The everyday speech environments of preschoolers with and without cochlear implants

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Abstract

Purpose Children with severe to profound deafness who receive cochlear implants develop speech and language on a protracted timescale, owing to the *absence* of auditory input pre-implantation, and the *degraded* speech signal transmitted by the cochlear implant post-implantation. The home environment facilitates children's speech-language development, yet it is relatively unknown how the home environment differs between children with cochlear implants and children with typical hearing. This study asked how hearing status impacts the everyday speech-language environments of preschoolers with cochlear implants, compared to their peers with typical hearing.

Method Eighteen children with cochlear implants (31-65 months) were matched by chronological age and hearing age to two groups of children with typical-hearing. Each child completed a long-form, naturalistic audio recording of their home language environment (appx. 16 hrs/child; >730 hours of observation) to evaluate the impact of hearing status upon early speech-language experience: speech input from adults, child vocal productivity, and caregiver-child interaction. The *quantity*, *consistency*, and experience-related *growth* of each component was computed and compared across hearing groups. We additionally assessed how measures of the environment predicted the children's speech outcomes.

Results Unlike children with typical hearing, children with implants do not hear more speech input from caregivers as they age, and measures of the speech environment (words, interaction) do not predict their vocal outcomes as strongly. Nevertheless, all children, regardless of hearing status, engage in similar amounts of caregiver interaction. All children's own speech production matures with age, but at a much slower rate for children with implants than hearing age matched controls. All children produce more contingent speech in response to louder caregiver input.

Conclusions Children with cochlear implants are exposed to and engage in similar amounts of language with caregivers as children with typical hearing. However, over development, the at-home speech environment does not appear to reflect developmental stages as closely for children with implants as those with typical hearing. Home-based language interventions should focus on the unique input-outcome relationships for this group of children with hearing loss.

1 Introduction

Children learn the sounds and structure of their native language(s) from the input that they receive from caregivers around them. Yet children of the same age, exposed to the same language, vary in the type and quantity of their speech-language exposure. These differences include the number and diversity of word types (Rowe, 2012), ratio of male to female speakers (Bergelson et al., 2019), syntactic complexity of phrases (Huttenlocher, Vasilyeva, Waterfall, Vevea, & Hedges, 2007), amount of child-directed speech (Rowe, 2008; Rowe & Weisleder, 2020; Schwab & Lew-Williams, 2016), and acoustic realization of speech (Dilley, Millett, Mcauley, & Bergeson, 2014; Kalashnikova & Burnham, 2018), amongst others.

Crucially, individual differences in linguistic exposure may drive some aspects of children's speech-language development. For example, in infancy, 6- to 14-month-olds who engage in more contingent interactions with caregivers—typically defined as conversational exchanges that take place in quick succession ($\leq$ 2 seconds)—produce more babbling sounds and eventually grow larger expressive and receptive vocabularies (Ferjan Ramírez, Lytle, Fish, & Kuhl, 2019; Ferjan Ramírez, Lytle, & Kuhl, 2020). Similarly, infants who hear more child-directed speech at seven (Newman, Rowe, & Bernstein Ratner, 2016) or nineteen months (Weisleder & Fernald, 2013) learn to process words from running speech more efficiently, helping them grow larger vocabularies by two years of age.

This causal link between individual differences in linguistic input and speech-language development, which persists independent of family socioeconomic status or caregiver characteristics (Romeo et al., 2018), likewise extends to non-typically developing groups such as children who go on to receive autism spectrum disorder diagnoses (Swanson et al., 2019). And most critically for the current work, individual differences in linguistic input and caregiver-child interaction impact speech-language outcomes among children with hearing loss, including those who receive cochlear implants (CIs) (Ambrose, VanDam, &

Moeller, 2014; Ambrose, Walker, Unflat-Berry, Oleson, & Moeller, 2015; Arjmandi, Houston, Wang, & Dilley, 2021; DesJardin & Eisenberg, 2007; Dilley et al., 2020; Wang, Jung, Bergeson, & Houston, 2020) (see Nittrouer, Lowenstein, and Antonelli (2019) for review). For example, Dilley et al. (2020) correlated acoustic-lexical properties of speech directed to a cohort of recently-implanted infants (8-29 months at implantation) and found that more diverse word types, and more dispersed vowel spaces in infant-directed compared to adult-directed speech, predicted greater scores on standardized language assessments such as the Preschool Language Scales two years post-implantation (see also Wang, Jung, et al. 2020). Elsewhere, caregivers of children with CIs who had greater mean lengths of utterance, and used more open-ended and/or recast questions, likewise had children with higher standardized receptive and expressive language assessment scores (DesJardin & Eisenberg, 2007). Although standardized assessments never capture the full complexity of a child's linguistic development, these results do show that individual differences in linguistic input to children with a variety of speech and language experiences can predict some variation in developmental outcomes. As such, having a clear characterization of children's everyday speech-language environments is fundamental to understanding how they develop speech and language.

1.1 How cochlear implantation might shape the early language environment

There are reasons to believe that the speech-language input directed to children, and caregiver-child interaction, may vary by hearing status, particularly for children with severe to profound hearing loss who receive cochlear implants (CIs) (Houston, 2022). A CI is an auditory prosthesis with an audio processor worn external to the ear and an electrode array inserted into the cochlea that directly stimulates the auditory nerve, partially restoring the sensation of hearing. Pediatric CI candidates must pass a series of candidacy requirements (e.g., >70dB pure-tone thresholds in both ears, limited benefit from acoustic amplification, typical anatomical cochlear development). Although the Food and Drug Administration permits implantation in children as young as 9 months of age (USFDA, 2020), recipients are often only implanted between 24 and 36 months (Fitzpatrick, Ham, & Whittingham, 2015). Prior to implantation, some pediatric CI recipients are exposed to one or more forms of signed language (e.g. American Sign Language), but the vast majority are not or are instead exposed to more limited home sign systems if they are born to hearing parents (Humphries et al., 2012).

There are two components of cochlear implantation that may systematically alter child implantees' speech-language environments and everyday input. First, as previously stated, prelingually-deafened children often do not receive one or both of their CIs until their second or third birthdays (Fitzpatrick et al., 2015), resulting in an extended period of AUDITORY ABSENCE pre-implantation where (1) the children are not exposed to oral language models and (2) caregivers may direct less oral language to the child. Second, once CIs are activated, recipients have the added challenge of compensating for SIGNAL DEGRADATION: CI electrode arrays stimulate the cochlea at discrete points, discretizing the speech envelope. There are additional issues inherent to the hardware such as electrode interaction and interaural mismatch, as well as physiological aspects such as irregular neuronal survival, that together result in a highly degraded auditory signal from which pre-lingual implantees must nevertheless learn speech and language. CIs also only restore the sensation of hearing when the devices are being worn, and children vary greatly in the number of hours of typical device use (Ganek, Cushing, Papsin, & Gordon, 2020; Majorano et al., 2021).

Thus, both auditory absence pre-implantation and signal degradation post-implantation characterize the listening experiences of children with CIs. And these early auditory differences may lead to changes in the children's linguistic input and subsequent interactions with caregivers, shaping the children's everyday speech and language environments. For example, among children with aided hearing loss (hearing aids), those with better-ear pure tone averages tend to receive more language input from adult caregivers (VanDam, Ambrose, & Moeller, 2012). Children with severe to profound hearing loss additionally engage in fewer vocal turns with caregivers than both children with typical hearing (TH) and children with hearing aids[1], showing a link between the degree of hearing loss and the type of input that children receive.

Similar patterns emerge for the speech production of children with severe to profound hearing loss. In infancy, children with TH who vocalize more receive more contingent responses from caregivers (and vice versa) resulting in a social feedback loop that spurs early speech development (Gros-Louis, West, Goldstein, & King, 2006; Warlaumont, Richards, Gilkerson, & Oller, 2014). Yet despite a common trope that "*even children who are deaf babble*" (orally), prior to intervention, children who go on to receive CIs vocalize infrequently and babble immaturely (Fagan, 2014, 2015).[2] In reality, it takes many months post-implantation for pediatric CI recipients to produce speech on par with their peers with TH and even longer to engage in socially-contingent linguistic interactions with caregivers (Fagan, Bergeson, & Morris, 2014; Kondaurova, Fagan, & Zheng, 2020; Kondaurova, Smith, Zheng, Reed, & Fagan, 2020), demonstrating how the period of auditory absence pre-implantation shapes the children's early speech-language experiences.

Finally, the degraded signal transmitted by the CI likely also shapes the home language environment. For example, even several years post-implantation in middle childhood, pediatric CI recipients experience reduced sound localization cues (Todd, Goupell, & Litovsky, 2016), in part due to interaural differences in frequency-to-place mismatch.[3] These deficits can make it more difficult for these children to *locate* the source

[1] Note that the mean ages of the children with hearing aids in Kondaurova, Zheng, VanDam, and Kinney (2022) was 26.3 months, while the mean age of the children with CIs was 63.2 months, potentially explaining some of the differences in vocal turn taking dynamics.

[2] Early evidence for mature babbling among children with hearing loss often confounded the degree of hearing loss; see Oller and Eilers (1988) for discussion.

[3] Reduced sound localization cues are also due to lack of experience with acoustic hearing (for pre-lingually

of a caregiver's voice—and a failure to look towards a speaker could alter the feedback loop that drives caregiver speech input (Wang, Bergeson, & Houston, 2017; Wang, Shafto, & Houston, 2018). The deficits also may make it difficult for children to *attune* to audio-visual cues from the lips that may help compensate for a degraded auditory signal (Bergeson, Pisoni, & Davis, 2005). Alternatively, children with CIs could simply rely on different cues during interactions with caregivers. For example, two- to three-year-olds with hearing loss, including those with CIs, rely on both caregiver gaze and hand gestures during joint attention episodes, where much early word learning occurs, while children with TH rely predominantly on hand gestures (Chen, Castellanos, Yu, & Houston, 2020).

