Auditory feedback experience in phonetic development: Evidence from preschoolers with cochlear implants and their normal-hearing peers

Margaret Cychosz,[1, a)] Benjamin Munson,[2] Rochelle S. Newman,[1] and Jan R. Edwards[1]

[1)] *Department of Hearing and Speech Sciences, University of Maryland, College Park, College Park, MD*

[2)] *Department of Speech-Language-Hearing Sciences, University of Minnesota, Twin Cities, Minneapolis, MN*

Previous work has found that preschoolers with greater phonological awareness and larger lexicons, who speak more throughout the day, exhibit less intra-syllabic coarticulation in controlled speech production tasks. These findings suggest that both linguistic experience and speech motor control are important predictors of spoken phonetic development. Still, it remains unclear *how* preschoolers' speech practice when they talk drives the development of coarticulation because children who talk more are likely to have both increased fine motor control and increased auditory feedback experience. Here, the potential effect of auditory feedback is studied by examining a population—children with cochlear implants—naturally differing in auditory experience. Results show that (1) developmentally-appropriate coarticulation improves with increased hearing age, but not chronological age, (2) children with cochlear implants pattern coarticulatorily closer to their younger, hearing age-matched peers than chronological age-matched peers, and (3) the effects of speech practice on coarticulation, measured using naturalistic, at-home recordings of the children's speech production, only appear in the children with cochlear implants after several years of hearing experience. Together, these results indicate a strong role of auditory feedback experience upon coarticulation and suggest that parent-child communicative exchanges could stimulate children's own vocal output, which drives speech development.

[a] mcychosz@umd.edu; Also at: Center for Comparative and Evolutionary Biology of Hearing, College Park, MD

I. INTRODUCTION

Child speech differs from adult speech in several ways. Children speak more slowly than adults (Lee *et al.*, 1999), have higher fundamental and formant frequencies (Eguchi and Hirsh, 1969; Hillenbrand *et al.*, 1995), and exhibit more between- and within-speaker temporal and spectral variability (Lee *et al.*, 1999; Smith and Goffman, 1998). An additional characteristic of child speech that has received considerable attention is the degree of children's anticipatory (lingual) coarticulation that is purported to reduce over the course of development (Nittrouer *et al.* 1989, 1996; Noiray *et al.* 2018, 2019a,b; Zharkova *et al.* 2011, cf. Barbier *et al.* 2020; Zharkova 2016). In adults, coarticulation reflects speech planning as speakers anticipate forthcoming segments and calculate appropriate amounts of spatio-temporal gestural overlap on the basis of speaker efficiency and listener comprehension (Whalen, 1990). Thus, a certain amount of gestural overlap across phonetic boundaries is expected. In children, however, coarticulation reflects immature speech motor control (Barbier *et al.*, 2020) and, some work suggests, a general narrowing of larger syllable-sized phonological representations to phoneme-sized units throughout development (Nittrouer, 1993; Nittrouer *et al.*, 1989; Noiray *et al.*, 2019a; Zharkova *et al.*, 2011). As such, children are usually described as coarticulating *more* than adults because children and adults coarticulate for different reasons. Only as children's speech and fine motor control can they control their articulators and exhibit adult-like levels of lingual coarticulation.

Because children's coarticulation matures with age, it has, unsurprisingly, also been found to interact with various components of children's language experience like vocabulary size, phonological awareness, and speech-language practice (Cychosz *et al.*, to appear; Noiray *et al.*, 2019a). This study delves into this interaction between the degree of children's anticipatory lingual coarticulation and their speech-language experience. (Unless stated otherwise, this work focuses on lingual coarticulation, as this been the focus of most child coarticulation research.) In our previous work, we found that 4-year-old children who vocalized more, and thus practiced speech more, during a naturalistic audio recording made in their home, coarticulated less within CV sequences in an in-lab speech production task (Cychosz *et al.*, to appear). The frequency of children's own vocalizations made during the at-home recording—and not the amount of adult speech produced in the children's ambient environments—predicted the degree of their coarticulation. Still, it remains unclear *how* children's increased vocalizations and speech practice drove the their coarticulatory patterns. Two possibilities emerge: speech practice may drive coarticulatory maturity because as young children vocalize more (1) they are practicing and refining the fine motor movements required of adult-like levels of anticipatory coarticulation or, and perhaps in addition, (2) they are experiencing increased auditory feedback as a result of their increased vocalic output which they can then integrate into their speech motor plans (Guenther, 2006).

