

Journal of Speech, Language, and Hearing Research

Examining spoken language input to infants with cochlear implants

--Manuscript Draft--

Manuscript Number:	JSLHR-25-00669	
Full Title:	Examining spoken language input to infants with cochlear implants	
Article Type:	Research Article	
Section/Category:	Hearing	
Funding Information:	National Science Foundation (2337766)	Elika Bergelson
	National Science Foundation Graduate Research Fellowship Program (2019274952)	Erin E. Campbell
Keywords:	cochlear implants; language input; language development	
Manuscript Classifications:	Infant (0 - 1 year); Toddler (1 - 3 years); Pediatric Cochlear Implants; Congenital Hearing Loss; Profound Hearing Impairment; Language Development; Psycholinguistics; Spoken Language Comprehension; Language Acquisition and Development; Expressive Language Skills	
Abstract:	<p>Purpose</p> <p>To compare spoken language input to young deaf/hard of hearing (DHH) children with cochlear implants and matched chronological- and hearing-age hearing controls.</p> <p>Method</p> <p>We used long-form audio-recordings (M=14.3hrs) from 48 6-32mo's (16/group). We manually transcribed 40min/recording, and ran automated LENA algorithms over the full daylong recording. We computed 10 automated and manually annotated metrics of input quantity, complexity, and conceptual content. We also computed speech outcomes, and linked the input metrics to those outcomes.</p> <p>Results</p> <p>There were no significant cross-group differences in input quantity, or in any input metrics between DHH and chronological age-matches. The DHH group heard significantly shorter sentences and more highly auditory words than hearing-age matches. While they produced more (and more mature) vocalizations than hearing-age matches, they produced fewer mature vocalizations than age-matched peers. DHH vocalizations also increased less robustly with age. In regression models, only hearing status explained variance in child vocalizations for DHH and hearing-age matches. For DHH and same age matches, age, hearing status (hearing>DHH), input quantity, and shorter MLU input collectively predicted >50% of the variance in children's vocal maturity.</p> <p>Conclusions</p> <p>DHH children and hearing children differed little in their language input. Differences from hearing-age controls are likely explained by their younger age. Nevertheless, we find lower rates of child vocalizations in the DHH group and a weaker increase over age. This extends prior findings through its in-depth look at a young cohort using both automated and manual measures of speech.</p>	
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1 Running head: CI LANGUAGE INPUT

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4 Examining spoken language input to infants with cochlear implants

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Abstract

Purpose: To compare spoken language input to young deaf/hard of hearing (DHH) children with cochlear implants and matched chronological- and hearing-age hearing controls.

Method: We used long-form audio-recordings (M=14.3hrs) from 48 6-32mo's (16/group). We manually transcribed 40min/recording, and ran automated LENA algorithms over the full daylong recording. We computed 10 automated and manually annotated metrics of input quantity, complexity, and conceptual content. We also computed speech outcomes, and linked the input metrics to those outcomes.

Results: There were no significant cross-group differences in input quantity, or in any input metrics between DHH and chronological age-matches. The DHH group heard significantly shorter sentences and more highly auditory words than hearing-age matches. While they produced more (and more mature) vocalizations than hearing-age matches, they produced fewer mature vocalizations than age-matched peers. DHH vocalizations also increased less robustly with age. In regression models, only hearing status explained variance in child vocalizations for DHH and hearing-age matches. For DHH and same age matches, age, hearing status (hearing > DHH), input quantity, and shorter MLU input collectively predicted >50% of the variance in children's vocal maturity.

Conclusions: DHH children and hearing children differed little in their language input. Differences from hearing-age controls are likely explained by their younger age. Nevertheless, we find lower rates of child vocalizations in the DHH group and a weaker increase over age. This extends prior findings through its in-depth look at a young cohort using both automated and manual measures of speech.

Keywords: cochlear implants, language input, language development, children

Word count: 6781

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Examining spoken language input to infants with cochlear implants

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Introduction

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The last few decades have seen a widespread implementation of newborn hearing screenings (Edmond et al., 2022). For children with severe-to-profound sensorineural hearing loss, cochlear implantation has become commonplace; in developed countries, approximately 80% of deaf/hard-of-hearing (henceforth DHH) children receive cochlear implants, with even higher rates in some areas (Peters, Wyss, & Manrique, 2010; Reynolds, Werfel, Vachio, & Lund, 2023). For many DHH children, cochlear implantation is the first time they gain access to language input at all (Levine, Strother-Garcia, Golinkoff, & Hirsh-Pasek, 2016): since the majority of deaf children are born to hearing parents, very few are regularly exposed to sign language, with many families prioritizing spoken language learning (Campbell & Bergelson, 2022; M. L. Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017; W. C. Hall, 2017; Mauldin, 2016; Pontecorvo et al., 2023). We first provide relevant background for understanding early language development for these learners.

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Cochlear Implants and Early Language Development

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Cochlear implants (CIs) bypass the inner ear by directly stimulating the auditory nerve. For children born deaf, learning to interpret these electrical signals as meaningful sounds, and ultimately as language, requires adjustment and explicit, often protracted rehabilitation (Kutlu, Ozkan, & Yucel, 2021; Werfel & Hendricks, 2016). Following implantation, children often show rapid increases in expressive spoken language and social skills (Cychosz et al., 2025; Hardman, Kyle, Herman, & Morgan, 2022; Niparko et al., 2010; D. Snow & Ertmer, 2009), as well as generally typical word comprehension skills in ideal listening conditions (Bergeson, Houston, & Miyamoto, 2010; Houston, Carter, Pisoni, Kirk, & Ying, 2005).

72 However, challenges remain. Many children with CIs experience listening difficulties in
73 noisy environments (Eisenberg et al., 2016; Mishra, Boddupally, & Rayapati, 2015) and complex
74 comprehension tasks (Mandal, Kumar, & Roy, 2016; Percy-Smith et al., 2013). Auditory fatigue is
75 common, and pediatric CI users report lower quality of life than hearing children (Haukedal, Lyxell,
76 & Wie, 2020; Hornsby, Werfel, Camarata, & Bess, 2014). Children with CIs exhibit persistent
77 spoken language delays and greater variability compared to same-age hearing children (Duchesne,
78 Sutton, & Bergeron, 2009; Pisoni, Cleary, Geers, & Tobey, 1999), including slower syntactic growth
79 (Nikolopoulos, Dyar, Archbold, & O’Donoghue, 2004; Werfel, 2018) and reduced vocabulary
80 acquisition throughout childhood (Lund, 2016; Warner-Czyz, Anderson, Graham, & Uhler, 2024).

81 The most powerful factors predicting language outcomes after implantation generally are
82 how early a child receives the implant (Kirk et al., 2002; Nittrouer, Lowenstein, & Holloman, 2016),
83 how frequently they use it (Park, Gagnon, Thompson, & Brown, 2019), device integration and
84 efficacy (Houston & Miyamoto, 2010; Kutlu et al., 2021), and exposure to a sign language pre-
85 implantation (Delcenserie, Genesee, & Champoux, 2024; Pontecorvo et al., 2023) – in other words,
86 early and reliable access to language input. Nonetheless, these factors only partly explain variability
87 in children’s outcomes. The present work explores another dimension that may substantially differ
88 among DHH children with CIs: the properties of their spoken language input.

89 **Connecting Language Input with Early Language Knowledge and Skills**

90 Differences in language input in early life predict some aspects of children’s language
91 outcomes. For instance, children who hear more speech or see more sign language input tend to
92 produce more language earlier, with e.g. faster and more accurate processing, bigger vocabulary
93 sizes, etc. (Anderson, Graham, Prime, Jenkins, & Madigan, 2021; Bergelson et al., 2023; Gilkerson
94 et al., 2018; Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991; Rowe, 2012; Watkins, Pittman, &
95 Walden, 1998; Weisleder & Fernald, 2013). The amount of back-and-forth conversational exchange

96 between infants and adults likewise predicts some early language outcomes (Cychosz et al., 2025;
97 Donnellan, Bannard, McGillion, Slocombe, & Matthews, 2020; Hirsh-Pasek et al., 2015). This may
98 be specifically connected to child-directed speech in cultures where this speech style is common
99 (Casillas, Brown, & Levinson, 2020; Shneidman, Arroyo, Levine, & Goldin-Meadow, 2013). Other
100 research finds that the complexity of language input is particularly predictive of child language
101 outcomes. For instance, greater diversity of words and syntactic structures, and longer sentences in
102 the input predict more diversity and complexity in children’s later language production (De Villiers,
103 1985; Hadley et al., 2017; Hsu, Hadley, & Rispoli, 2017). Likewise, increased use of
104 decontextualized language supports early abilities to discuss topics outside of the “here and now,”
105 and learn abstract word meanings (Demir, Rowe, Heller, Goldin-Meadow, & Levine, 2015; Rowe,
106 2013; Uccelli, Demir-Lira, Rowe, Levine, & Goldin-Meadow, 2019).

107 Across each of these features, we see a relationship between variation in the input and
108 variation in children’s expressive language skills (which are imperfect proxies for their knowledge).
109 It may thus be fruitful to examine differences in input to young DHH and hearing children.
110 Fortunately, prior work has already laid a strong groundwork for considering group-level
111 comparisons between DHH and hearing children. For instance, Wang, Cooke, Reed, Dilley, and
112 Houston (2022) examined the auditory environments of DHH children with CIs and hearing children
113 over the course of a year. Using LENA wearable audio recorders, they found that the overall quantity
114 of adult speech was not different between DHH children and their hearing peers, but found less non-
115 speech noise for DHH children. This suggests that caregivers may not modify their linguistic
116 behavior based on children’s hearing status, but may decrease competing environmental noise. The
117 most striking differences between DHH children and hearing children were the growth of children’s
118 own productions: Conversational turns (i.e. back-and-forths with adults) and child vocalizations both
119 increased with age for hearing children, but not for DHH children (Wang et al., 2022).

120 In related work, Cychosz et al. (2024) examined the language environment of 31-65 month-
121 old DHH CI users, matched to hearing children both by chronological age and by hearing age (i.e.
122 length of time with CIs). Like Wang et al. (2022), they found no differences in the quantity of adult
123 input, conversational turns, or child vocalizations between DHH children and either match type.
124 However, adult speech increased with age for both hearing groups, but not for the DHH group. The
125 environment also did not predict speech outcomes as strongly for the DHH children as for hearing
126 matches.

127 The studies reviewed so far paint a picture where families of young DHH children do not, by
128 and large, seem to speak to them in systematically different ways than families of hearing children do
129 (Aragon & Yoshinaga-Itano, 2012; Sultana, Wong, & Purdy, 2024; VanDam, Ambrose, & Moeller,
130 2012). At the same time, children with CIs are delayed in spoken language development relative to
131 hearing peers, consistent with delayed language access (Levine et al., 2016). While CIs are an
132 impressive technological achievement, the auditory signal provided by a CI, even at peak efficacy, is
133 not the same as what hearing listeners process: CIs can flatten pitch variation, distort phonetic detail,
134 and are susceptible to degradation in noisy environments, making it harder for children to
135 comprehend speech in everyday settings (Houston et al., 2005; Välimaa, Määttä, Löppönen, & Sorri,
136 2002). Thus, even though caregiver input may appear similar when *produced*, the actual quantity of
137 speech input audible to DHH children will be lower than the input present in their environment
138 (Houston, 2022).

139 In a mixed sample of CI users and hearing aid users with varying initial degrees of hearing
140 loss, Arora et al. (2020) found that input quantity but not linguistic complexity predicted language
141 outcomes, whereas DesJardin and Eisenberg (2007) found that complexity mattered. For DHH
142 children *without* hearing interventions, Ambrose, Walker, Unflat-Berry, Oleson, and Moeller (2015)
143 found quantity of adult input did not predict child language outcomes, while this relationship was

144 *only* significant for families who used some sign language along with spoken language in a study by
145 Vohr, Topol, Watson, St. Pierre, and Tucker (2014). In short, differences in the groups' access to
146 language might shift the link between specific input factors and measures of children's early
147 language.