The implant's signal is often degraded in predictable ways, with implications for children's language learning environments. CI users of all ages have reduced access to temporal fine structure cues, such as those that encode the fundamental frequency (f0) of the voice and reflect speaker pitch or lexical tone (Chatterjee & Peng, 2008; Stickney, Assmann, Chang, & Zeng, 2007), making it difficult to perceive differences in these measures (Deroche et al., 2019; Lee, van Hasselt, Chiu, & Cheung, 2002). Yet children with TH can use pitch cues to help differentiate between speakers in their environment (Nagels, Gaudrain, Vickers, Hendriks, & Başkent, 2021). Consequently, without access to these cues, certain aspects of speech processing such as normalization for speaking rate or vocal tract length differences, as well the ability to segregate overlapping speakers, prove more difficult for children with CIs (Cleary & Pisoni, 2002; Nittrouer, Caldwell-Tarr, Moberly, & Lowenstein, 2014). The result is that the children have to compensate and employ other processing strategies. Altogether, components of the degraded signal that the CI relays, including frequency-to-place mismatch and compromised f0 cues, may shape children's daily language environments and linguistic interactions with caregivers: the signal affects how children attune to linguistic input, potentially explaining some of the differences between children with CIs and TH in child-caregiver vocal contingency (Kondaurova,

deafened children) and lack of experience with binaural hearing (for single-sided deafness).

Smith, et al., 2020), and synchronization during joint attention (Chen, Castellanos, Yu, & Houston, 2019), even a year post-implantation. We elaborate upon these differences more in the following section.

1.2 Current study

Overall, the absence of auditory input that children with CIs experience pre-implantation and the signal degradation that they experience post-implantation, combined with differences in parental expectations, may cause the home language environments of child CI recipients to unfold differently in developmental time. The purpose of this study was to evaluate how the listening experiences of children with CIs shape their everyday speech and language environments. To evaluate this, we matched a cohort of 3- to 5-year-olds with CIs, with at least 8 months of hearing experience, separately to a group of their *hearing* age- and *chronological* age-matched peers. We densely sampled the children's naturalistic home environments using child-friendly wearable recording devices (appx. 16 hrs./child or >730 total hours of observation) allowing us to assess a battery of elements of the home speech-language environment. Specifically, we characterized the *quantity*, *consistency*, and age-related *growth* of children's speech input, vocal output, and conversational interactions with caregivers. In a secondary analysis, we additionally evaluated the vocal contingency dynamics between the children and their caregivers. Finally, we assessed how the children's speech-language input predicted their vocal productivity. Below we outline our predictions for how each metric may differ for children with CIs compared to their peers with TH:

1. *Why might quantity of caregiver input differ?* The quantity of speech and language directed to children with CIs could differ by hearing status for a number of reasons. Children with CIs could hear more caregiver input than HA matches because they are at a more advanced cognitive developmental stage, and caregivers of children with

TH use more words tokens and complex grammatical structures as children develop (Huttenlocher et al., 2007; Rowe, 2012). Or, alternatively, caregivers could talk more to children with CIs in an attempt to compensate, believing that their child needs more exposure. Children with CIs may receive less caregiver input than chronological matches, however, if caregivers are sensitive to the children's developing linguistic capabilities, especially in the first months and years post-implantation (DesJardin & Eisenberg, 2007).

2. *Why might the intensity/sound pressure level of caregiver input differ?* Caregivers could attempt to compensate for the CI's degraded signal by speaking louder to the target child and/or facing the child when they speak; both actions would manifest as increased intensity of caregiver speech relative to both groups of children with TH.

3. *Why might child vocal output differ?* The vocal output of children with CIs is likely to be less mature than chronological age matches (less frequent, shorter duration, reduced intensity) because the children with CIs have had less experience incorporating auditory and somatosensory feedback from their own speech production due to the time spent without access to sound pre-implantation (Fagan, 2014, 2015). Yet children with CIs would be expected to have more mature vocal output than HA matches because their speech-motor apparatuses are more mature and capable of sustaining phonation, and they are also more able to coordinate inter-articulatory movement such as the tongue and the jaw (Moore, 2004; A. Smith & Goffman, 1998). Signal degradation from the CIs post-implantation may also make it harder for children with CIs to establish reliable speech-motor maps, thereby delaying progression through later stages of speech development, and resulting in less mature or error-prone vocal production several months post-implantation (Serry & Blamey, 1999).

4. *Why might conversational interactions between the child and a caregiver, and the*

quantity of contingent vocalizations, differ?

The nature of caregiver-child linguistic interactions could differ by hearing status because the children with CIs had less opportunity to establish vocal contingency patterns (although not necessarily other forms of contingency such as gaze (Chen et al., 2020)) pre-implantation, in infancy, (Northrup & Iverson, 2020). Among children with TH, these early contingency behaviors are highly correlated with later linguistic outcomes in early childhood (Bornstein, Tamis-LeMonda, & Haynes, 1999; Donnelly & Kidd, 2021; Hirsh-Pasek et al., 2015), so the reduced interactions in infancy could set the stage for different quantities or types of interactions even post-implantation. Such a result would mean that at least early after gaining access to sound the children might pattern like the HA matches, not chronological matches. However, children with CIs may engage in fewer turns or contingent vocalizations than HA matches because they are chronologically older, granting them more bodily autonomy, distance from caregivers, and opportunity to interact with other interlocutors such as siblings—and indeed conversational turn development among children with TH follows this quadratic growth function through 48 months of age (Gilkerson et al., 2017).

Signal degradation also may play a role. Sound localization and f0 (and thus speech prosody) cues are compromised in electric hearing. So children may be less attuned to cues for speaker location, interlocutor identity, and utterance polarity (questions are produced with rising prosodic contours and statements with flat or downward sloping contours and/or a creaky voice modality), all causing children with CIs to respond or engage less readily with caregivers in their environments.

5. *Why might the timing of contingent vocalizations differ?* The developmental trajectory of contingent vocalization timing through early childhood is not entirely clear (Nguyen, Versyp, Cox, & Fusaroli, 2022). Some work has shown that latencies

between caregiver and child speech in infancy increase between 5 and 9 months (Hilbrink, Gattis, and Levinson 2015; see also Table 1 in Hilbrink et al. 2015) but decrease between 4 and 60 months—including among children with hearing loss who eventually receive CIs (N. A. Smith & McMurray, 2018). Children with CIs have slower latencies than TH controls 3 and 9 months post-implantation (Kondaurova, Smith, et al., 2020), but the data that we will report on in the current study come from children with at least 8 months of hearing experience. Furthermore, all of the results previously mentioned were data elicited in semi-controlled lab environments, where the children interacted one-on-one with a caregiver, had few other items to capture their attention directly away from the caregiver, and did not engage in typical activities. The current data are elicited in the children's homes where they may interact with multiple adult interlocutors and engage in typical behaviors, such as independent play conducted at a distance from the caregiver, that may affect contingent interactions. Given the relative unknowns about vocal contingencies in this population and using this form of data, we make no strong predictions about the direction of the difference by hearing group.

6. *Why might the relationship between speech-language input and child vocal productivity differ?* Although children with TH who hear more speech and/or engage in more conversational turns have more mature speech production outcomes in infancy and early childhood (Cychosz, Munson, & Edwards, 2021; Ferjan Ramírez et al., 2019, 2020; Ruan, 2022; Wang, Williams, Dilley, & Houston, 2020), this relationship may be less predictive for children with CIs. As described in section 1.1, children with CIs could have more difficulty locating caregivers in the environment due to signal degradation and device limitations (Houston, 2022; Wang et al., 2018), making it more difficult to segment speech, separate speech from other sounds, and process words (Vavatzanidis, Mürbe, Friederici, & Hahne, 2018).

2 Methods

2.1 Participants

Fifty-two children participants in this study. The N=18 children with CIs were one-to-one matched by parent-reported gender, socioeconomic status, and age to two groups of children with TH: (1) *chronological* age matches, to match for cognitive and articulatory development (N=18), and (2) *hearing* age matches, to match for auditory experience (N=16 as 2 children with CIs had <1 year of hearing experience). All children were monolingual English speakers and age matching was made within 3 months whenever possible. See Table 1 for demographic information by hearing group.

Socioeconomic status was instantiated as maternal education. To facilitate matching, we binned education into seven levels: 1) less than high school, 2) high school equivalent certificate (e.g., General Education Development [GED]), 3) high school diploma, 4) technical-associate degree, 5) some college (2+ years)/ trade school, 6) college degree, and 7) graduate degree. All maternal education matching was made within 1 degree of freedom (i.e., caregiver with level 3 education preferentially matched to caregiver with level 3 whenever possible, and if not then matched to caregiver with level 2 or 4).

The children with CIs had profound deafness in both ears (N=14 bilateral CIs, N=2 unilateral, and N=2 bimodal CI+hearing aid). The children with CIs had hearing parents and were being schooled in auditory-verbal (N=11), auditory-verbal+aural focus (N=2), aural focus (N=1), cued speech (N=1), or auditory-verbal+total communication (N=1) environments.[4] All children with TH had parent-reported typical speech-language development at the time of participation.

[4] Data on school environments were unavailable for two children.

Table 1

Demographic and audiological information. Mean (SD), range.

	Chrono. age matches	**Cochlear implant**	**Hearing age matches**
Chrono. Age (mos)	46.28 (10.8), 32-66	47.72 (9.84), 31-65	35 (12.71), 17-52
Gender (F,M)	9,9	9,9	9,7
Mat. Ed.	6.22 (1), 3-7	6.11 (1.02), 3-7	6.25 (1), 3-7
Hearing Age (mos)	NA	31.28 (14.3), 8-54*	NA
Implant Age (mos)	NA	16.44 (9.7), 7-45	NA
Num. of siblings	1.61 (0.98), 1-5	1.39 (0.85), 0-3	1.12 (0.96), 0-3
Num. of household members	4.56 (1.04), 3-8	4.33 (0.97), 2-6	4.06 (1.06), 2-6
Ethnicity (N)†			
Hispanic	2	0	2
Race (N)			
Asian	0	1	2
Black	2	0	0
White	14	14	13
American Indian	1	0	0
Asian & white	0	0	1
Black & white	0	1	0
More than 1 race (unspecified)	1	0	0

*Includes the 2 children with cochlear implants who had hearing ages $<$ 12 mos and were thus not included in those matched by hearing age to children with typical hearing. †Ethnicity information was unavailable for one child with implants and race information unavailable for two children with implants.