We study these two explanations by examining a population with a vastly different early auditory, but not necessarily articulatory, feedback experience: children with cochlear implants (CIs). Prior to implantation, children with CIs receive little to no auditory feedback from their own vocalizations. In this study, the coarticulation patterns of a cross-sectional sample of children with CIs are measured to study the effects of hearing age on phonetic outcomes. Should hearing age (that is, the length of time children have had functional hearing, or the time since implantation), but not chronological age, predict the children with CIs' patterning, this would suggest a strong role for auditory feedback experience. Additionally, the children with CIs are compared to two groups of children with normal hearing (NH) who differ in auditory feedback experience: chronological-age matches (more auditory feedback experience than children with CIs but equivalent physiological and cognitive development) and hearing age matches (equivalent amount of auditory feedback experience to children with CIs but reduced physiological and cognitive maturity).

Matching the children in this way allows us to manipulate auditory feedback experience. However, it is important to acknowledge that children born with profound deafness, like these children with CIs, vocalize less frequently and less maturely pre-implantation, during infancy (Fagan, 2014, 2015; Iyer and Oller, 2008; McDaniel and Gifford, 2020). However, they *do* vocalize. The result is that the children with CIs may have more experience articulating sounds than their hearing age peers, but less experience than their chronological age peers. Still, should the children with CIs pattern more closely to the (younger) children with equivalent auditory feedback experience than the (same-aged) children with more auditory feedback experience, this would at least suggest that auditory feedback is one component driving the speech practice effect for phonetic development found in previous work.

A. Children's development of coarticulation

Coarticulation in adult speech requires mastery of both anticipatory speech planning capacities and domain-general fine motor control of speech articulators. Given children's protracted development in both of these areas (Perkell, 2013; Walsh and Smith, 2002), differences between adult and child coarticulation patterns are anticipated. Specifically, it seems logical that children should coarticulate less than adults because adults' coarticulation is planned (Whalen, 1990), and because coarticulation increases in fast speech and adults speak faster than children. Instead, most studies conclude that children coarticulate more than adults (Nittrouer *et al.*, 1989, 1996; Noiray *et al.*, 2018, 2019a,b; Zharkova *et al.*, 2011). Exceptions to this rule are usually attributed to older age groups studied and/or different units of analysis (inter- versus intra-syllabic environments tend to reveal different effects of age on coarticulation) (Barbier *et al.*, 2020; Rubertus and Noiray, 2020; Zharkova, 2016). For example, Zharkova *et al.* (2011) found that 6- to 9-year-olds coarticulated significantly more within /ʃ-V/ sequences than adult speakers, but Zharkova *et al.* (2014) found no differences between adult and 10- to 12-year-old children's anticipatory coarticulation patterns in /ə-fricative-V/ sequences, suggesting that adult-like levels of coarticulation may be acquired by early adolescence.

Recent studies on the interaction between coarticulation and children's developing language capacities have shed new light on the developmental timecourse of, and reasons for, children's coarticulation. New evidence suggests that 4- to 6-year-old children with greater phonological awareness and larger vocabulary sizes, who talk more throughout the day, coarticulate less within CV syllables (Cychosz *et al.*, to appear; Noiray *et al.*, 2019a). Documenting this relationship between linguistic and coarticulatory development in young children has been a crucial advance because it provides novel evidence that both fine motor/gestural control *and* developing language capacities predict children's coarticulatory patterns: children's intra-syllabic coarticulation decreases as both capacities mature. Noiray *et al.* (2019a) argue that the correlation between phonological awareness and/or expressive vocabulary size and the degree of anticipatory coarticulation manifests because children initially have larger, supra-phonemic phonological representations. Children with greater phonological awareness and larger vocabularies have more segmental phonological representations allowing them to distinguish between adjacent phonemes in their speech.