148 Notably, much of the work cited above has examined the language environment using high-
149 level automated measures. Comparisons between LENA measures and manual codings show a
150 reliable relationship between human and algorithmic annotation (Ferjan Ramírez, Hippe, Braverman,
151 Weiss, & Kuhl, 2023; Ferjan Ramírez, Hippe, & Kuhl, 2021; Ganek & Eriks-Brophy, 2018).
152 However, automated measures show systematic differences from a gold-standard human coder,
153 struggling in settings with multiple overlapping speakers, conversations that are far away, electronic
154 speech, and in multilingual or multi-child households (Cristia, Bulgarelli, & Bergelson, 2020; Cristia
155 et al., 2024; Ferjan Ramírez et al., 2021; Lehet, Arjmandi, Houston, & Dilley, 2021; McDonald,
156 Kwon, Kim, Lee, & Ko, 2021). These are also the kinds of noisy environments that may make it
157 difficult for CI users to comprehend speech (Ambrose, VanDam, & Moeller, 2014; Grieco-Calub,
158 Saffran, & Litovsky, 2009), and over time, to learn spoken language (Majorano et al., 2021; Poupore,
159 Chidarala, Morris, McRackan, & Schwartz-Leyzac, 2024). Therefore, for CI users' language
160 environments in particular, detailed manual analysis may be a critical complement to automated
161 measures at the daylong scale, and one that has yet to be sufficiently leveraged with this group of
162 children.

163 **Present Study**

164 The present study aims to increase our understanding of the spoken language environment of
165 young children with CIs, across a wide set of quantitative measures. We combined manual and
166 automated measures, and included both chronological- and hearing-age controls in a young sample
167 of CI users. We take this as an initial step towards being better able to estimate the language input

168 that children with CIs may actually *access*. We examined characteristics of the spoken language
169 environment that have been shown to predict children’s language outcomes, and those that may be
170 especially impactful to CI users. We split language input metrics into three main categories:
171 **quantity**, **complexity**, and **conceptual**. We additionally looked at a battery of measures that may
172 make **audibility** in the environment more difficult (e.g. overlapping speech, electronic noise), but
173 found no substantive differences across CI users and hearing peers; see Supplementals for details.

174 For each input metric, we asked if it differed between children with CIs and hearing children
175 of the same chronological age (chronological-age matches; CAM) and the same hearing age (hearing
176 age matches; HAM). We then asked if the feature of the input changes over developmental time, and
177 if the relationship between the input and age differs as a function of the child’s hearing status.
178 Finally, we asked if there is a relationship between the input and children’s own vocalizations for CI
179 users and hearing children, and whether this link differs between groups.

180 On one hand, DHH children’s caregivers may be sensitive to their child’s lack of early
181 language access and try compensate, or talk more as part of therapy strategies (e.g. DesJardin,
182 Eisenberg, & Hodapp, 2006). CI users might also receive less language input, since children
183 influence their language input with their own vocalizations, and CI users (as a group) are more likely
184 to be delayed relative to hearing peers (e.g. Duchesne et al., 2009). Either way, we would expect
185 significant differences across groups, and weaker relationships between the input, age, and language
186 outcomes for the CI group.

187 In contrast, we may find quite similar caregiver input across groups. This could stem from
188 high within-group variance swamping group differences, or it could be the case that caregivers
189 simply do not talk differently on the basis of child hearing status. Specific predictions for each
190 measure are detailed in “Language Annotation and Metric Operationalization” below.

191 **Methods**

192 All interaction with human subjects, data collection, and storage procedures were conducted
193 in accordance with the Declaration of Helsinki. All activities were approved by Institutional Review
194 Boards at Duke, The Ohio State, and/or Harvard University.

195 **Participants**

196 A total of 16 DHH children with cochlear implants (henceforth CI group) contributed
197 recordings during a larger study conducted at the Ohio State University (for general results about the
198 larger sample, see Wang et al., 2022). All DHH children in this sample experience bilateral severe-to-
199 profound hearing loss (i.e., better-ear pure-tone average >70dB HL), use bilateral cochlear implants
200 (age at first activation 7.96-23 months, $M = 13.92$ months), and are acquiring spoken English as
201 the target language; minimal to no sign language exposure was reported. Each DHH child was
202 demographically-matched with two typically-hearing children: one based on chronological age (CA)
203 and one based on hearing age (HA). Hearing age was operationalized as the amount of time that
204 children had auditory access to spoken English. For hearing children, this is the same as
205 chronological age, as they have had access to sound from birth. For DHH children, this is the amount
206 of time since activation of their first CI (age at the time of recording minus age at activation). As a
207 result, HA matches (HAM) are younger than DHH children and their CA matches (CAM), but have
208 the same amount of hearing experience as their DHH matches.

209 Recordings from hearing children were gathered from preexisting English corpora or
210 collected from the Durham, N.C. area. All children were monolingual English learners (parents
211 reported that >75% of children's language input was spoken English), and were matched to DHH
212 children based on infant sex, maternal education (within one level, see Table 1), and number of older
213 siblings (0, 1, 2, >2; no twins in the present dataset).

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216 The age matching guidelines were based on the age or hearing age being matched: <12mo.,
217 the control infant's age was within +/- 2wk; at 12-24mo. the control infant's age fell within +/- 1mo.
218 of the DHH child's age; >24 months, the infant's age was within +/-2mo. Full demographics for each
219 group are in Table 1.

220 **Data collection**

221 Each child contributed one day-long recording (48 recordings, mean duration = 14.37 hours)
222 using LENA devices (Ganek & Eriks-Brophy, 2018; Gilkerson & Richards, 2008; Zimmerman et al.,
223 2009). Parents were instructed to start the recording when the child woke up and to keep it nearby if
224 the vest had to be removed (e.g. for baths or naps). Parents received instructions for pausing and
225 resuming recordings in the case of private conversations, and were given the option to have any part
226 of the recording permanently deleted after data collection.

227 **Language Annotation and Metric Operationalization**

228 Each recording was algorithmically analyzed in its entirety by LENA software (Xu, Yapanel,
229 & Gray, 2009), and a portion of each recording was further transcribed and annotated by trained
230 annotators using ELAN (versions 5.7–6.8; Brugman & Russel, 2009; Sloetjes & Wittenburg, 2008).
231 Fifteen two-minute intervals were extracted randomly in each recording for hand annotation, in
232 addition to five “high-volubility” two-minute intervals containing dense speech, as identified by a
233 voice type classifier for child-centered daylong recordings (Lavechin, Bousbib, Bredin, Dupoux, &
234 Cristia, 2020). This resulted a total manual annotation time of 40 minutes/recording. To establish the
235 context, annotators listened to (but did not annotate) two minutes prior and one minute following
236 each two-minute interval.

237 Manual annotation used the ACLEW annotation style (Soderstrom et al., 2021), with speech
238 by individuals other than the target child transcribed using minCHAT transcription (MacWhinney,
239 2019; Soderstrom et al., 2021). Each non-target-child utterance was classified based on the role of

240 the addressee (child, adult, both child and adult, pet, other, or unknown) and lexically transcribed.

241 The target child’s vocalizations were annotated for maturity (non-canonical babbling, canonical
242 babbling, laughter, crying) and lexicality (contains no words, contains one word, contains multiple
243 words). Thirty annotators contributed to this data set over 6 years.

244 We conducted a 10% recode on the closed-set coding categories to assess inter-coder
245 reliability. More specifically, we extracted two transcribed intervals from each file and re-annotated
246 addressee, vocal maturity level, lexicality, and multi-word utterances. Overall agreement across these
247 four categories between the original coder and recoders was 90.6%, Cohen’s kappa 0.88, indicating
248 high consistency; kappas were similar across hearing groups and coding categories. See
249 Supplementals for category and group reliability breakdown.

250 **Input Quantity Measures.** Overall quantity of environmental speech has been found to
251 predict language outcomes (Cartmill et al., 2013, *inter alia*). We opted to calculate Total Word Count
252 based on the manual annotations for each recording. This value is a count of all individual words
253 produced by speakers *other than* the target child. Words were defined as strings separated by spaces
254 in the transcription.

255 From the automatic LENA output, we extracted Adult Word Count (AWC), which estimates
256 the number of words produced by adults near the child; we normalized this measure to a words-per-
257 hour value. The data for AWC are a subset of data already reported in Wang et al. (2022). We present
258 them here to verify the pattern in a smaller sample and for comparison to measures generated from
259 manual transcriptions. Prior work from automated LENA measures suggests we are unlikely to find
260 differences in AWC (Cychosz et al., 2024; VanDam et al., 2012; Wang et al., 2022).

261 Each manually-coded utterance was also annotated for its addressee: child, adult, both
262 children and adults, a pet, other (e.g., virtual assistants, higher powers, themselves), or unknown
263 addressee. We calculated the overall proportion of speech directed to each category and compared

264 the difference in the proportion of child-directed speech (CDS). Prior work finds that child-directed
265 speech increases as a function of the child’s age and whether they have begun talking (Casillas et al.,
266 2017; Cychosz et al., 2024; Dailey & Bergelson, 2023). Therefore, because DHH children often
267 experience more rapid language growth (following implantation) than their *hearing* age peers but
268 persistent spoken language delays compared to *age*-matched peers, we expect the CI group to
269 experience less child-directed speech than the CA group but a higher proportion than the HA group.

270 To more closely estimate the rates of these speech types in the recordings, we calculated Total
271 Word Count and proportion of CDS only in the 30 randomly-sampled minutes of transcription, not
272 the 10 minutes selected for high-density talk.

273 **Input Complexity Measures.**

274 We computed language complexity by calculating mean length of utterance (MLU) and type-
275 token ratio (TTR). These metrics were used to help evaluate whether speakers around children with
276 CIs use shorter, less lexically-varied utterances. We predict less complex language input to DHH
277 children, in line with research on other groups with perceived cognitive disabilities (Lorang, Venker,
278 & Sterling, 2020), delayed developmental level (Odijk & Gillis, 2021; C. E. Snow, 1972), and
279 reduced auditory access (Dirks, Stevens, Kok, Frijns, & Rieffe, 2020).

280 Mean Length of Utterance was quantified as the mean number of morphemes per utterance in
281 the speech input. Utterances’ morpheme counts were parsed and counted using the morphemepiece
282 package in R (Bratt, Harmon, & Learning, 2022). We excluded utterances containing unintelligible
283 speech.

284 Type-Token Ratio was computed by “chunking” the input speech into 100-word bins across
285 each group, then calculating the proportion of unique words out of the 100 in each bin. These
286 uniqueness values were then averaged to produce a single value for Type-Token Ratio for each
287 recording. Normalizing the denominator in this way allows for a measure of lexical diversity that is

288 less coupled with the raw quantity of speech in the input (Campbell, Righter, Lukin, & Bergelson,
289 2025; Montag, Jones, & Smith, 2018).

290 **Input Conceptual Measures.**

291 To examine the sensory associations of words in the input, we filtered the input to only
292 content words (excluding function words like *the* and *of*). We then categorized the perceptual
293 modalities of words' referents using the Lancaster Sensorimotor Norms, which are ratings from
294 sighted and hearing adults that score the extent to which a word evokes a sensory experience in each
295 modality (auditory, haptic, gustatory, interoceptive, olfactory, visual; Lynott, Connell, Brysbaert,
296 Brand, & Carney, 2020). A word's dominant perceptual modality is the modality which received the
297 highest mean rating. 61.74% of the words in our corpus had a corresponding word in the Lancaster
298 ratings and could be categorized in this way.