2.2 Data collection

Each child completed one daylong audio recording where they wore a small, lightweight Language ENvironment Analysis (LENA) recording device (2”x3”; 2 oz.) in a specialized vest for an entire day. Families received the devices and vests either in the mail or upon a visit to the research lab along with written instructions for use. Recordings were completed on a typical, non-school day in the child’s life. Families were instructed to turn the device on in the morning when the child awoke and continue recording for the duration of the device battery (16 hrs.). The device continued recording while the child napped. During bathtime and other water activities, parents were told to place the recorder in a safe, dry place as close to the child as possible. One family instead only completed a 12.83 hour recording.

2.3 Audio processing

Measures of the children’s home speech-language environments were semi-automatically derived from each child’s recording using LENA’s diarization algorithm which assigns speaker tags, timestamps, and intensity/sound pressure levels to audio clips (Xu, Yapanel, & Gray, 2009). To minimize inter-recorder differences, LENA hardware captures intensity in dBC SPL as this frequency response is flat across the speech range (Ford, Baer, Xu, Yapanel, & Gray, 2008). The intensity measures are reported in dBFS, with 0 as the maximum signal level; to facilitate interpretation of the intensity values, each value was offset by +97dB. All audio processing scripts are included in the project’s Github repository (`https://github.com/megseekosh/everyday_CI`).

All speech clips tagged as “Target child near” (CHN), “Male adult near” (MAN), and “Female adult near” (FAN) were extracted. We filtered out all CHN clips that contained cries, all FAN/MAN clips that contained any non-speech elements, and FAN/MAN clips greater than 10s (574 clips, 0.07% of total) since in our experience these clips longer than

10s tend to be mislabeled.[5] The average intensity value (in dBC) from each clip was extracted.[6] Word token count estimates from the adult clips were likewise extracted. Finally, algorithmic estimates of "conversational turns", defined as target child and adult utterances spoken within 5 seconds, were extracted (see Figure 1).

For each construct, speech input, vocal production, and caregiver-child interaction, we extracted different metrics. Speech input was instantiated in minutes (total duration of FAN and MAN clips in the child's recording) and the number of words from adults. Speech output was instantiated in seconds (total duration of CHN clips in the recording) and the number of vocalizations from the target child. Caregiver-child interaction was instantiated as the number of total back-and-forth conversational turns.

We normalized all measures by hour to account for time-of-day differences across recordings, as well as different recording lengths. To derive *quantity* estimates of each construct, we computed the average of (words, vocalizations, turns) per hour. For *consistency* estimates, we followed King, Querdasi, Humphreys, and Gotlib (2021) in computing the percentage of units containing at least one measure. For speech input, this was the percentage of minutes in the recording containing at least one adult word and for output the percentage of minutes containing at least one child vocalization. For interaction, this measure constituted the percentage of 5-minute epochs containing at least one conversational turn. Finally, to derive *growth* of the estimates, we computed the slope of the relationship between child age (in months) and each measure (we elaborate upon

[5] The decision to remove all FAN/MAN clips that contained *any* non-speech elements inevitably resulted in the removal of some adult speech near the child, but the step was maximally conservative and allowed us to be sure that the adult speech clips in the final analysis contained only speech.

[6] Wu et al. (2018) and Benítez-Barrera, Grantham, and Hornsby (2020) report intensity expansion (< approximately 50dBA/C) and compression (> approximately 80dBA/C) in the LENA recording hardware. The intensity ranges reported here fall more or less within this range (e.g., 45.46-87.94 dBC for adult speech segments) so no expansion or compression adjustments were made.

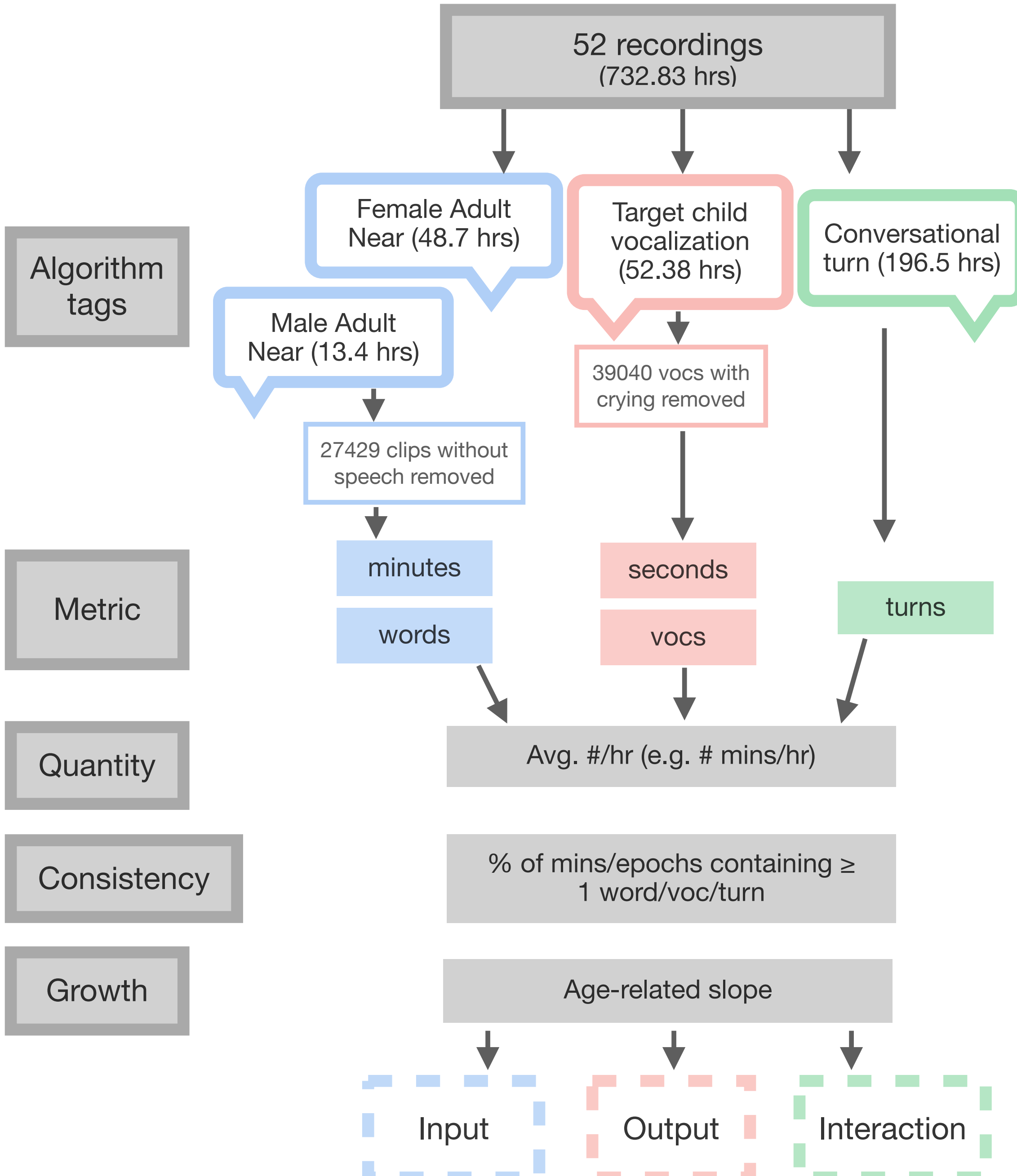

Figure 1. Daylong audio recording processing steps for the primary analysis.

this modeling in the results). Together, this workflow allowed us to assess the quantity, consistency, and experience-related growth of various metrics of the children's speech-language environments.

The secondary analysis concerned the contingent vocalizations in each child's recording. We followed previous work in considering a child's vocalization "contingent" if it occurred ≤ 2 seconds following a caregiver vocalization (FAN or MAN segment) (Egeren, Barratt, & Roach, 2001; Elmlinger, Goldstein, & Casillas, 2022; Elmlinger, Schwade, & Goldstein, 2019). We computed the percentage of contingent child vocalizations in each recording, where the denominator was the total number of vocalizations from the target child (Figure 2).

During processing, the LENA speaker/sound source diarization algorithm performs an initial pass where it assigns labels and timestamps to audio segments based on acoustic features within the segment. Each segment has a minimum length; for example, the minimum duration of a potential target child (CHN) audio segment is 600ms and the minimum length of a female adult near the target child (FAN) audio segment is 1000ms. During a subsequent pass, the algorithm may re-assign some of these labels. As a result of the minimum audio segment length, *no intervening segment between a FAN/MAN and CHN clip can be shorter than 600ms*, or the minimum CHN clip length. Consequently, the lag time between adult and child speech in this analysis is either 0 (indicating that a child spoke directly after an adult) or 600-2000ms (600 indicating the minimum audio segment duration and 2000 indicating the upper bound for contingent vocalizations commonly used in the literature). For this reason, we limit our analysis to the *percentage* of contingent vocalizations, and do not report the timing (in ms) of contingent vocalizations because we do not have reports of contingent vocalizations occurring between 0.00001-599.99 ms, as an artifact of the algorithm. (We include the results about vocal contingency timing in Supp. Materials I.) We therefore stress that our analyses are at the group level—we compare relative differences in the percentage of contingent vocalizations across hearing groups—and values reported are relative, not absolute.