Cychosz *et al.* (to appear) replicated Noiray *et al.* (2019a)'s finding that 4-year-old children with larger receptive and expressive vocabularies coarticulate less. That study also concluded that children who vocalized and practiced speaking more during a daylong audio recording made in the children's homes coarticulated less during an in-lab speech production task. However, while we understand why children with larger vocabularies and greater phonological awareness should coarticulate less (see above), the reasons for effects of daily speech practice on coarticulation are less clear. Why should children who speak more in naturalistic, at-home environments coarticulate less during controlled, in-lab speech production tasks? Clearly children who speak more throughout the day practice articulating speech more, entrenching their motor routines and refining control over articulators like the tongue tip that are implicated during lingual coarticulation. However, children who speak more also hear themselves talk more (self-auditory feedback), with strong downstream implications for speech-motor commands and the formation of robust acoustic-auditory categories. To compare these two explanations—articulatory practice and auditory feedback—for the effect of speech practice on children's coarticulation, we will study coarticulation in children with different auditory feedback experiences. In the following section we outline how auditory feedback informs phonetic development and helps establish mature acoustic-articulatory mappings.

B. Auditory feedback in speech development

SELF-AUDITORY FEEDBACK, or the auditory consequences of one's own speech production, is a crucial component of speech development throughout infancy and childhood (Fagan, 2014; Guenther, 2006; Iuzzini-Seigel *et al.*, 2015; Koopmans-van Beinum *et al.*, 2001; Oller and Eilers, 1988; Perkell, 2012; Stoel-Gammon and Otomo, 1986; Terband *et al.*, 2014). In the first months of life, infants begin to sketch out the phonological categories of their native language(s). They construct rudimentary acoustic-auditory categories from the complex, highly variable speech stream around them. Then, beginning during vocal play and early babbling, infants compare the auditory information from their own vocalizations to the phonological categories formulated from the surrounding acoustic input. When a mismatch between the acoustic-auditory category and the vocalization's acoustics is detected, feedforward motor commands that map auditory representations to speech-motor plans are updated (Guenther, 2006). SOMATOSENSORY FEEDBACK, or the tactile sensations associated with a speech sound, operate in tandem with auditory feedback and result in similar discrepancy-based updates over the course of development (Moulin-Frier *et al.*, 2014). With sufficient repetitions and productions of a sound or sound sequence, feedforward motor commands can become established motor programs, and create an overarching, mature FEEDFORWARD CONTROL SYSTEM. Initially in development, this feedforward control system co-exists with the auditory and somatosensory feedback subsystems. The feedback subsystems may be activated in development, for example, because children's speech articulators are growing non-linearly so children must update their acoustic-articulatory mappings (Callan *et al.*, 2000; Vorperian *et al.*, 2005). However, with time, the feedforward control system replaces the auditory and somatosensory feedback subsystems entirely. This replacement is a hallmark of speech maturation and permits adult-like speech planning (Guenther, 2006). The shedding of the auditory and somatosensory feedback subsystems permits, among other things, faster, less variable speech that would not be possible under the auspices of slow, feedback-only planning (Perkell, 2012) (it nevertheless remains possible to activate the feedback subsystems, even in adulthood, via altered feedback manipulations [e.g. Katseff *et al.* 2012]).