299 We then calculated the proportion of words in the input with referents that are highly and
300 exclusively auditory (as this is the most relevant modality for the present work). We had no
301 prediction for the direction of this measure. Caregivers of children with cochlear implants might talk
302 *more* about sound to help accustom them to the new sensory experience, or might talk *less* about
303 sound given their child's deafness.

304 Finally, we examined the quantity of decontextualized language input, which has been
305 associated with later language abilities (Demir et al., 2015; Rowe, 2012, 2013). We focused on its
306 temporal component: talk about events that are not concurrently happening. Given prior work that
307 shows parents use less decontextualized speech in earlier language development (Tamis-LeMonda,
308 Kuchirko, & Song, 2014; Uccelli et al., 2019) and DHH children's overall less developed language
309 production relative to hearing peers, we predicted DHH children too would hear relatively less
310 decontextualized speech.

311 We determined the temporality of each utterance following the procedure in Campbell et al.
312 (2025). In brief, we used the R package *udpipe* (Wijffels, 2023) to tag the first verb in each utterance
313 with tense and mood features. Past tense, going to/want to/got to, and modal verbs were classified as
314 *decontextualized* utterances, and present tense and gerunds were classified as *present* utterances.
315 Fragments and other utterances for which no temporality features were tagged were left unclassified.
316 For further discussion of ³²⁵the benefits and limitations of this analysis, see Campbell et al. (2025).

317 **Language Outcome Measures.** We derived three language outcome measures—two
318 automatically and one from manual annotations—that assess features of the target child’s own
319 utterances: child vocalization count, conversational turn count, and proportion of canonical babble.

320 Child Vocalization Count (CVC) is the number of times the target child makes a speech-
321 related vocalization. Conversational Turn Count (CTC) counts utterances produced by an adult and
322 the target child occurring within 5 seconds of each other. While CTC is both an input and outcome
323 measure, driven both by child productions and caretaker input, but we grouped it as an outcome
324 measure for expository simplicity. If, as in prior research, children with CIs respond to and initiate
325 conversations less often (Cychosz et al., 2024), we’d expect to see a lower CTC for our CI group, as
326 compared to the (same age) CAM group in particular.

327 Proportion of canonical babble indexes vocal maturity. All child utterances in the manually
328 annotated portions were tagged for whether they contained a canonical consonant-vowel sequence
329 (e.g. bababa), *including* recognizable lexical productions (‘dog’). As children get older and develop
330 language, the ratio of canonical babble and words (which we call **canonical utterances** hereafter) to
331 other vocalizations types (crying, grunting, non-canonical babbles, etc.) gets higher. To maximize
332 power, we did not separately analyze the proportion of lexical utterances (which constitute 19.94% of
333 all child utterances) or multiword utterances (8.32%).

334 **Language Input-Output Links.**

335 As noted above, prior work finds properties of the language input have a measurable
336 relationship with language skills in toddlerhood and beyond (Gilkerson et al., 2018; Rowe, 2012,
337 *inter alia*). Noting that quantity and complexity of the input often have weak or inconsisten tlinks to
338 the CI group’s language skills (Arora et al., 2020; Cychosz et al., 2024; DesJardin & Eisenberg,
339 2007; Wang et al., 2022), we hypothesized that the input will differently predict the quantity of child
340 vocalizations and the maturity of those vocalizations for hearing children than for DHH children.

341 **Results**

342 We took a model building approach to assessing differences between hearing status groups
343 and whether age or hearing age additionally predict the way caretakers tailor the language
344 environment to children. First, for each input variable, we ran a linear modelwith Group (CI, CAM,
345 or HAM) as the only predictor of the input variable. We report results of these models for each
346 metric in Table 2. If Group was a significant predictor, and the overall model was at least marginally
347 significant ($p < .1$) we then conducted two 2-sample t-tests (or a Wilcoxon signed-rank test, if
348 Shapiro-Wilk test indicated non-normal distribution) between CI and CAM and CI and HAM,
349 respectively, to test for significant difference between the CI group and each of the match groups¹.

350 If the 2-sample indicated a group difference (i.e. CI vs. HAM or CI vs. CAM)), we then ran a
351 linear model with Group as a predictor, and compared this to a second model with group and age (for
352 CI vs. CAM) or group and hearing age (for CI vs. HAM) asadditive predictors of the input variable
353 (*input variable ~ group + age*). Then, if adding age as a predictor significantly improved model fit,
354 checked if an interaction term further improved model fit (*input variable ~ group : age*) via model
355 comparison of the main effect vs. interaction models.

¹ We did not test CAM vs. HAM differences to minimize extra comparisons, as this was not our research goal.

Code/data are provided for those interested in age comparisons for the hearing children.

356 For metrics with a non-normal distribution, we assessed the normality of model residuals
357 using the olsrr package in R (Hebbali, 2024); residuals were normally distributed for all models. We
358 also ran an outlier analysis, which found one outlier for one metric (Adult Word Count); results
359 without this outlier are reported in Supplementals.

360 **Quantity**

361 Input quantity was broadly similar between the CI group and each hearing match group.
362 Linear models revealed no effect of group on Adult Word Count and Total Word Count, and a
363 marginal effect of group on the proportion of CDS (which is likely due to a HAM vs. CAM
364 difference). See Fig. 1.

365 **Complexity**

366 There was no effect of group on Type-Token Ratio. In contrast, there was an effect of group
367 on MLU; T-tests showed no difference in MLU heard by children in the CI and CAM groups
368 ($\text{Mean}_{\text{CI}}=5.02$, $\text{Mean}_{\text{CAM}}=5.41$, $T(24.21)=-1.32$, $p = .198$), but children in the HAM group heard
369 speech with a higher MLU (i.e. longer utterances) than children in the CI group ($\text{Mean}_{\text{HAM}}=5.7$,
370 $T(29.16)=-2.94$, $p = .006$). Adding hearing age as a predictor did not significantly improve fit ($F(1,$
371 $29) = 0.19$, $p = 0.67$).

372 **Conceptual**

373 We next analyzed the proportion of highly auditory content words. There was a marginal
374 effect of group in our linear model. T-tests show that the CI group heard roughly the same proportion
375 of highly auditory words as the CAM group ($\text{Mean}_{\text{CI}}=0.07$, $\text{Mean}_{\text{CAM}}=0.054$, $T(29.39)=1.46$, $p =$
376 $.156$), but *more* auditory words compared to HAM group ($\text{Mean}_{\text{HAM}}=0.047$, $T(27.88)=2.2$, $p = .036$).
377 Adding hearing age as a predictor did not improve model fit, per model comparison ($F(1, 29) =$
378 0.26 , $p = 0.61$).

379 The proportion of decontextualized speech did not show an effect of group (Fig. 3).

380 **Child Production Outcomes**

381 We next looked at our three child production outcomes: child vocalization count,
382 conversational turn count (automated LENA measures) and proportion of canonical
383 utterances (manual measure). Group was a significant predictor of variance in Child Vocalization
384 Count in our model. The CI group vocalized roughly the same amount as the CAM group
385 ($Mean_{CI}=163.36$, $Mean_{CAM}=187.91$, $W=108$, $p = .468$), but more than the HAM group
386 ($Mean_{HAM}=73.03$, $W=209$, $p = .002$). Adding hearing age as a predictor did not result in a better
387 fitting model ($F(1, 29) = 0.73$, $p = 0.40$).

388 Correspondingly, there was a main effect of group on CTC. Subsequent Wilcoxon tests
389 showed only a marginally significant difference in CTC per hour between the CI group and CAM
390 ($Mean_{CI}=40.14$, $Mean_{CAM}=54.93$, $W=79.5$, $p = .070$), but that the CI group had a higher CTC than
391 HAM ($Mean_{HAM}=22.34$, $W=196$, $p = .010$).

392 Analogously, there was a significant effect of group on CTC comparing CI and HAM only,
393 but adding Hearing Age as a separate predictor did not significantly improve model fit ($F(1, 29) =$
394 0.21 , $p = 0.65$).

395 Finally, group was a significant predictor of the proportion of child utterances that were
396 canonical. Notably, Wilcoxon tests revealed that the proportion of canonical utterances from the CI
397 group was different than both HAM and CAM groups: lower than CAM ($Mean_{CI}=0.3$,
398 $Mean_{CAM}=0.54$, $W=63$, $p = .014$), but higher than HAM ($Mean_{HAM}=0.11$, $W=200.5$, $p = .007$).
399 Adding hearing age did not improve model fit relative to group alone for the followup model with
400 the CI group and HAM group ($F(1, 29)= 0.01$, $p = 0.92$).

401 In contrast, adding chronological age did significantly improve model fit over a model with
402 group alone for the follow up model with the CI group and CAM group ($F(1, 29) = 10.57$, $p = 0.00$),

403 indicating a significant effect of age on children's canonical productions. Adding an interaction
404 between group and age to this model did not further improve model fit ($F(1, 28) = 2.64, p = 0.12$).

405 To more thoroughly investigate the relationship between age and canonical utterances in the
406 CI and CAM groups, we ran exploratory Pearson's correlations separately in each group. This
407 showed a significant, positive relationship between age and higher canonical utterances for CAM
408 ($R(14) = 0.70, p = .002$), but not for the CI group alone ($R(14) = 0.28, p = .287$).

409 **Input-Outcome relationship**

410 For our last analysis, we implemented stepwise regression to select the best fitting linear
411 model when assessing the predictors of children's language outcomes. We examined two outcome
412 variables, CVC and proportion of canonical utterances, and for each variable we built two possible
413 models, comparing the CI group to each of the match groups (i.e., just CAM or HAM). We used the
414 `olsrr` package (Hebbali, 2024) to conduct a both-directions progression with all of our input metrics,
415 plus age (or hearing age) and group, as possible predictors. The stepwise regression minimizes AIC.

416 For the CI and HAM groups, the best fitting models include *only* group as a significant
417 predictor for both CVC and proportion of canonical utterances. The model accounts for ~32% of
418 variance in CVC ($R^2_{\text{adjusted}}=0.29, p < .001$) and ~28% of variance ($R^2_{\text{adjusted}}=0.26, p = .002$) in
419 proportion of canonical utterances. The CI group produced more vocalizations ($Beta=-90.33, p <$
420 $.001$) and more mature utterances ($Beta=-0.19, p = .002$). Comparing CAM and CI in predicting
421 CVC, the selected model accounts for ~38% of variance and has three predictors: MLU (lower =
422 higher CVC), proportion of temporally displaced verbs (higher = higher CVC), and proportion of
423 highly auditory words (lower = higher CVC). Notably, group was not selected. We report full model
424 tables in Supplementals.

425 Finally, predicting proportion of canonical utterances in CI and CAM, the final model selects
426 age, group, total word count, and MLU as significant predictors, accounting for ~54% variance.

427 More specifically, our model finds more mature vocalizations from older children, the CAM group,
428 children hearing more total words, and lower input MLU. While we can't simultaneously show all of
429 these relationships, we visualize a subset in Figure 5 and return to these patterns in the discussion.

430 **Discussion**

431 We examined children's spoken language environment in a sample of DHH children using
432 cochlear implants (CI group) and hearing peers matched on age (CAM) or hearing age (HAM). In
433 many ways, language input looked similar across groups. None of our input metrics differed
434 significantly between the CI and CAM group, and none of the quantity metrics differed across any
435 group.

436 In terms of the *content* of the language input, we observed a few group differences between
437 the DHH and HAM groups: utterances to DHH children were slightly shorter (by~12%), and
438 contained marginally more "auditory" words (e.g., *loud*, *hear*, *song*) than those to hearing
439 age matches. Because groups are matched on length of hearing experience (not chronological age),
440 the HAM group is younger than the DHH and CAM groups by design. This suggests variations in the
441 way people talk to children could have more to do with their age than their hearing status.