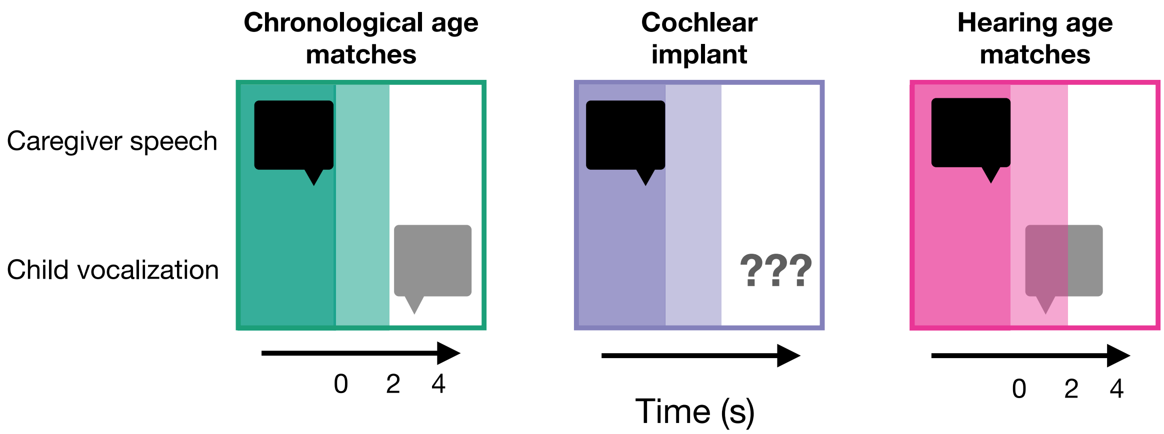

Figure 2. Contingent vocalizations are those that occur within a 2-second window (light colored shading) following caregiver speech. Hearing age matches (younger children) are predicted to have a greater percentage of contingent vocalizations than chronological matches (older children). It is unclear how children with cochlear implants will pattern. Illustration partially adapted from Elmlinger et al. (2022).

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There has been substantial work evaluating the LENA system's validity, in particular its algorithmic performance (Cristia, Bulgarelli, & Bergelson, 2020; Gilkerson et al., 2017; ?). Crucially, our analyses relied on diarization and tags that have relatively high recall and precision for the language and age group studied (e.g., "Female adult near" > 60% for English-learning infants and preschoolers (Cristia, Bulgarelli, & Bergelson, 2020)) and not those categories, such as electronic speech, that have poorer reliability. Nevertheless, as algorithmic performance is not exact for any of the analyzed categories, we interpret our results by comparing *across* hearing groups. There should be no reason why algorithmic performance would be better or worse by hearing group, and we stress that reports of exact amounts of e.g., words, vocalizations, or turns per hour, should be interpreted with caution (Ferjan Ramírez, Hippe, & Kuhl, 2021).

3 Results

We divide the results section into the various components of each child's daily speech-language experience—caregiver input, target child output (production), caregiver-child interaction, and contingent child vocalizations—and evaluate the impact of hearing group upon each outcome. See Table 2 for summary statistics of the measures.

Data were analyzed in the RStudio computing environment (R version 4.2.1; RStudioTeam, 2022). All computing and statistical analyses are included in the GitHub repository affiliated with this project (`https://github.com/megseekosh/everyday_CI`). Visualizations were made using `ggplot2` (Wickham, 2016) and modeling was conducted using `lme4` and `lmerTest` packages (Bates, Maechler, Bolker, & Walker, 2015; Kuznetsova, Brockhoff, & Christensen, 2017); see project documentation for package versions. All model fitting began with a baseline, random-effects only model. Model fit improvements were evaluated by comparing model log-likelihood values and AIC estimates. Unless noted otherwise, the predictor Hearing Group (3-levels: CI, chronological age matches, hearing age matches) was contrast-coded with 'CI' as the reference level so model coefficients for the chronological and hearing age match groups refer to deviance from the CI group as this is our main comparison of interest. All continuous variables were mean-centered for modeling but visualizations present the unscaled data.

3.1 Input

We quantified the children's speech-language input by computing the average number of minutes/hour that contained speech from an adult female or male near the child. We additionally computed the average number of words/hour spoken by an adult near the child.

For all examples of repeated measures, such as speech intensity, we fit linear mixed effects models with random intercepts by child and a fixed effect of **Hearing Group**.

Table 2

Measures of the naturalistic speech environment, by hearing group. Mean(SD), range.

	Chrono. age matches	**Cochlear implant**	**Hearing age matches**
Recording duration (hrs)	15.82(0.75), 12.83-16	16(0), 16-16	16(0), 16-16
Input			
Adult speech intensity (dB)	68.21(5.97),48.98-83.7	68.87(5.81),45.46-84.03	68.92(6.15),48.08-87.94
Adult speech/hr (words)	1081.49(481.29),285.63-2250.39	1217.23(508.87),411.36-2127.7	1105.54(433.01),170.88-1630.86
Adult speech/hr (s)*	258.36(118.69),72.79-533.67	288.52(121.52),95.31-499.53	264.55(102.57),43.67-386.22
Adult word consistency	0.52(0.13),0.31-0.78	0.58(0.11),0.25-0.7	0.51(0.12),0.19-0.66
Output			
Voc. intensity (dB)	76.78(4.39), 47.51-84.77	76.95(4.35), 43.16-85.79	77.15(4.95), 44.79-90.31
Child voc. quantity	308.03(142.81), 90.12-575.81	271.75(69.23), 48.75-381.62	254.5(108.83), 42.5-424
Voc. duration (ms)	1004.46(662.3), 80-10940	937.93(569.76), 80-13270	966.59(627.6), 80-19730
Child voc. consistency	0.55(0.15), 0.34-0.84	0.58(0.13), 0.17-0.72	0.49(0.14), 0.22-0.69
Interaction			
Convo. turn quantity	61.71(32.78), 20.69-150.94	68.17(26.47), 8.5-116.75	65.13(25.47), 11.12-92.62
Convo. turn consistency	0.58(0.14), 0.38-0.84	0.64(0.13), 0.22-0.77	0.56(0.12),0.36-0.74

*Descriptive statistics are reported for seconds of speech/hour, but modeling was conducted on minutes of speech/hour.

Models of hourly measures (words, minutes) additionally included random intercepts by hour of recording. There were no reliable differences by **Hearing Group** for speech input intensity, or measures of input quantity (hourly words, hourly minutes of speech; log-likelihood tests all $p > .05$); thus, speech input was produced at a similar intensity regardless of the child's hearing experience, and all hearing groups received similar amounts of input in the environment (words and minutes). See Figure 3 for distributions of speech input sound levels by household.

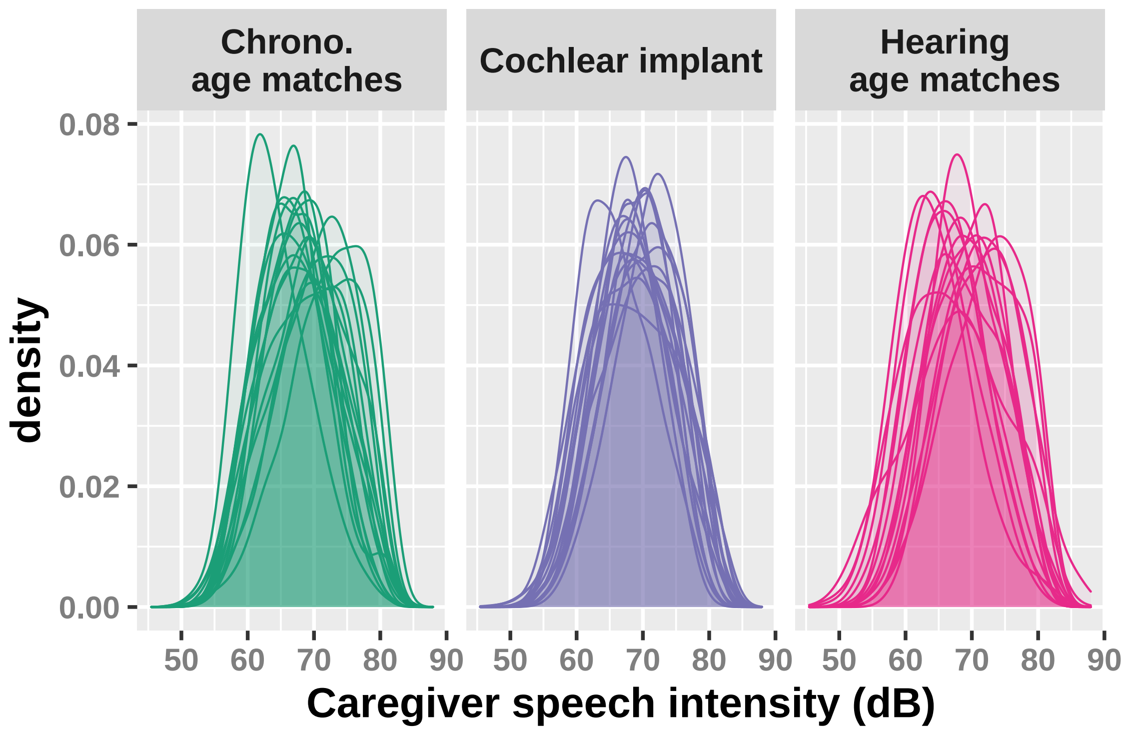

Figure 3. Distribution of caregiver speech intensity levels within individual households. Each distribution reflects the levels for speech input in one household, from adult females and males near the child. There were no differences by hearing status, but notable differences between households.

We evaluated the consistency of speech input by hearing group by computing the percentage of minutes in each recording containing ≥ 1 word from an adult (King et al., 2021). There were no differences in speech input consistency by **Hearing Group** (p >.05). However, speech input became more *consistent* with **Child Age** (age coded continuously, in months) across the entire sample, independent of hearing status (model fit: β=0.004, t=3.16, p=.003). This result indicates that as children aged, speech became more continuously present throughout their day (Figure 4). Note that this measure of consistency is independent of speech quantity, or the overall *amount* of speech input (words or minutes), which we explore below. Speech input becomes more consistent—more evenly spread out and less clustered into bursts over the course of the day—with child age across the sample.

Finally, we evaluated differences by hearing group in age-related growth of speech input. For this analysis, we modeled the effect of **Child Age** (in mos) upon hourly adult word token count and minutes of adult speech/hour in the children's environments and compared the values across all three hearing groups (CI, chronological age matches, hearing age matches). For the children with CIs, we modeled both their growth by *chronological* age as well as *hearing* age (time since implantation). Hourly word counts and minutes of speech/hour increased with child age in both groups of children with TH, but not by hearing or chronological age among the children with CIs (Table 3): for every month of development, chronological age matches (spanning 32-66 mos) received approximately 21 additional words/hour and 5 additional seconds of speech/hour while hearing age matches (17-52 mos) received an additional 16 words/hour and 4 seconds of speech/hour. Again, no such age-related growth was seen for the children with CIs.

