz, A. D. (2018). Inconsistent device use in pediatric cochlear implant users: Prevalence and risk factors. *Cochlear Implants Int, 19*, 131–141.

Xu, D., Yapanel, U., Gray, S. (2009). Reliability of the LENA™ language environment analysis system in young children's natural home environment. http://www.lenafoundation.org/TechReport.aspx/Reliability/LTR-05-2.

Yoshinaga-Itano, C., Sedey, A. L., Mason, C. A., Wiggin, M., Chung, W. (2020). Early intervention, parent talk, and pragmatic language in children with hearing loss. *Pediatrics, 146*(Suppl 3), S270–S277.

Zimmerman, F. J., Gilkerson, J., Richards, J. A., Christakis, D. A., Xu, D., Gray, S., Yapanel, U. (2009). Teaching by listening: The importance of adult-child conversations to language development. *Pediatrics, 124*, 342–349.