442 More pronounced differences emerged when we examined language outcomes. Despite
443 similarity in overall quantity and audibility of spoken language input, given the degraded auditory
444 signal from CIs, children with cochlear implants *receive* less spoken language input than their
445 typically-hearing peers, likely impacting their learning. CI users may have more difficulty
446 extrapolating linguistic patterns from the input available to them due to the degraded signal.
447 Consistent with this, our CI group produced less vocally mature utterances than their chronological
448 age matches. And while the hearing children show a significant increase in their canonical
449 productions with age, DHH children do not show age-related increases in canonical productions, in
450 line with results from Wang et al. (2022).

451 That said, the CI group did produce more and higher maturity vocalizations than their hearing
452 age matches, and participated in more conversational turns. These results are somewhat unsurprising
453 given the CI group's mean age of 21 months vs. the HAM group's mean age of 7 months. Older
454 children produce more speech and drive more conversational turns, even with differing hearing
455 statuses (Cychosz et al., 2024; Wang et al., 2022).

456 Among children matched on age, while hearing status (CI vs. CAM) didn't predict how *much*
457 a child vocalizes, it did predict the proportion of more mature, canonical utterances. Moreover,
458 features of the input seem to matter: proportion of displaced verbs in the input (more
459 decontextualized language), was associated with more child productions, in line with past work
460 (Demir et al., 2015; Rowe, 2012, 2013). Surprisingly, quantity of child vocalizations was also
461 predicted by a *decreased* proportion of highly auditory words. We had no *a priori* reason to predict
462 that caregiver use of auditory words would predict child language outcomes. One possibility is that
463 caregivers use more auditory language when hearing challenges with CIs occur, and this variable
464 thus picks upon some signal regarding auditory access. It could also be a statistical fluke, and we
465 encourage cautious interpretation.

466 In our sample, DHH children hear shorter sentences than hearing age peers, similar to prior
467 work (Ambrose et al., 2015; Dirks et al., 2020). We were surprised to find, however, that across both
468 hearing and DHH children, a shorter MLU in the input is related to *more* child speech and a higher
469 proportion of canonical utterances (based on the regression results, Figure 5). Prior work with
470 hearing toddlers has found that higher MLU is associated with higher child language skill (Bornstein,
471 Haynes, & Painter, 1998). Previous results within DHH children have been more mixed, with
472 differences varying in strength and direction by age (e.g. Ambrose et al., 2015). However, the
473 children in our sample are under 3 years old, and we assess language outcomes using expressive

474 language only. These relationships may change later in development or when considering receptive
475 language.

476 Our findings confirm and extend several recent studies. Like prior work, we find no hearing
477 status differences in the amount of caregiver input, including number of adult words, and proportion
478 of child-directed speech, *inter alia* (Aragon & Yoshinaga-Itano, 2012; Cychosz et al., 2024; Sultana et
479 al., 2024; VanDam et al., 2012; Wang et al., 2022). This work addresses open questions from prior
480 work about whether highly-coarse automated measures are obscuring differences in input: across
481 automated and manual measures alike, we find no differences in input quantity². However, we note
482 that our sample is powered only at .59 to find a large effect size in two-way group comparisons,
483 given our relatively small sample.

484 In practice, the actual quantity of input that is accessible and useful to infant cochlear implant
485 users is likely *lower* than their hearing peers. An important step in identifying support and
486 intervention strategies for pediatric cochlear implant users is to quantify CI children's *received* input.
487 A second concern is that the accessible input is not just lower in quantity, but less regular, meaning
488 CI users may have more difficulty extrapolating linguistic patterns from the evidence available to
489 them. For example, in modeling the auditory properties of child- and adult-directed speech as
490 processed through a cochlear implant, Arjmandi, Houston, and Dilley (2022) find decreased acoustic
491 distinctiveness between CDS and ADS—making the prosodic patterns of CDS a less reliable cue for
492 infant attention. Likewise, noise in the signal can disrupt the regularity of transitional probabilities
493 that infants use to identify phonemes and wordforms (cf. Levine et al., 2016 for review).

² Considering MLU, total word count, and type-token ratio in child-directed input only (as opposed to all input) revealed the same pattern.

494 Our production analyses replicate Cychosz et al. (2024), in that DHH children’s vocalization
495 maturity falls below same-aged peers. In typically-developing children, this proportion grows as
496 children get older and develop language skills (Cychosz, Villanueva, & Weisleder, 2021). We
497 observe this pattern for our hearing participants, but our CI group shows limited growth with age.
498 Likewise, hearing age (i.e. language experience), did not predict language outcomes for hearing age
499 matches *or* DHH children. In order for children with CIs to “catch up” to same-age peers in language
500 skills, the frequency and maturity of their productions would need to be growing *faster* post-
501 implantation than hearing children of the same age and with the same amount of language exposure;
502 this is not what we see. This finding falls in line with spoken language delays that persist into
503 preschool and school age (Duchesne et al., 2009; Nikolopoulos et al., 2004; Niparko et al., 2010;
504 Nittrouer et al., 2016).

505 Our results leave us with three takeaways: first, with few exceptions, we found that
506 caretakers did not generally modify their speech based on children’s hearing status. Second,
507 children’s own productions varied based on their hearing status. This in turn suggests that DHH and
508 hearing children are unable to access and leverage the input in the same way. Future work should
509 focus on quantifying DHH children’s *access* to their everyday input. Finally, we find that language
510 input is highly-variable across families in ways only partly explained by age and hearing status. All
511 of these takeaways are consistent with prior work, but add nuance via manual and automated metrics
512 with a relatively young sample of CI users.

513 CI users may be a population where individual differences in accessible input and device
514 efficacy matter substantially, due to the iterative nature of learning through processing (Meylan &
515 Bergelson, 2021): children actively help shape their input (Dailey & Bergelson, 2023), and parents
516 respond sensitively based on the child’s behavior (Lam & Kitamura, 2012). For infants and toddlers

517 with CIs in particular, efficacy of hearing provisions may play a key role in the degree to which
518 children can be active elicitors of interactive and complex input.

519 **Conclusion**

520 This study compared the input to children with cochlear implants to peers matched on chronological
521 age and children matched on length of hearing experience; we found few differences between groups
522 (and those we did find were generally attributable to age differences rather than hearing differences).
523 Nevertheless, children with cochlear implants tended to produce less mature language than their
524 typically-hearing peers. We suggest the locus of support and intervention strategies should be on
525 getting high-quality language access to DHH children as early as possible – rather than coaching
526 caregivers to modify their speaking style. We underscore that support for spoken language
527 development—and by extension cognitive and social development (M. L. Hall et al., 2017) – can
528 come from a combination of early identification of hearing loss (Campbell & Bergelson, 2022; Peters
529 et al., 2010), early implantation (Hardman et al., 2022; Kirk et al., 2002; Niparko et al., 2010; D.
530 Snow & Ertmer, 2009), improving comfort and frequency of CI use (Haukedal et al., 2020; Park et
531 al., 2019), and early sign language input (Delcenserie et al., 2024; Pontecorvo et al., 2023).

532

533 **Acknowledgments**

534 We are indebted to the diligent work of the many research assistants who contributed to annotations.
535 This work was supported by NSF CAREER Award 2337766 to EB and NSF GRFP 2019274952 to
536 EC.

537 **Data Availability Statement**

538 Deidentified text data, analysis code, and manuscript files are available to view on OSF:

539 https://osf.io/73uq4/?view_only=87385f1c5a344b12a027781e8466b39e

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Figure and Table Captions

880 *Figure 1.* Box plots demonstrating group comparisons in input quantity. Each dot represents
881 one child. Navy circle marks group mean with 95% confidence limits. Whiskers extend to highest
882 value within 1.5*IQR. CI group is exposed to a similar quantity of spoken language and child-
883 directed speech as both hearing groups. Brackets indicate two-way comparisons between CI and
884 HAM and CI and CAM. ns indicates t-test $p > .05$.

885

886 *Figure 2.* Plot elements as in Figure 1. ** indicates t-test $p < .01$. CI group hears shorter
887 utterances than HAM, and a similar TTR to both groups.

888

889 *Figure 3.* Plot elements as in Figure 1. * indicates T-test $p < 0.05$. All groups hear a similar
890 proportion of displaced verbs, DHH children hear slightly (but significantly) more auditory words
891 than HAM.

892

893 *Figure 4.* Boxplot elements as in Figure 1. The DHH group produces more vocalizations and
894 more conversational turns than HAM (top), less mature vocalizations than CAM but more mature
895 than HAM (bottom), and exhibit a weaker relationship between age and canonical utterances than
896 CAM. On scatterplots, the relevant age variable is plotted on x-axis, canonical utterance proportion
897 on the y-axis. Confidence bands show 95% CI.

898

899 *Figure 5.* Child speech (CVC or proportion canonical) as a function of MLU by group (CI,
900 HAM, CAM). Confidence bands show 95% CI. Lower MLU was associated with higher child
901 speech.

902

903

904 *Table 1. Demographic information by group, n = 16 per group.*

905

906 *Table 2. Analysis summary. (prop.=proportion, voc=vocalization, utt=utterance, MLU=mean*
907 *length of utterance; Model=overall effect of group (betas relative to CI group). See text for details*
908 *and each post-hoc p-value (post-hocs only run when initial model was significant).*