3.2 Output

To assess each child's speech output (production), we computed the average number of vocalizations from the target child spoken/hour. We additionally analyzed the impact of hearing group upon the children's vocalization intensity and duration.

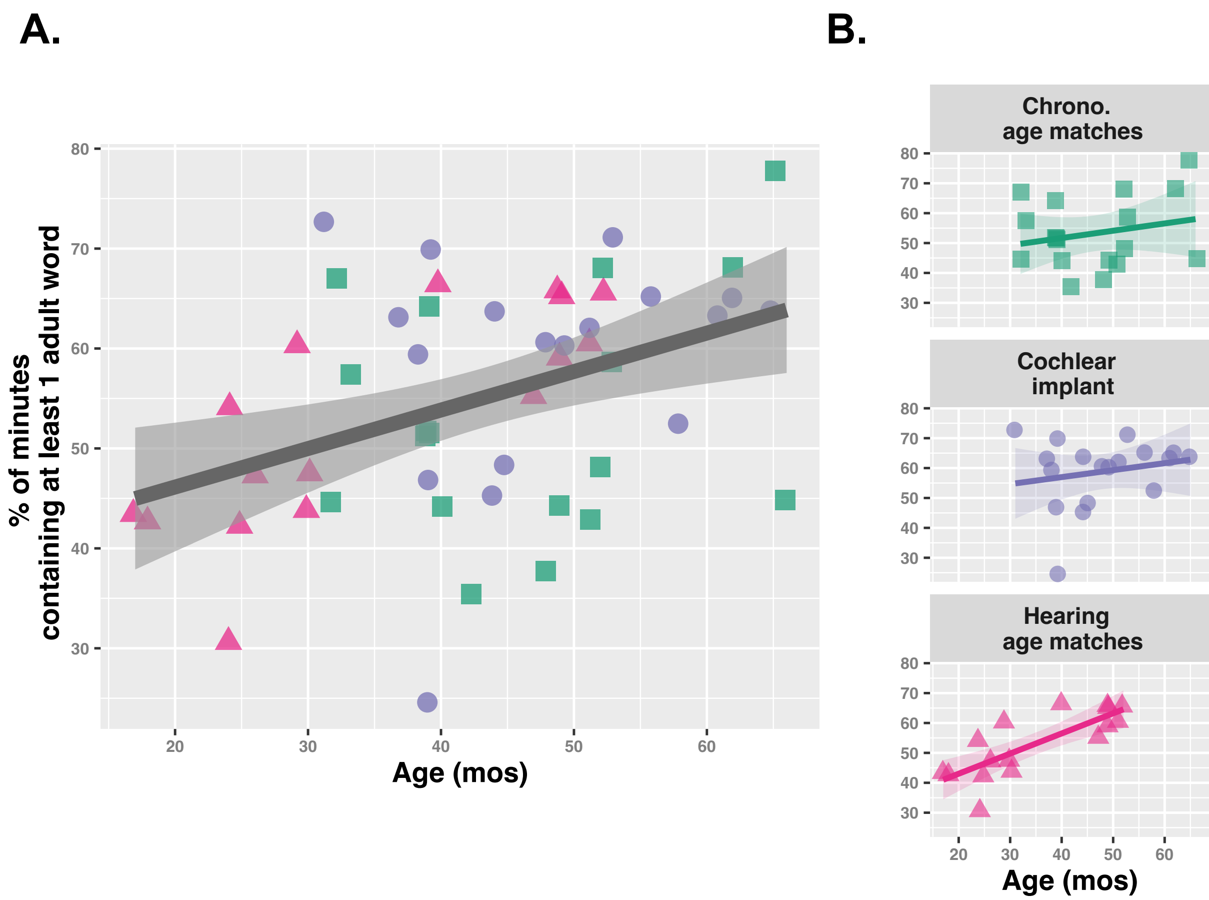

Figure 4. Age-related growth in speech input consistency across entire sample (A) and by hearing status (B). Each point represents one child. Dark, gray regression line represents local regression fit to all children; ribbons represent 95% confidence intervals. Speech input becomes more consistent, and less bursty, as children age with no interaction by hearing status.

Table 3

*Relationship between age (mos) and measures of the naturalistic speech environment, by hearing group. β=model coefficient from linear regression, p-value from linear model parameter (***p <.001, **p <.01, *p <.05), +p <.1, r=Pearson correlation coefficient. No p-value annotation indicates p > .1.*

	Chrono. age matches	**CI chrono. age**	**CI hearing age**	**Hearing age matches**
Adult words	β=20.7+ r=0.46	β=3.81 r=0.07	β=0.77 r=0.02	β=16.49+ r=0.48
Adult speech (s)	β=5.27* r=0.48	β=1.12 r=0.09	β=0.31 r=0.03	β=3.78+ r=0.47
Child voc. quantity	β=3.98 r=0.34	β=2.71 r=0.33	β=1.06 r=0.17	β=8.03*** r=0.89
Child voc. duration (ms)	β=.59 r=0.02	β=3.16* r=0.05	β=1.84 r=0.03	β=6.59** r=0.11
Convo. turn	β=0.83 r=0.29	β=0.01 r=0	β=-0.33 r=-0.16	β=2.18*** r=0.93

Once again for the repeated measures (vocalization intensity and duration), we fit linear mixed effects models with random intercepts by child and a fixed effect of **Hearing Group**. Models of the hourly vocalizations additionally included random intercepts by hour of recording. There was no effect of **Hearing Group** on the number of vocalizations/hour or vocalization intensity (both tests p >.05); so, hearing status did not dictate the amount or intensity of the children's speech. However, there was an effect of hearing status in the model predicting vocalization duration (comparison of models with and without **Hearing Group**: χ^2=6.95, df=2, p=.03): the chronological age matches produced significantly longer vocalizations than both the children with CIs (β=59.25) and hearing age matches (β=78.71).

We additionally measured the consistency of children's speech output which we quantified as the percentage of minutes in each recording containing at least one vocalization from the target child; there was no effect of hearing experience upon children's vocalization output consistency.

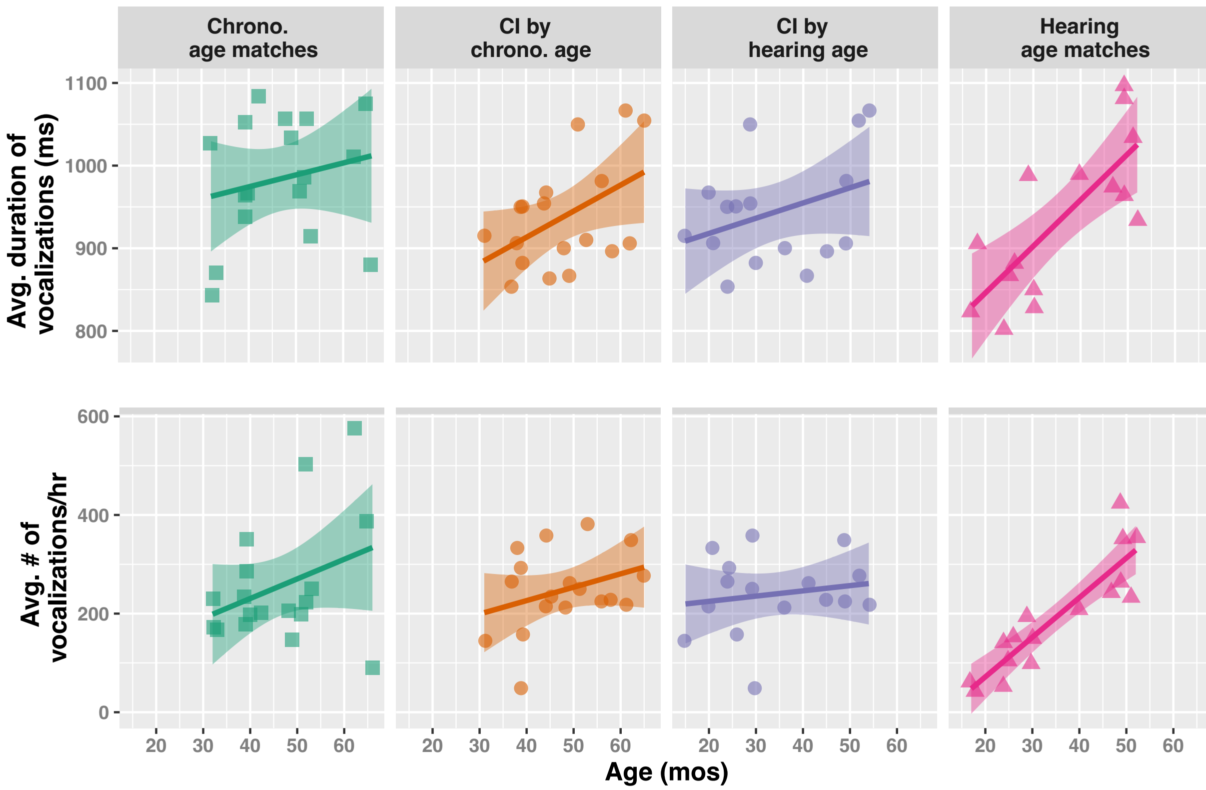

Figure 5. Age-related growth in child vocalization duration (top) and vocalization quantity (bottom), by hearing group. Given the number of distinct data points (N=167130 across all children), local regression lines are fit to averages over each child; ribbons represent 95% confidence intervals. See Table 3 for exact model fit statistics for each outcome.

Finally, we measured the age-related growth in vocalization quantity and duration: there was a significant, positive effect of **Child Age** (mos) on vocalization duration among the children with CIs by chronological age, and for the hearing age matches (Figure 5). Over each month of development, the duration of the children with CIs' vocalizations increased by approximately 3.16ms, that is, at a much slower pace than the rate of increase (6.59ms/month) for the hearing age-matched children with TH (Table 3). With developmental time, it is possible that the vocalizations grow at a faster rate among the children with CIs; however, this growth rate suggests that the children with CIs may be falling further behind over time.