There are several pieces of evidence demonstrating why auditory feedback matters for accurate acoustic-articulatory mappings in early speech development. First, infants with reduced access to auditory feedback—for example those with severe hearing loss—show delays in the onset and quality of critical speech development milestones like canonical (e.g. CV) syllable production (Koopmans-van Beinum *et al.*, 2001; Nathani *et al.*, 2007; Oller and Eilers, 1988; von Hapsburg and Davis, 2006). They also have less diverse consonant inventories (Stoel-Gammon and Otomo, 1986) in the first two years of life. Additional evidence comes from Speech Sound Disorder which can sometimes be attributed to a breakdown in auditory feedback mechanisms in early childhood: children with speech delays show evidence of imprecise auditory-phoneme mappings even though their abstract phonological processes remain intact (Munson *et al.*, 2005; Rvachew *et al.*, 2003). Foundational auditory categories, based on robust acoustic cues from the input, are a pre-requisite to employing auditory feedback and updating feedforward commands to the articulatory system (see previous paragraph). So, imprecise auditory categories, which inhibit auditory feedback programs, may in part explain the articulatory delays typical of children with speech delays (Shiller *et al.*, 2010).

Additional evidence that a disrupted auditory feedback mechanism affects speech development comes from individuals with childhood apraxia of speech, a communication disorder characterized by very low intelligibility and abnormal prosody. Both of these characteristics are potentially caused by an age-inappropriate overreliance on auditory feedback which inhibits establishment of mature, feedforward mechanisms (Iuzzini-Seigel *et al.*, 2015; Terband and Maassen, 2010; Terband *et al.*, 2014).

And finally, the importance of auditory feedback in early speech development is shown in correlational studies demonstrating that children aged 4-8 years who compensate more for experimentally induced auditory perturbations have stronger phonological awareness and pre-literacy skills (Caudrelier *et al.*, 2019; van den Bunt *et al.*, 2018) and perform better on tests of nonword repetition (Terband *et al.*, 2014).

The above studies summarize some evidence for the importance of age-appropriate auditory feedback to establish robust acoustic-articulatory mappings. Auditory feedback lays the foundation for efficient feedforward speech-motor commands that characterize mature speech (Guenther, 2006; Perkell, 2012) and allows children to compensate for non-linear changes in vocal tract morphology (Callan *et al.*, 2000). Disruptions at any point in the progression—from the establishment of auditory categories in infancy to the eventual replacement of feedback subsystems by an overarching feedforward system later in childhood—will impair speech development, as studies of infants with hearing loss and children with various types of speech disorder demonstrate (Iuzzini-Seigel *et al.*, 2015; Oller and Eilers, 1988).

II. CURRENT STUDY

The goal of this work is to determine if auditory feedback experienced during vocal output could explain the previously documented benefit of speech practice for coarticulation development (Cychosz *et al.*, to appear). Do children who talk more tend to coarticulate less because they have more articulatory practice or because they have more auditory feedback experience? We address this question by studying coarticulation in a population with reduced auditory feedback experience—children with CIs—and comparing them to two groups of their peers with NH.

A. Speech development in children with CIs

Prior to implantation, children with CIs experience little to no auditory feedback, from themselves or their caretakers. This absence of auditory feedback could make it difficult for them to establish reliable auditory categories and acoustic-articulatory mappings and could potentially explain the reduced intelligibility of their speech post-implantation (Allen *et al.*, 1998; Flipsen, 2008; Freeman and Pisoni, 2017). Consequently, in this study, comparing children with CIs to those with NH allows us to study if auditory feedback experience could in part explain the relationship between speech practice and the degree of children's coarticulation.

Hearing loss and the early absence of oral language models from caregivers does not impact children's physiological development or their domain-general fine motor control over speech articulators. Furthermore, infants and children with hearing loss, including those with the most severe hearing loss who eventually receive CIs, still vocalize and engage in vocal play (Fagan, 2014; Iyer and Oller, 2008; Koester *et al.*, 1998), suggesting that their somatosensory feedback subsystem is at least partially in place. However, children with severe hearing loss vocalize less frequently than their age-matched peers with NH throughout the first year of life (Fagan, 2014), and the vocalizations they do produce are less mature (Fagan, 2015; Iyer and Oller, 2008; McDaniel and Gifford, 2020). Consequently, in this study, while the children are matched for auditory feedback experience, they are not necessarily matched for somatosensory feedback experience: pre-implantation, children with CIs vocalize, so they have more somatosensory feedback experience than their hearing age-matched peers, but the quantity and quality of children with CIs' vocalizations is diminished, so they have less somatosensory feedback experience than their chronological age-matched peers.