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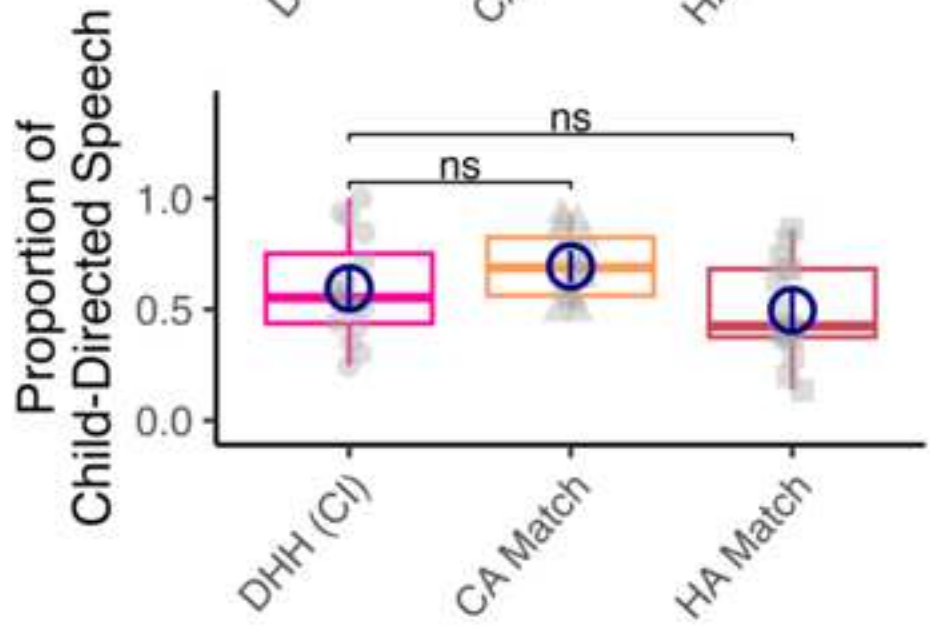
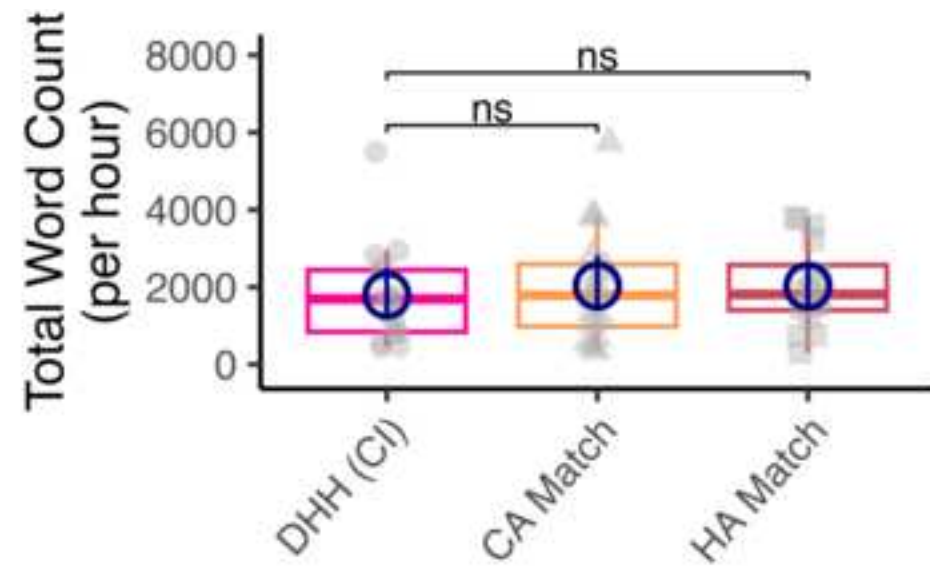
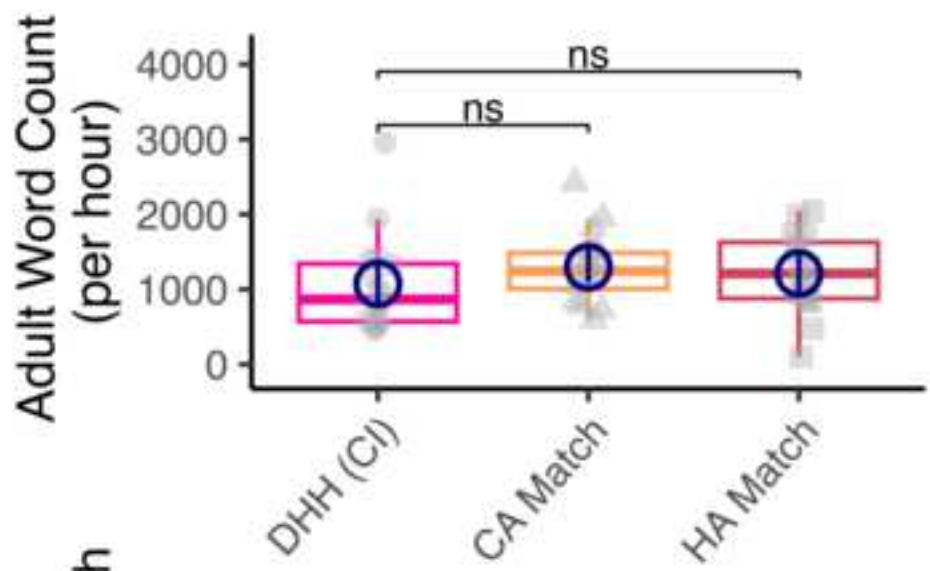
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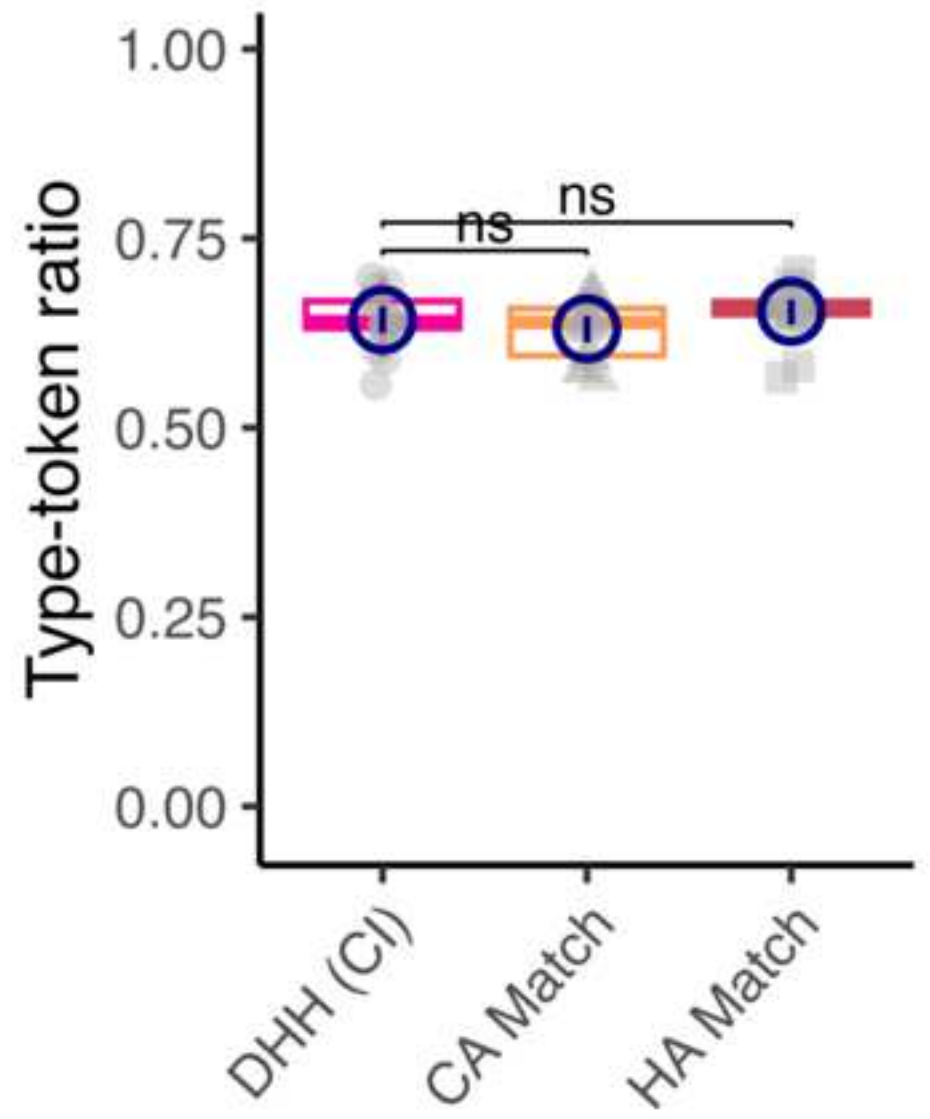
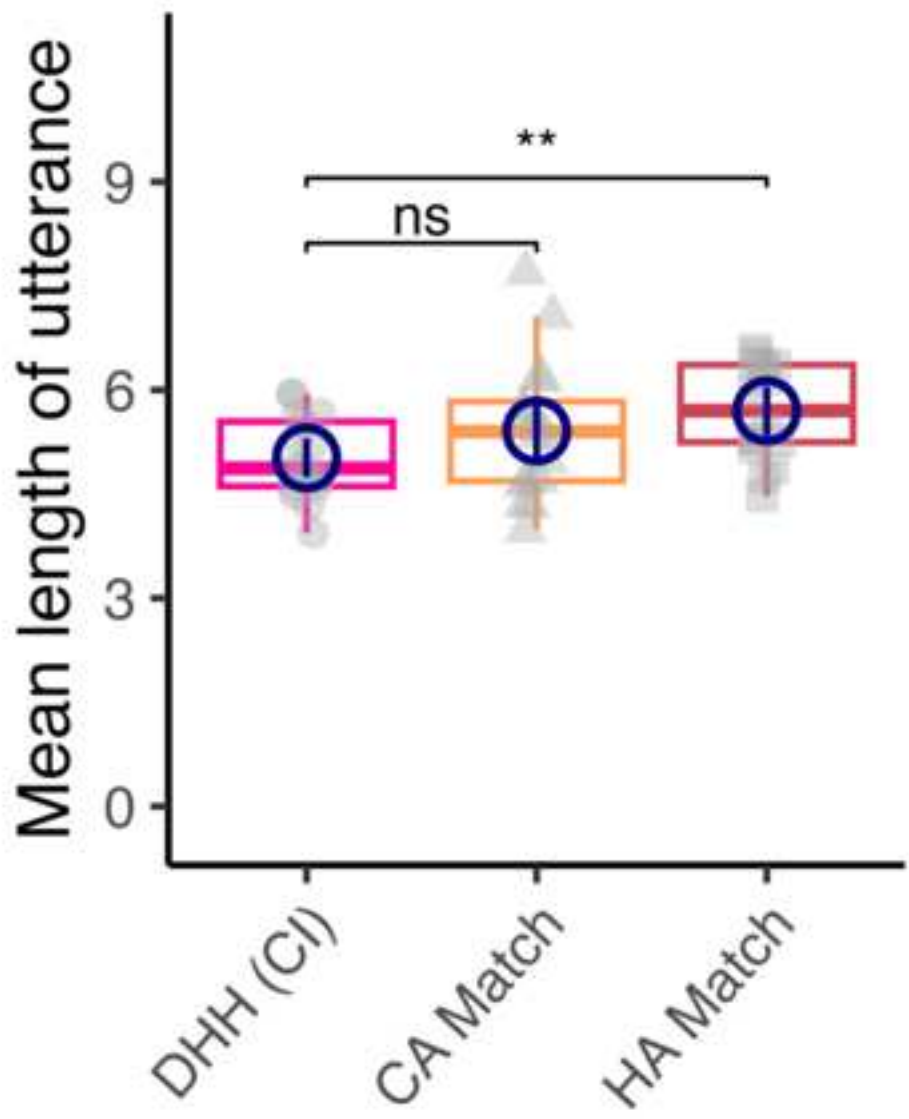
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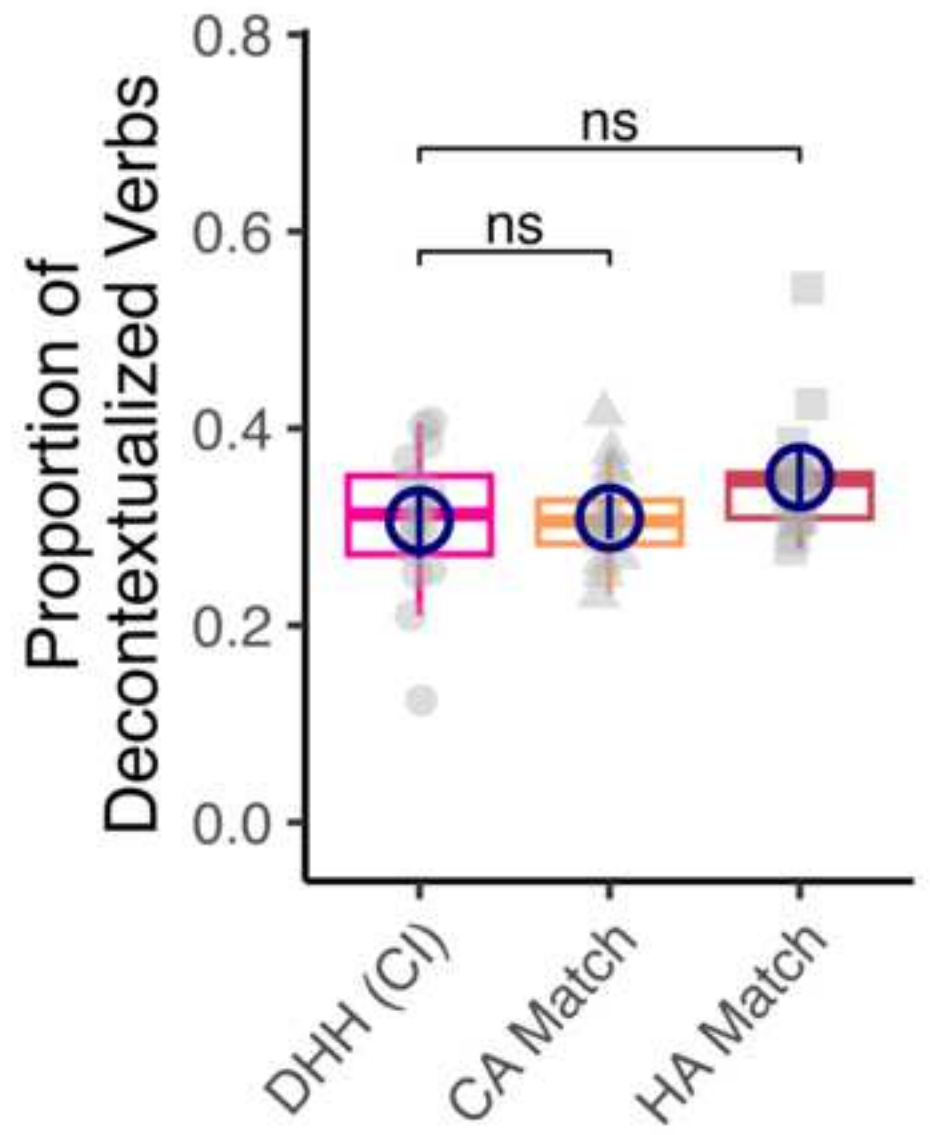