3.3 Interaction

We next evaluated the impact of hearing group upon caregiver-target child interactions. We instantiated the quantity of interaction as the average number of back-and-forth conversational turns/hour. We evaluated the consistency of interaction as the percentage of 5-minute epochs containing at least 1 conversational turn. There was no effect of **Hearing Group** upon the quantity or consistency of turns (both $p > .05$). The age-related growth analysis showed increases in conversational turns only for the hearing age matches (e.g. for the youngest children). The fact that this age-related growth was not present in the children with CIs may suggest that this developmental change, even in the children with TH, is driven by cognitive development within the child rather than by language experience.

3.4 Vocal contingency

In our second analysis, we evaluated how contingent vocalizations varied by hearing experience. For this analysis, we computed the *percentage* of all child vocalizations that were contingent with a caregiver (occurring within 2 seconds of caregiver speech); see section 2.3 of Methods for further explanation.

Effects of age and group. There was no main effect of **Hearing Group**, **Child Age** (hearing age or chronological age for the children with CIs), or their interaction, upon the percentage of vocalizations that were contingent. However, within the CI group, there was a weak *negative* relationship between vocal contingency and chronological age (Pearson's r=-0.24) but not hearing age (Pearson's r=-0.09): as children with CIs age chronologically, they tend to have smaller percentages of contingent vocalizations in their recordings (Figure 6).

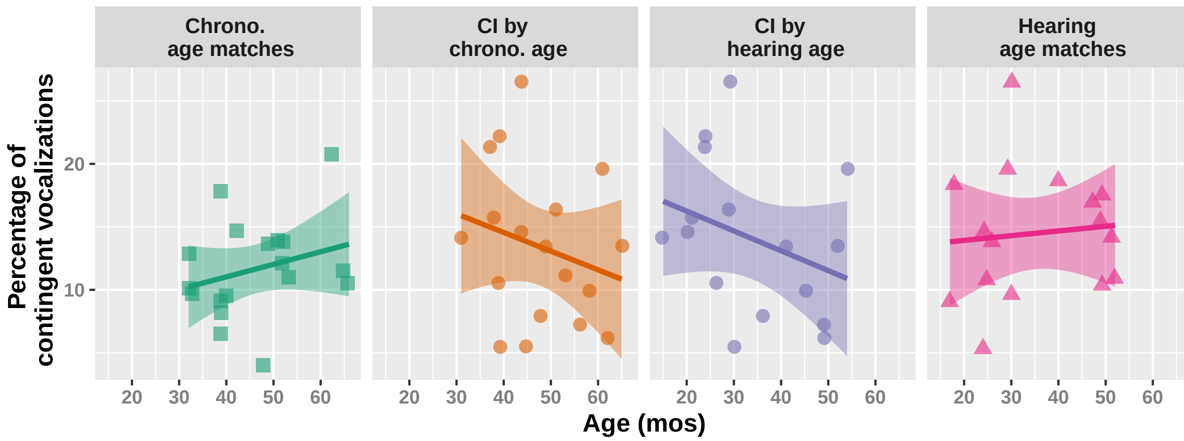

Figure 6. Age-related growth in percentage of contingent child vocalizations, by hearing group. There was no relationship between age and percentage of contingent vocalization for the groups with TH and weak, negative relationships between age and contingency for the children with CIs. Each point is a child and colored lines represent local regression; ribbons represent 95% confidence intervals.

Characteristics of caregiver speech and vocal contingency. We were additionally interested in the relationship between acoustic characteristics, specifically the volume, of caregiver speech and vocal contingency. For this analysis, each child had one measure, corresponding to the percentage of contingent vocalizations in their recording. Consequently, to evaluate the impact of caregiver speech intensity, we performed a median split by intensity over all caregiver speech utterances in each child's recording. Caregiver utterances that were above the child's median caregiver speech intensity (in dB) were classified as "louder" and those that were below the median were classified as "softer." We then fit a linear mixed effects model, with random intercepts by child, to predict the percentage of each child's vocalizations from the binary predictor variable **Adult speech intensity** (2-level factor variable; contrast-coded). Modeling demonstrated that there was indeed a larger percentage of contingent vocalizations in response to relatively louder caregiver speech than softer caregiver speech (β=-2.13, t=-7.82, p <.001) (Figure 7). This result could reflect child proximity to caregivers or the difference between speech directed to the target child, another child, or an adult. An interaction of **Adult speech intensity** and **Hearing group** did not improve upon model fit, demonstrating that this "loudness" benefit was similar across groups.[7]

3.5 Predicting vocal productivity from input measures

For the final analysis, we examined how measures of the speech environment predicted children's speech productivity and how this varied by hearing group. The measures of the speech environment that we examined were **Average number of adult words/hr**[8] and the **Average number of conversational turns/hr**. The measure of speech productivity that we used was the average number of target child vocalizations/hour in each recording (Figure 8).

It is expected that children who hear more speech, and engage in more linguistic interactions with caregivers, should vocalize more (Albert, Schwade, & Goldstein, 2018; Ferjan Ramírez et al., 2020; Harbison et al., 2018; Long et al., 2020; Ruan, 2022; Warlaumont et al., 2014). Consequently, in our modeling, we first set to evaluate *which* measure of linguistic input best predicted the children's vocal productivity outcomes. To examine this, we fit two different linear regression models, controlling for chronological age

[7] In Supplementary Materials I, we replicate this effect in a repeated measures analysis that evaluates the relationship between the intensity of *each* caregiver utterance and the speed of *each* subsequent child vocalization.

[8] We additionally computed the average number of seconds of adult speech/hr but this measure was virtually indistinguishable from the average number of adult words (r=0.997, p<.001).

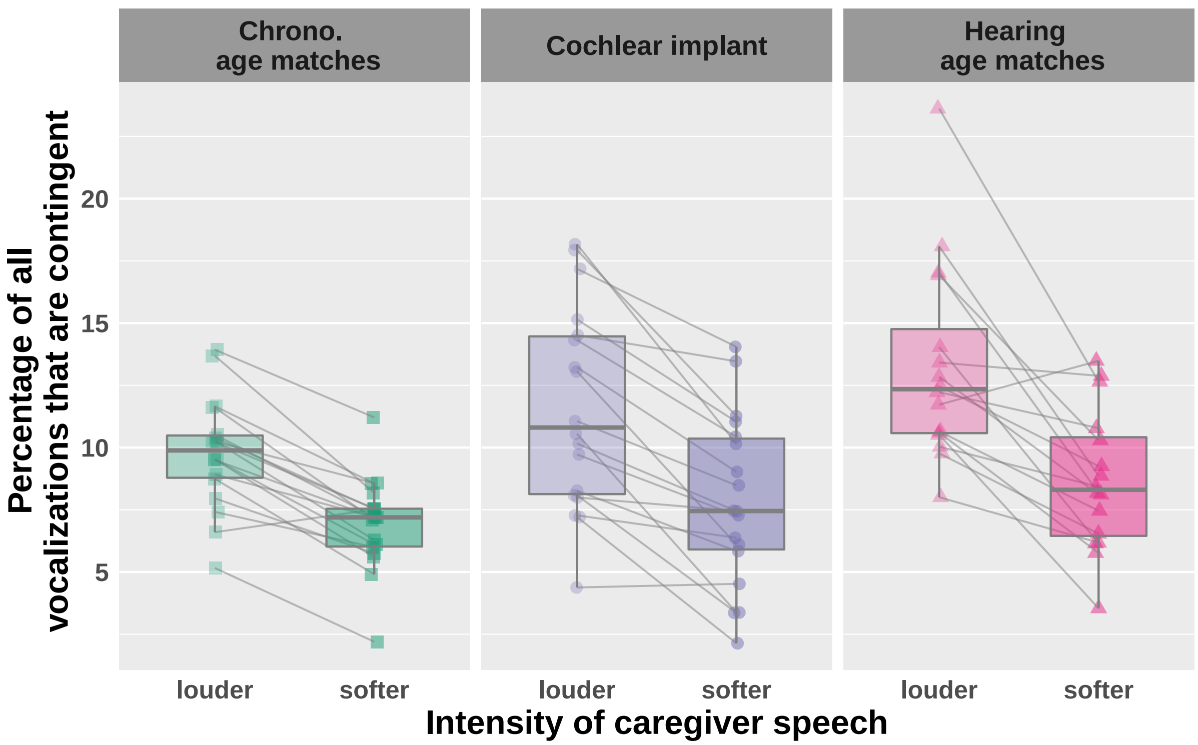

Figure 7. Relationship between intensity of caregiver speech and quantity of contingent vocalizations (see also Supp. Materials I): there is a significantly higher percentage of contingent vocalizations in response to louder caregiver speech, and no interaction with hearing status. Lines connect points referring to individual children. Boxes represent the interquartile range and whiskers 1.5x the interquartile range in each direction. Gray, horizontal lines represent the median percentage for each grouping and notches represent 95% confidence intervals surrounding the median.

(in mos), to predict the average number of target child vocalizations per hour in each recording. We compared the AIC values of a model predicting the vocalizations per hour from the parameter **Average number of conversational turns/hour** and another model with the parameter **Average number of adult words/hour**; the model with conversational turns resulted in a better fit to the data (lower AIC score), suggesting that hourly conversational turns are a better predictor of child vocal productivity than hourly adult words.