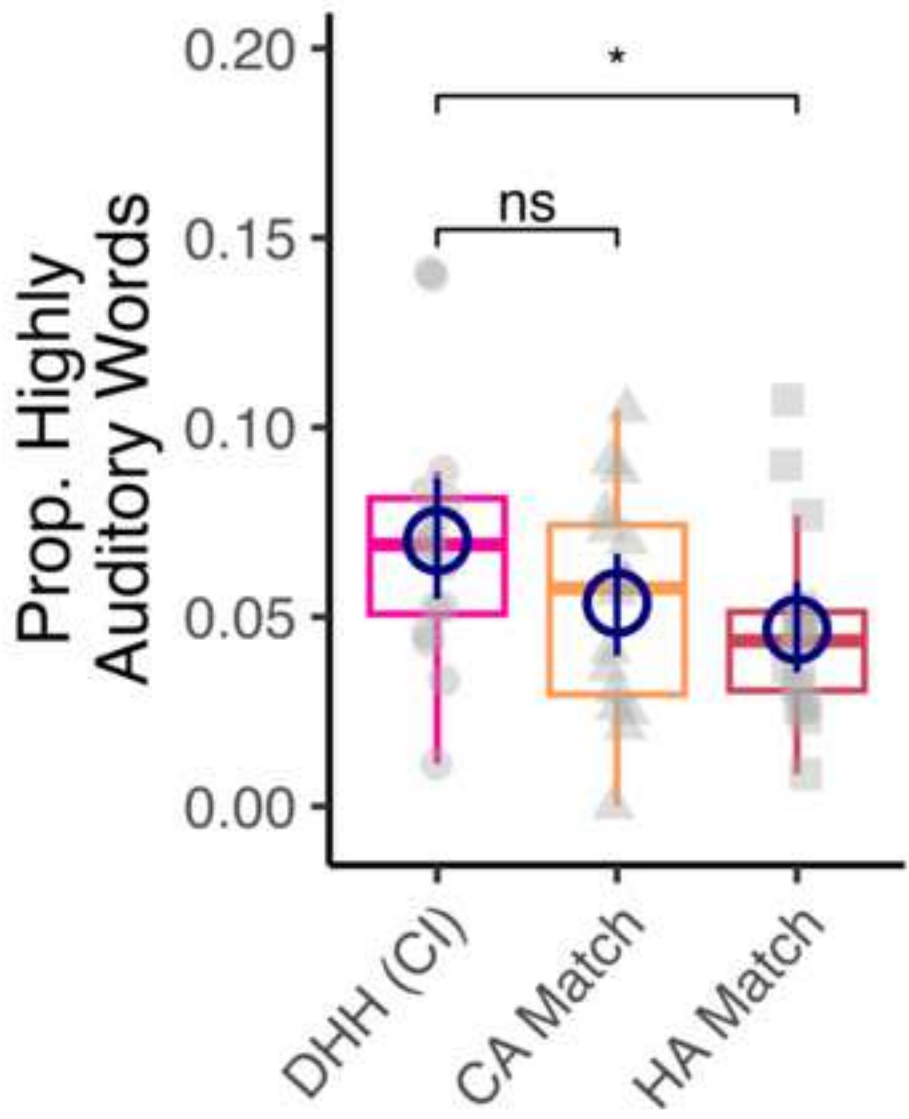
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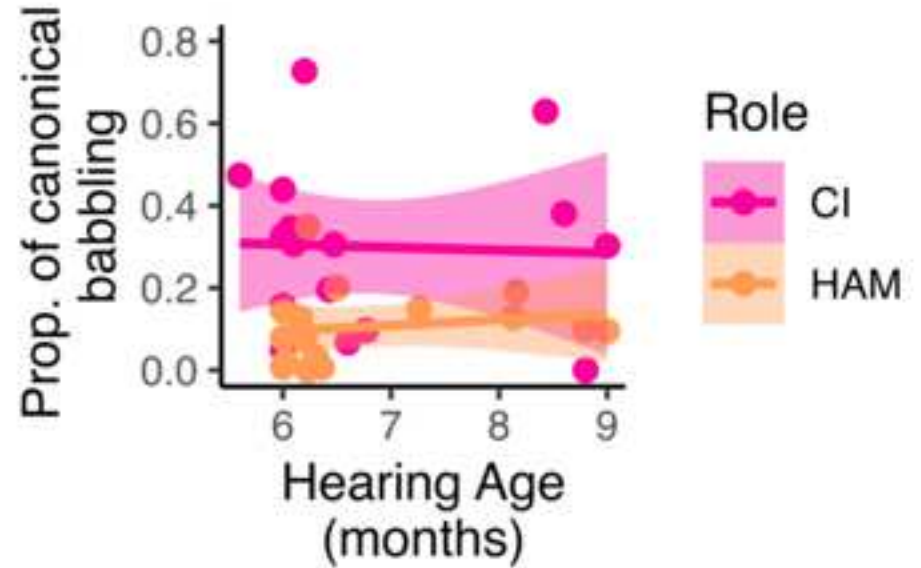
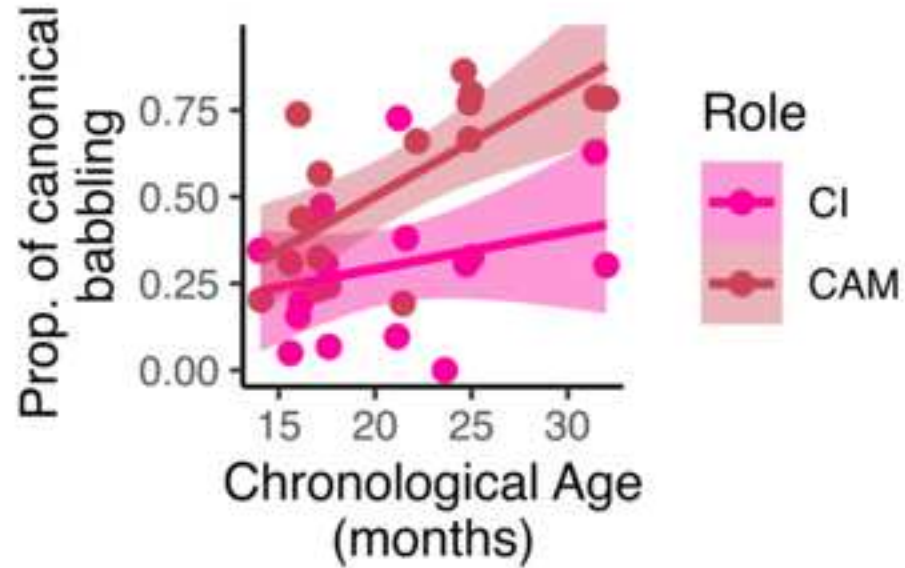
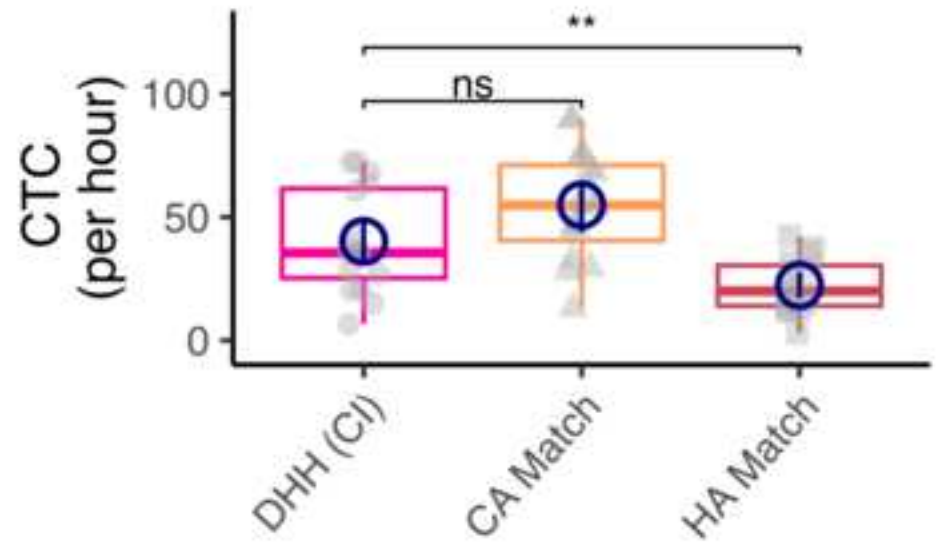
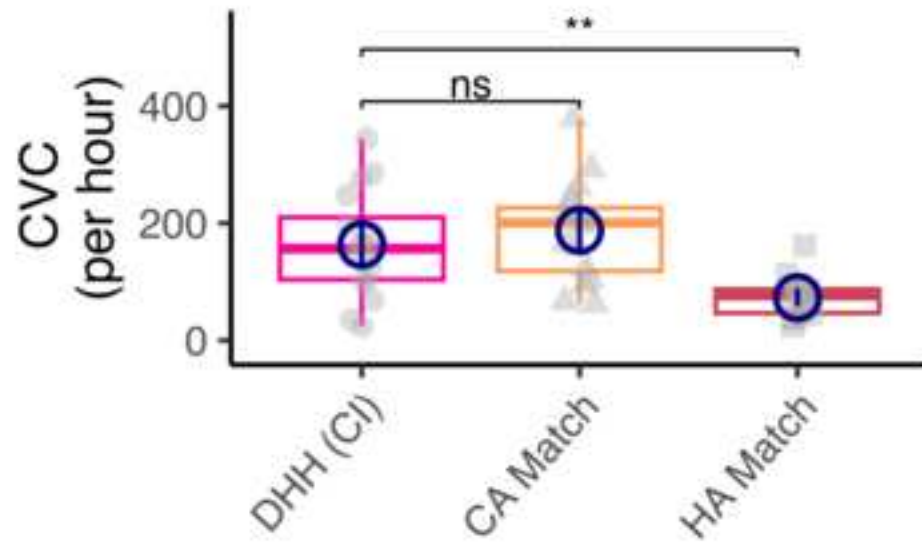
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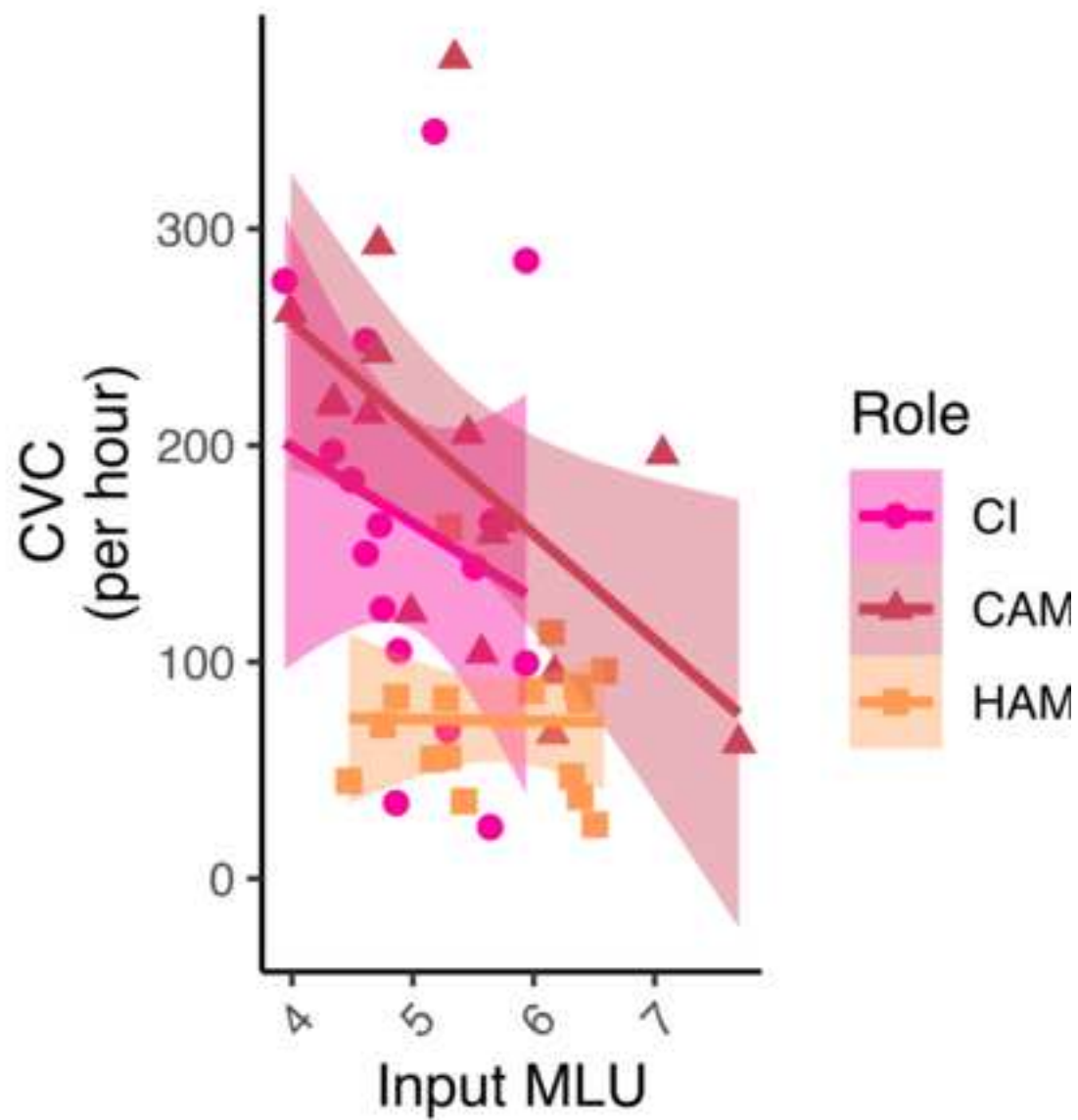
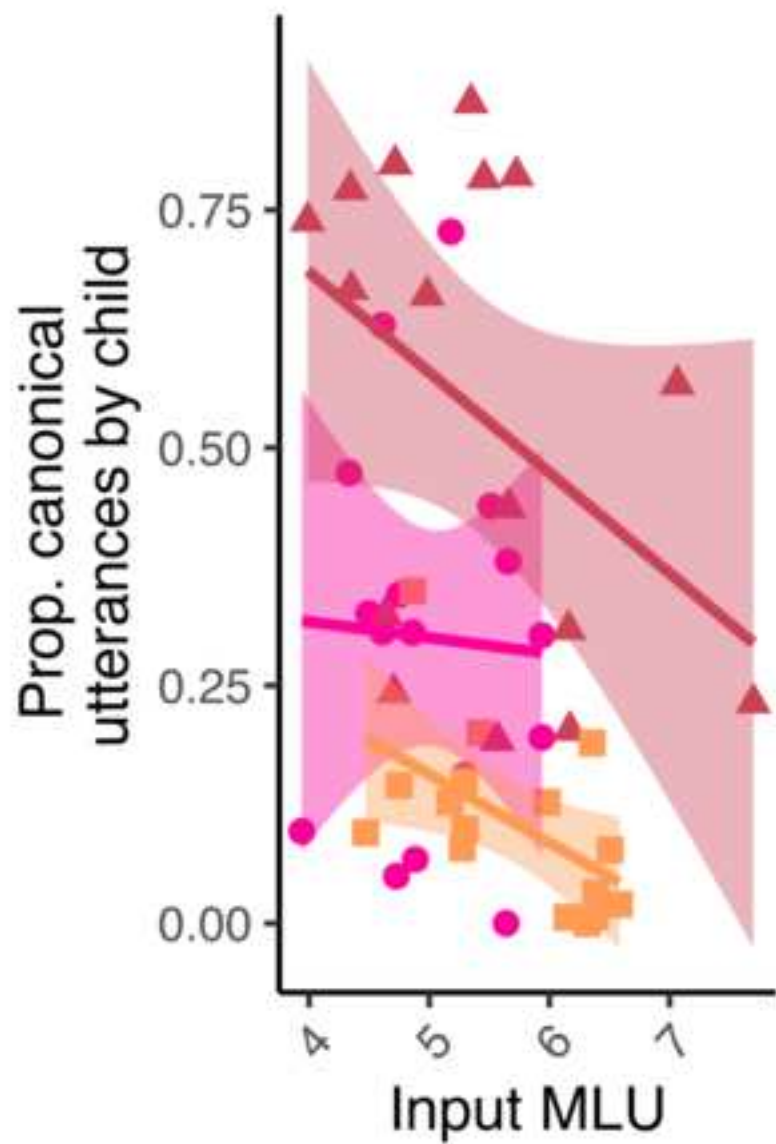
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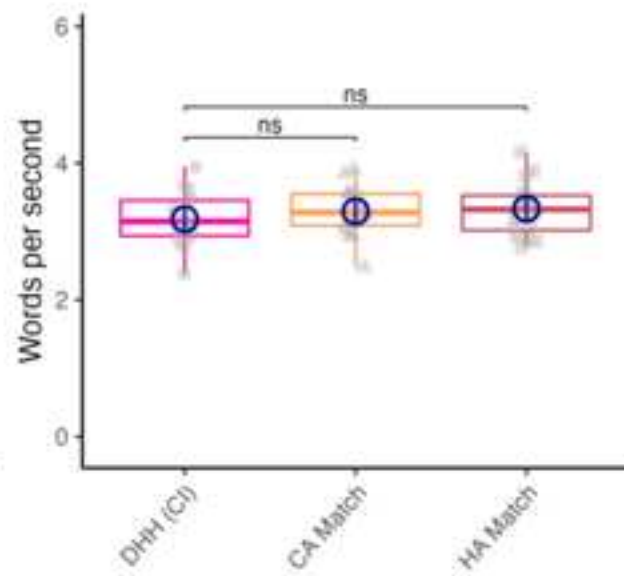
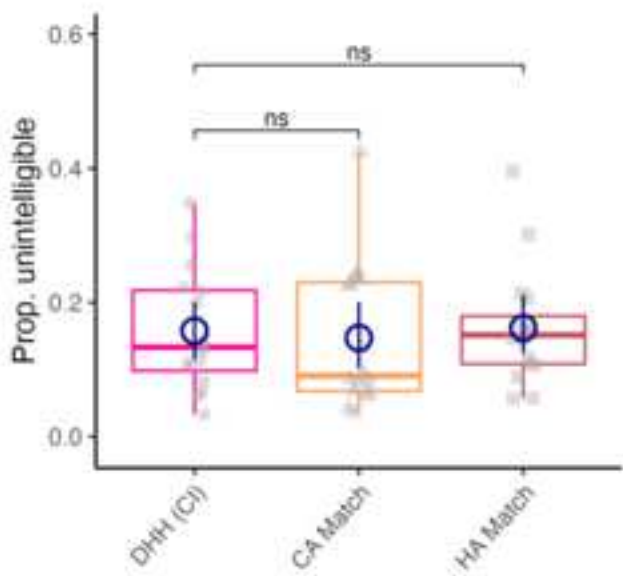
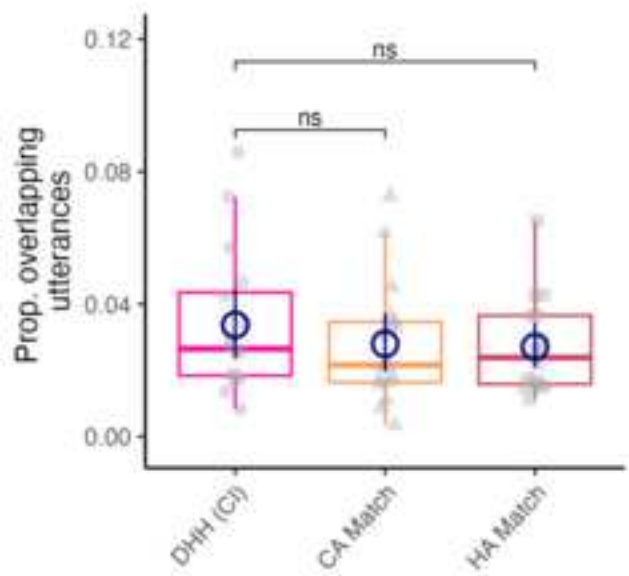
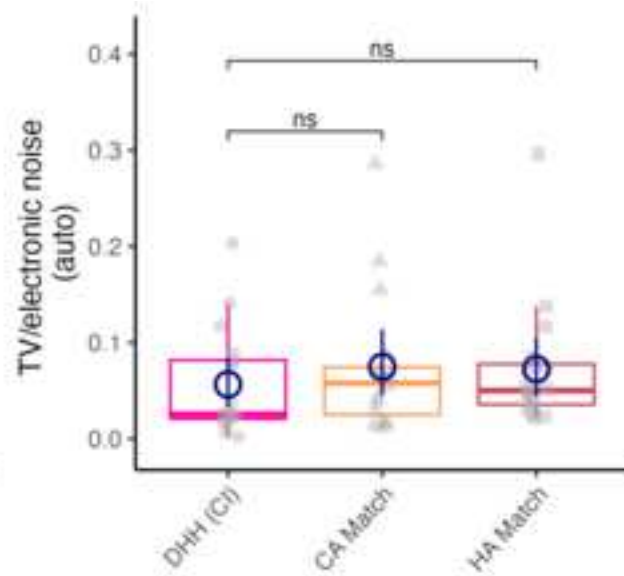
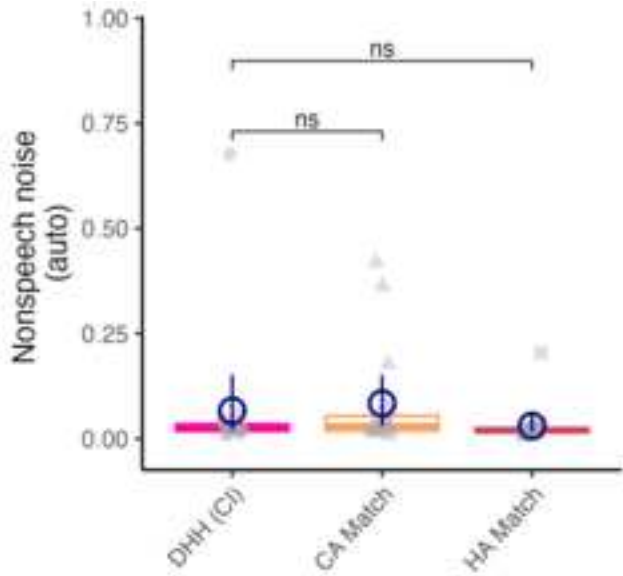
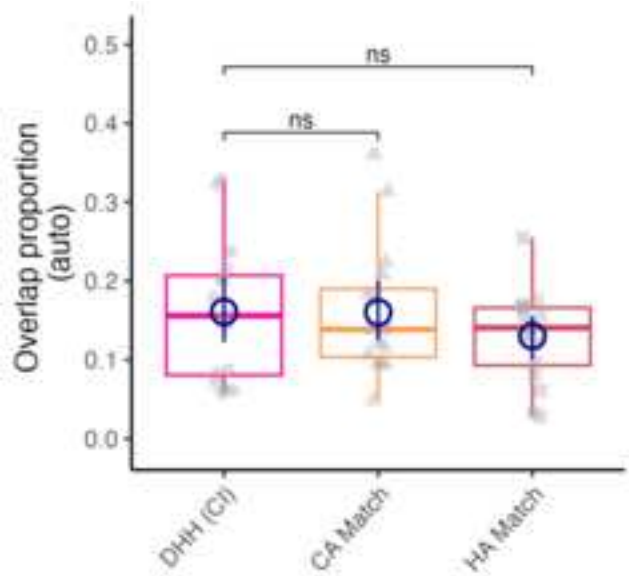