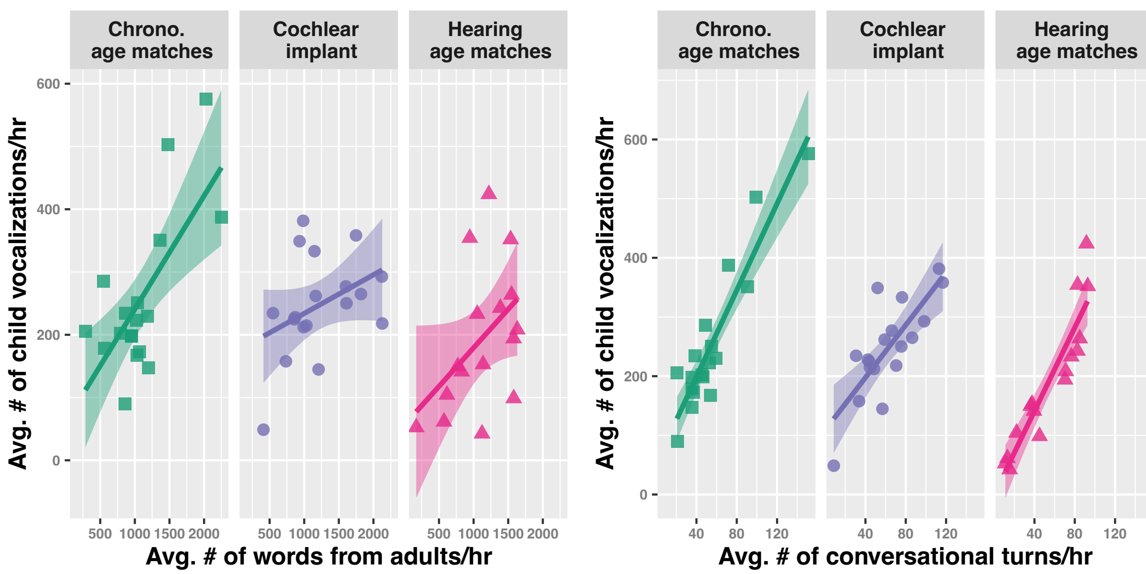

Figure 8. Relationships between child vocal productivity and words spoken by adults near the child (L) and conversational turns between adult and child (R). Each point represents the averaged values from one child's recording and dark lines represent the local regression around those values; ribbons represent 95% confidence intervals. Hourly conversational turns are stronger predictors of child vocal productivity than hourly adult words. The relationship between hourly conversational turns, as well as hourly adult words, and child vocal productivity is weakest for the children with CIs.

Next, we aimed to evaluate how this relationship between conversational turns and child vocal productivity might differ by hearing status. The interaction of **Average**

number of conversational turns/hour and **Hearing Group** did indeed improve upon a model without the interaction (model fit comparison: χ^2=3.72, df=2, p= .03), suggesting differences in the strength of this relationship by hearing status. Modeling demonstrated that for every additional conversational turn per hour that children with CIs engaged in, they produced approximately two additional vocalizations per hour (β=2.22, t=5.28, p<.001). However, this relationship between turns and child vocal productivity was significantly steeper for both groups of children with TH who produced approximately 3 or 4 additional vocalizations per hour for every hourly conversational turn that they engaged in (chronological matches: β=1.44, t=2.53, p=.02, or a slope of 3.66; hearing age matches: β=1.31, t=2.18, p=.03, or a slope of 3.53).

4 Discussion

Results from this study can be distilled into three main findings. First, *the language environment does not reflect development as closely for children with CIs.* Unlike children with TH, children with CIs do not hear more speech as they grow (in hearing or chronological years). And hourly adult words and turns were less predictive of vocal productivity for children with CIs than either group of children with TH.

Second, *children respond faster to louder caregiver speech, regardless of hearing ability.* Whether it indicates proximity to the caregiver, a child re-orienting themselves (and thus the recorder), or children learning that a caregiver's heightened voice intensity signals expectations for a response, all children had a higher percentage of contingent vocalizations in response to louder caregiver speech. Thus, despite differences in the distribution and peak sound levels of speech input within homes (Figure 3), louder speech still unilaterally confers a benefit for contingent vocalization production.

Finally, *children with CIs engage in just as much caregiver-child vocal interaction as children with TH.* Despite decades of research arguing that children with hearing loss interact less with caregivers (Lederberg & Mobley, 1990; Meadow-Orlans, 1997; Meadow-Orlans & Steinberg, 1993; Spencer & Meadow-Orlans, 1996), including recent evidence from more controlled but less densely sampled lab-based work (Kondaurova, Smith, et al., 2020), we show no evidence that children with CIs vocally engage with caregivers less frequently, or more slowly.

In the following sections, we explore each of these points in detail and situate the results in the context of previous work, especially work involving lab-based samples and/or manual annotation.

4.1 Caregiver speech input

The amount of caregiver speech in the children's environments was predicted to differ by hearing status, but the direction was not clear. Perhaps the children with CIs would hear more speech input than the hearing age matches (due to differences in cognitive maturity) but less than the chronological age matches (due to differences in linguistic ability). The final picture was more complex: although all groups heard similar *amounts* and *intensity* (volume) of adult speech input, this differed systematically by age. In typical development, children hear more word types, tokens, and overall amounts of speech as they progress from infancy to preschoolhood (Cychosz, Edwards, Bernstein Ratner, Torrington Eaton, & Newman, 2021; Glas, Rossi, Hamdi-Sultan, Batailler, & Bellemmouche, 2018; Rowe, 2008, 2012)—we replicated this developmental growth finding in both of our TH samples. However, there was no such age-related growth for the children with CIs, not by hearing age or chronological age. Again, it is not the case that children with CIs simply hear more speech in general and are thus "saturated," with little room for growth over development; there were no differences in input quantity by hearing group. Instead, we take this as the first piece of evidence that the language environments of children with CIs may *reflect the individual child less* (in this case the child's developmental stage) than the environments of children with TH.

4.2 Child vocal output

As predicted, the children with CIs produced less mature (shorter) vocalizations than chronological age matches; crucially, however, they did not vocalize less *overall* than either TH group and had some age-related growth in vocalization duration (albeit less than the hearing age matched group). So, the children with CIs vocalize just as frequently as TH groups and are progressing developmentally. Nevertheless, given the differences in vocalization length between the children with CIs and chronological matches, and the significantly shallower growth function among the children with CIs, it appears that the children with CIs follow a different vocal growth pattern than either TH group. It could be that children with CIs produce shorter vocalizations but supplement them with other modalities within this developmental window. Note that this conclusion differs from a number of studies looking at short-term changes in vocal productivity following cochlear implant activation which have found that children produce developmentally-appropriate (for their hearing age) amounts of canonical and reduplicated babble months post-activation (Fagan, 2014; Schauwers, Gillis, Daemers, De Beukelaer, & Govaerts, 2004; Schauwers, Gillis, & Govaerts, 2008). The duration of a child's vocalizations, however, reflects a number of different components in speech development: how long can a child sustain phonation, how many sequential syllables can the child produce, how many phonemes is the child producing, etc. and as such might be a more comprehensive, but admittedly far less distinct, metric of speech development than babbling landmarks. The vocal development findings from Fagan, Schauwers, and other colleagues also stemmed from shorter observations (ranging 15-80 mins/child), often collected in the lab. Going forward we plan to evaluate vocal maturity in this maximally naturalistic dataset that we have collected using a combination of vocal maturity algorithms (e.g., Räsänen, Seshadri, Lavechin, Cristia, and Casillas 2020) and hand-coding which should allow us to compare our results more directly with previous research.

At-home language interventions among children with TH often target caregiver input (caregiver-child conversational turns: Ferjan Ramírez et al. (2019); Romeo et al. (2021); caregiver words: Greenwood, Schnitz, Carta, Wallisch, and Irvin (31); Suskind, Leffel, et al. (2016); or both: Suskind et al. (2013)). But child vocal productivity partially *drives* caregiver input (Gros-Louis et al., 2006; Warlaumont et al., 2014). Indeed, a number of interventions for groups with different developmental profiles, including less verbal profiles such as children with autism spectrum disorder diagnoses or classic galactosemia, instead target the child's own vocal productions (Peter et al., 2021). Results here suggest that preschoolers with CIs are not necessarily lacking speech input—there were no differences in overall amounts of input by group (though quantity of input vs. intake could differ by hearing group). Instead, the children may require increased opportunity for their own vocal practice in order to progress developmentally and hit speech production landmarks.

4.3 Contingent vocalizations

In typical development, the frequency of contingent vocalizations initially increases through infancy, and then progressively decreases, at least through 60 months (Gilkerson et al., 2017; Nguyen et al., 2022). As such, we strongly predicted that older, chronological matches would have fewer contingent vocalizations than younger, hearing age matches (Figure 2). Instead, there were no differences in contingent vocalization frequency by hearing status, and minimal differences by age. We considered that perhaps we did not have sufficient degrees of freedom to unearth differences by hearing group (especially since we could not assess contingencies between 0.00001-599ms; see section 2.3 for detail). But differences by hearing group did not emerge even when we extended the definition of contingent vocalization to larger windows spanning 600-3000, -4000, or -5000ms. Furthermore, in Supplementary Materials I we model vocal contingency *timing*—a much more sensitive measure since it captures the temporal lag between each caregiver utterance and the subsequent contingent child vocalization—and likewise find no effect of hearing group (although children with CIs responded significantly less quickly to louder caregiver speech than both groups of children with TH).

The absence of effects of hearing status or even age differs from some previous work that found that children with CIs produce less contingent speech, with longer lags, at least through 9 months post-implantation (Kondaurova, Smith, et al., 2020) (see also Kondaurova et al. (2022), Lederberg and Mobley (1990), Meadow-Orlans and Steinberg (1993), Spencer and Meadow-Orlans (1996), and Meadow-Orlans (1997) although we stress that work such as Lederberg and Mobley (1990) and Meadow-Orlans (1997) confound the degree of hearing loss and include children spanning mild to profound). Differences between this work and previous studies could have a couple of different sources. First, most obviously, our samples to derive vocal contingency were algorithmically, not manually, derived—and indeed previous work using LENA-derived estimates of turn taking and vocal contingencies likewise did not find differences by hearing status (VanDam et al., 2012). The LENA speaker diarization tags that we employed for the contingency analysis, FAN, MAN, and CHN, are relatively reliable and valid across a number of populations, languages, and ages (including those that did not make up the original training dataset) (Canault, Le Normand, Foudil, Loundon, & Thai-Van, 2016; Cristia, Lavechin, et al., 2020; Gilkerson et al., 2015; McDonald, Kwon, Kim, Lee, & Ko, 2021). Nevertheless, a purely automated pipeline will inevitably introduce some diarization and time alignment error which could have masked developmental or hearing status effects. Still, our sample was magnitudes larger, denser, and more naturalistic than much previous work: we report on >730 hours of observation across 52 children compared to 5.6 hours across 24 children (Kondaurova, Smith, et al., 2020) or appx. 73 hours across 16 children (N. A. Smith & McMurray, 2018), to name a few examples of comprehensive, lab-based studies.