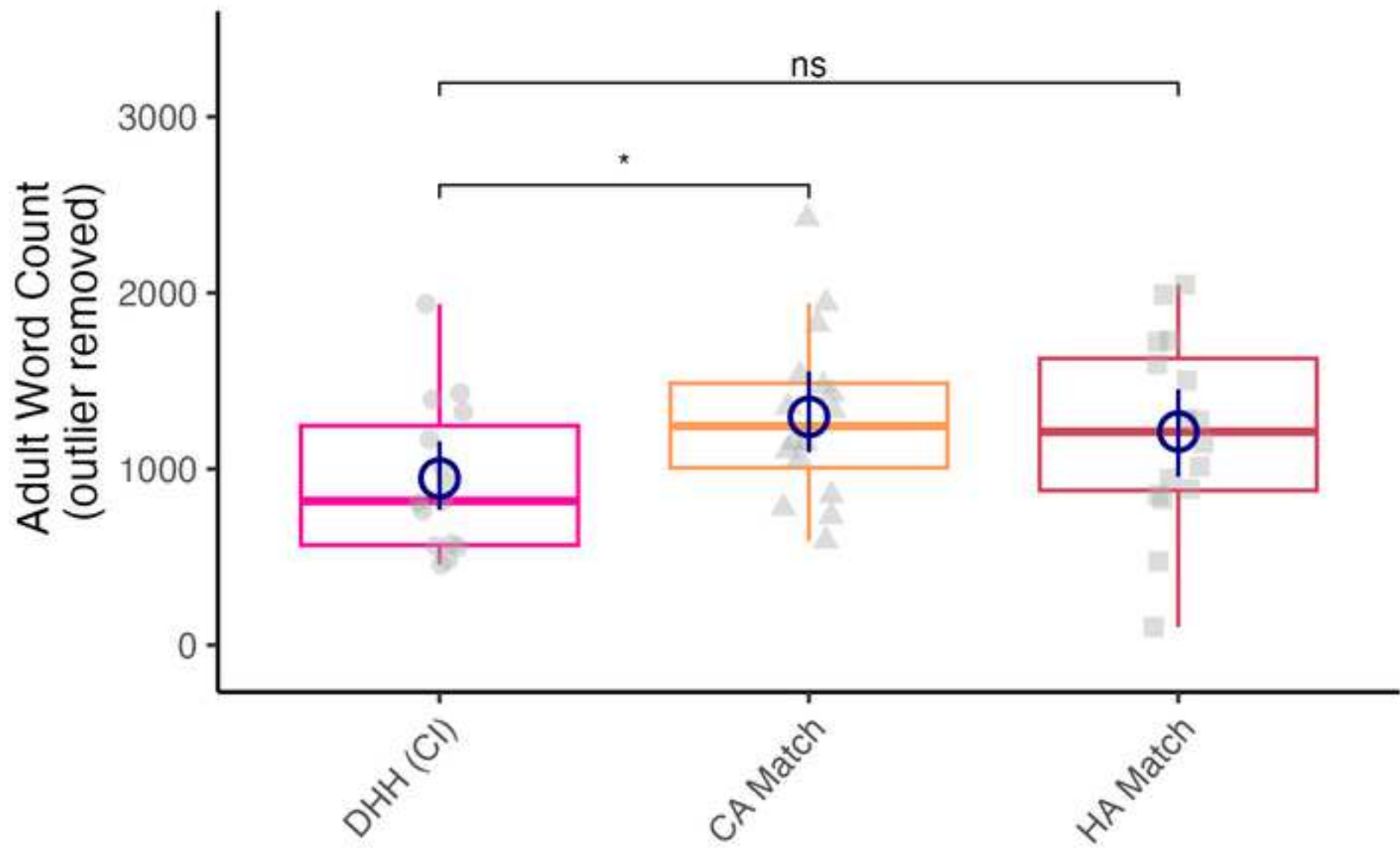












Demographic	CAM	CI
Age (Mean(Range)), months		
Chronological Age	21.1 (14.1-32.0)	20.7 (14.0-32.0)
Hearing Age	21.1 (14.1-32.0)	6.8 (5.6-9.0)
Age at CI Activation	NA	13.9 (8.0-23.0)
Gender %		
Female		81.25
Male		18.75
Maternal Education Level %		
Less than H.S.		6.2
H.S. Diploma		12.5
Some College		50
Bachelor's Deg.		18.8
Advanced Deg.		12.5
Race %		
White		62.5
Multiple Races		6.25
Unreported		31.25
Ethnicity %		
Not Hispanic or Latino		68.8
Unreported		31.2
Hispanic or Latino		0

HAM

6.9 (6.0-9.0)

6.8 (6.0-9.0)

NA

81.25

18.75

0

18.8

25

57.5

18.8

87.5

6.25

6.25

93.8

6.2

0

Variable	Description
Adult Word Count	LENA-estimated # of nearby adult words/hour
Prop. Child-Directed	child/(total (non-key child) utt's)
Total Word Count	Manually annotated # words/hour
MLU	morphemes)/utterance
Type-Token Ratio	# unique words/total words, across 100-word bins
Prop. Decontextualized	prop. of non-present tense verbs
Prop. Auditory	prop. words w/ uniquely high auditory ratings
Child Voc. Count	LENA-estimated # key child voc/hour
Conversational Turn Count	child-to-other turns/hr
Prop. Canonical	prop. key child voc's w/consonant-vowel sequence

Model Adj. R2, p, and Beta**Post-hoc T-test or Wilcoxon**

-0.02, p = .529, CAM B= 223.39, p=.267, HAM B= 139.93, p = .485
0.11, p = .029, CAM B= 0.10, p=.171, HAM B= -0.10, p = .173

NA

$M_{CI}=M_{HAM}$, $M_{CI}=M_{CAM}$

-0.04, p = .844, CAM B= 235.25, p=.610, HAM B= 227.62, p = .622
0.08, p = .062, CAM B= 0.39, p=.172, HAM B= 0.68, p = .019

NA

$M_{HAM}=5.7 > M_{CI}=5.02$

0.02, p = .227, CAM B= -0.01, p=.371, HAM B= 0.01, p = .402
0.06, p = .095, CAM B= 0.00, p=.912, HAM B= 0.04, p = .054

NA

$M_{CI}=M_{HAM}$, $M_{CI}=M_{CAM}$

0.06, p = .086, CAM B= -0.02, p=.128, HAM B= -0.02, p = .032

$M_{CI}=0.07 > M_{HAM}=0.05$

0.29, p < .001, CAM B= 24.55, p=.359, HAM B= -90.33, p = .001

$M_{CI}=163.36 > M_{HAM}=73.03$

0.32, p < .001, CAM B= 14.80, p=.033, HAM B= -17.79, p = .011

$M_{CI}=40.14 > M_{HAM}=22.34$

0.44, p < .001, CAM B= 0.24, p=.001, HAM B= -0.19, p = .007

$M_{CAM}=0.54 > M_{CI}=0.3 > M_{HAM}=0.11$

Tier	Num. of annotations used	Kappa
Addressee	4195	0.87
Lexicality	444	0.79
Multi-word utterance	227	0.84
Vocal maturity	1499	0.79

Role	Num. of annotations used	Kappa
CAM	2323	0.84
CI	2172	0.86
HAM	1870	0.94

Role	Tier	Num. of annotations used	Kappa
CAM	Addressee	1585	0.81
CI	Addressee	1138	0.87
HAM	Addressee	1472	0.94
CAM	Lexicality	199	0.66
CI	Lexicality	215	0.79
HAM	Lexicality	30	0.86
CAM	Multi-word utterance	143	0.79
CI	Multi-word utterance	73	0.91
HAM	Multi-word utterance	11	1.00
CAM	Vocal maturity	396	0.83
CI	Vocal maturity	746	0.73
HAM	Vocal maturity	357	0.81

Stepwise Regression: Best model to predict CVC

Call

lm(CVC ~ Prop. Decontextualized + Prop. Auditory + MLU)

Residuals

Min	1st Quartile	Median	3rd Quartil	Max
-158.576	-38.172	-4.294	42.895	167.474

Coefficients

Estimate	Standard Error	t	value	Pr(> t)	Signif.
Intercept	322.97	100.26	3.221	0.000323	**
Prop. Decontextualized	606.08	223.32	2.714	0.01125	*
Prop. Auditory	-981.52	416.9	-2.354	0.0258	*
MLU	-52.37	16.11	-3.25	0.003	**

Significance Codes

<0.001	<0.01	<0.05	<0.1	<1
***	**	*	.	

Residual Standard Error: 72.9 on 28 degrees of freedom

Multiple R-squared: 0.3782, Adjusted R-squared: 0.3115

F-statistic: 5.676 on 3 and 28 DF, p-value = 0.003626

Stepwise Regression: Best model to predict Canonical utterances

Model

lm(Prop. Canonical ~ Age + Group + Total Word Count + MLU)

Residuals

Min	1st Quartile	Median	3rd Quartile	Max
-0.30991	-0.12931	-0.00045	0.14012	0.37129

Coefficients

Estimate	Standard Error	t	value	Pr(> t)	Signif.
Intercept	0.0649694	0.2730878	0.238	0.81375	
Age	0.0226571	0.0063193	3.585	0.00131	**
Group (CAM)	0.2419349	0.0682525	3.545	0.00146	**
Total Word Count	0.0000473	0.0000251	1.885	0.07028	.
MLU	-0.0636495	0.0413665	-1.539	0.13552	

Significance Codes

<0.001	<0.01	<0.05	<0.1	<1
***	**	*	.	

Residual Standard Error 0.1863 on 27 degrees of freedom

Multiple R-squared: 0.5353, Adjusted R-squared: 0.4664

F-statistic: 7.774 on 4 and 27 DF, p-value: 0.0002645



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