Finally, our window of analysis was limited—perhaps age or hearing group-related differences are most detectable between 0.00001 and 599ms. Indeed, N. A. Smith and McMurray (2018) report that vocal contingency timing speeds up at a rate of 15ms/month between 4 and 60 months, with no rate differences between children with and without hearing loss. Absent *extensive*, manual time-alignment of each adult speech utterance (N=149,561 across the samples) and each child vocalization (N=167,130), we may not be able to assess vocal contingency timing within a perhaps more critical 0.00001 and 599ms window, but future work with more controlled samples could at least evaluate if effects of child age or experience (including hearing) differ by the window of analysis.

4.4 Caregiver input and child vocal output

Infants and children speak more when spoken to (Albert et al., 2018; Ferjan Ramírez et al., 2020; Harbison et al., 2018; Long et al., 2020; Ruan, 2022; Warlaumont et al., 2014). Yet children with CIs may be less likely to notice when a caregiver is speaking to them, or distinguish caregiver speech input from distractors, because CIs compromise sound localization and speaker identity cues (Chatterjee and Peng 2008; Stickney et al. 2007; Todd et al. 2016; see also section 1.1). We confirmed our prediction that the daily speech-language environment was *less* predictive of vocal productivity for children with CIs than either TH group. In doing so, we also replicated the finding, across all groups, that conversational turns between children and their caregivers are a stronger predictor than adult words for a variety of speech-language outcomes (Gilkerson et al., 2018; Romeo et al., 2018) (work on children with CIs has come to similar conclusions (Vanormelingen, De Maeyer, & Gillis, 2016)).

There are a variety of reasons why children with CIs may be less responsive to their speech environments. Our evidence on ambient sound levels (volume) of caregiver speech suggests that children with CIs *are* noticing and (presumably) orienting themselves towards caregivers—if not we would see differences in caregiver speech volume by hearing group and we don't. Furthermore, note that the children with CIs were less responsive to the environment than even their hearing age matches, so it is not simply the case that more auditory experience is needed to benefit from ambient speech and language. Rather, we think the implant device construction limits the speech-language signal available to children. Consider the following aspects of CI design and how they would systematically shape how a child could access and parse the speech-language signal and learn from it:

1. **Word segmentation:** Speech is a running signal, with cues to word boundaries often masked by resyllabification and lexical stress displacement. Infants and children with TH take advantage of statistical regularities in the syllabic and prosodic structure of running speech to segment words and build a vocabulary (Christophe, Gout, Peperkamp, & Morgan, 2003; Saffran, 2003); for example, in American English, creaky voice often indexes the ends of phrases, and thus words (Davidson, 2021). But children with CIs have reduced access to f0 cues, including those that differentiate modal from creaky voice. The result could mean inappropriate word segmentation at a phrasal boundary, which would systematically shape the number and structure of words that the children hear.

2. **Morphological parsing:** In language, there are robust cues[9] to internal word structure (inflectional and derivational morphology)—cues that infants with TH can take advantage of to learn morphological suffixes like *-s* and *-ing* even in the absence of meaning (at least in American English) (Kim & Sundara, 2021). However, CIs discretize the speech envelope, compromising the primary acoustic cue to contrasts such as /s-ʃ/ and /t-k/—both of which contain phonemes implicated in English inflectional morphology (*-s*, *-ed*). Consequently, when processed through a CI, many English inflectional suffixes are not highly perceptually salient, and are instead confusable. The result is that, for example, plural word forms could be parsed as entirely different words (“pats” > [pætʃ]). Of course there is evidence that school-aged children with CIs are capable of revising a number of original hypotheses during online language parsing (Klein, Walker, & McMurray, 2022), and children of

[9] These cues are present in oral and signed languages.

this age with CIs can incorporate morphological cues (Davies, Holt, & Demuth, 2023), but at a young age, recognition of morphological information among these children is slower and subsequent processing of unique word forms hampered (Davies, Xu Rattanasone, Davis, & Demuth, 2020).

Now, in our analysis linking aspects of the daily environment with speech development, we only assessed a single outcome measure: hourly child vocalizations. We cannot say with certainty that the speech-language environment would likewise be less predictive of some of the additional outcomes outlined above. But since we have evidence that the daily linguistic environment doesn't predict child vocal productivity as strongly for children with CIs as children with TH, future work should evaluate if additional outcomes are implicated (segmentation, parsing, perception) in order to structure more effective, CI-centered clinical therapies and interventions.

4.5 Potential for at-home interventions

Children with CIs consistently underperform their peers with TH on almost every measure of speech, language, and literacy (Mayer & Trezek, 2018; Morini, Golinkoff, Morlet, & Houston, 2017; Nittrouer & Caldwell-Tarr, 2016). This speech-language gap persists into adolescence and even adulthood (Desai, Stickney, & Zeng, 2008; Schorr, Roth, & Fox, 2008). And while some children with CIs develop stronger speech-language skills than others—nearly on par with their TH peers (Niparko et al., 2010)—even 4-6 years post-implantation, more than 50% of child CI recipients perform 1-2 standard deviations below peers on many standardized measures of speech and language (James, Rajput, Brinton, & Goswami, 2009; Pisoni et al., 2008).

Since the richness of the home language environment is a strong predictor of future speech, language, and literacy outcomes for a variety of populations of children with TH (Ferjan Ramírez et al., 2019; Hurtado, Marchman, & Fernald, 2008; Rowe, 2012; Swanson et al., 2019; Weisleder & Fernald, 2013), and child CI recipients are at risk of speech and language delays, providing caregiver counseling to optimize the home language environments of children with CIs could be a promising method to close the speech-language achievement gap for these children (Suskind, Graf, et al., 2016). Many unknowns remain before such interventions could reliably be implemented, but the work we present here is an important step towards making at-home interventions a reality. Demonstrating how the home environment systematically differs by hearing status affects how clinical interventions to *shape* the home linguistic environment should be implemented. For example, our results suggest that the daily speech environment is less predictive of vocal productivity among children with CIs than children with TH. So we might not expect interventions targeting increased caregiver-child vocal interaction to elicit the same vocal productivity benefit for preschoolers with CIs as those with TH; instead, we should be evaluating intervention success based on the unique input-outcome relationships that are documented for children with CIs.

4.6 Limitations

Sampling biases are a concern for developmental research in general (Draper et al., 2022; Singh, Rajendra, & Mazuka, 2022), but may be especially prevalent for methodologies such as at-home recordings since some families are unwilling to record in their homes. Marginalized groups with a history of being tracked or observed by the state may, understandably, be especially wary. As such, samples in developmental science that already skew white and middle to upper class may be *especially* biased for at-home methods such as these. Thus, we stress that current findings about e.g. the strength of the relationship between adult input and child vocal production may not generalize to all children, even within North America.

Another limitation of this study is that recordings were only taken on one day of the child's life. Although our own work and others suggests that differences across days *within* households are far less than differences *between* households (de Barbaro & Fausey, 2022; Havard et al., 2023), future work could more comprehensively address this concern by ensuring that all families record over two or three days, as some others have done (Orena, Byers-Heinlein, & Polka, 2020; Romeo et al., 2018). Another way to ensure sampling consistency, but instead between families, would be to request that families record, for example, on both one weekend and week day, or for an entire weekend. Observing each child for 16 hrs. already lends insight that more limited, in-lab observations cannot; yet collecting even denser samples than those we present here—those that span longer time periods—could ensure that the observations made on a single day in the child's life are not biased by exceptional events.

5 Conclusion

This work evaluated the daily speech environments of preschoolers with cochlear implants in comparison to two groups of their peers with typical hearing. Using incredibly dense sampling of children's everyday environments in their homes, we assessed how a battery of everyday speech-language experiences—caregiver speech input, child vocal production, and caregiver-child interaction—differed by hearing status. Take-aways are that (1) the speech environment reflects development less closely for children with implants than typical hearing, (2) all children respond faster to louder caregiver speech, and (3) there were minimal differences by hearing status in caregiver-child interaction, even after implementing the measure in multiple ways. The unique experiences of preschoolers who receive cochlear implants, the time they spend without auditory access pre-implantation and the degraded device signal they learn from post-implantation, do shape their everyday speech and language environments.

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Data availability statement

All data and code used to generate the analyses in this paper are publicly available at: `https://github.com/megseekosh/everyday_CI`.

Author contributions

Conception: M.C., R.S.N., J.R.E. Data collection and funding: M.C., J.R.E., B.M., R.R.R., J.K. Manuscript writing: M.C. Results and analyses: M.C. Manuscript editing: all authors.

6 Appendix

Table 4

Audiological information from children with cochlear implants

Participant	Chronological age	Age at hearing loss (mos)	Age at activation	Hearing age (since activation)	Etiology	Device configuration	Activation
300ECV1	58	0	13	45	genetic	bilateral	simultaneous
301ECV1	53	0	45	8	unknown	bilateral	R-L
302ECV1	37	0	13	24	unknown	bilateral	R-L
303ECV1	65	6	13	52	unknown	bilateral	simultaneous
304ECV1	48	0	12	36	genetic	bilateral	R-L
307ECV1	44	0	15	29	genetic	bilateral	R-L
308ECV1	39	0	13	26	genetic	bilateral	simultaneous
311ECV1	62	9	13	49	unknown	bilateral	L-R
312ECV1	44	0	24	20	genetic	unilateral	R-L
314ECV1	38	10	17	21	unknown	bilateral	R-L
801ECV1	39	1.5	15	24	unknown	bilateral	simultaneous
804ECV1	56	0	7	49	genetic	bilateral	simultaneous
806ECV1	45	14	34	11	genetic	unilateral	L
807ECV1	51	10	22	29	Mondini malformation	bimodal	n/a
309ECV1	61	0.5	7	54	genetic	bilateral	simultaneous
306ECV1	49	0	8	41	unknown	bilateral	R-L
605LTP1	31	0	16	15	unknown	bimodal	n/a
608LTP1	39	0.5	9	30	Connexin 26	bilateral	simultaneous

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