These differences in somatosensory experience not withstanding, this study focuses on auditory feedback differences between children with different hearing statuses because auditory feedback may be more critical for speech development than somatosensory feedback. As children incorporate somatosensory feedback, they receive important self-tactile information, independent of their acoustic output (Tremblay *et al.*, 2003). However, unlike auditory feedback, somatosensory feedback is not comparable to caregiver speech models, and, for children with severe hearing loss, somatosensory feedback pre-implantation is also not comparable to acoustic-auditory categories. As a result, the auditory feedback subsystem is hypothesized to be the more powerful and predictive of the two sensory feedback subsystems for speech development which is why we focus on it here (Ménard *et al.*, 2008; Savariaux *et al.*, 1995).

B. Study hypotheses

We first evaluate the role of auditory feedback for coarticulation development by studying a cross-sectional sample of children with CIs. Following previous work (Nittrouer *et al.*, 1989; Zharkova *et al.*, 2011), we measure coarticulation between fricative-vowel sequences (see section III B for detail). We compare the children with CIs' coarticulation to their chronological age-matched peers (similar physiological development and domain-general fine motor control experience, but different auditory feedback experience) and hearing age-matched peers (similar amount of auditory feedback experience).

If the coarticulation patterns in the cross-sectional sample of children with CIs vary by hearing age, but not chronological age, this would suggest that children's vocalizations drive coarticulatory development via auditory feedback. Similarly, if the children's patterns correspond closely to their hearing-age matched peers, with whom they have similar auditory feedback experience, this would likewise suggest a strong role for auditory feedback for coarticulation. If, however, the children with CIs pattern more closely to their chronological age-matched peers, this would suggest that coarticulation can develop independently of auditory feedback experience. In that case, children might benefit from daily speech practice perhaps because it helps entrench speech-motor schemata. Crucially, in our results, we additionally measure the children's *current* daily speech practice with daylong audio recordings collected in their homes to ensure that differences by hearing status are attributable to children's overall speech practice experience, and not just how often they were speaking at home at the time of testing.

We additionally study the relationship between the children's coarticulation and four measures of speech-language practice/ability. The first measure, vocabulary size, is a known predictor of phonetic outcomes, including coarticulation, in preschoolers with and without hearing loss (Bergeson *et al.*, 2003; Cychosz *et al.*, to appear; Edwards *et al.*, 2004; Noiray *et al.*, 2019a): vocabulary size and intra-syllabic coarticulation are negatively correlated in children with NH (see section I A). But children with CIs tend to have smaller vocabularies, at least than their chronological age-matched peers. The auditory deprivation that children with CIs experience pre-implantation also doesn't impede vocabulary growth as much as speech development. Consequently, the predictive nature of vocabulary for phonetic outcomes like coarticulation may differ for children with CIs.

The second speech-language measure that we evaluate is the children's daily speech practice. In our previous work on 4-year-olds with NH, we collected daylong audio recordings in the children's homes and found that children who spoke more throughout the day tended to coarticulate less during in-lab tasks. In the current study, we anticipate replicating this effect of speech practice in children with NH and extending it to children with CIs. However, it is possible that the effect of speech practice in the home may interact with developmental variables, such as vocabulary size or hearing age, in the children with CIs. For example, we may see heightened effects of speech practice in the children with CIs who have smaller vocabularies.

The final two variables studied, articulatory skill and speech discrimination, are new to the study of coarticulation in child speech. We anticipate that children with greater articulatory skill should coarticulate less within the fricative-vowel sequences because these sequences require (1) precise articulatory postures to approximate the fricative, without rendering it a stop or glide, and (2) established motor schemata to transition between the consonant and vowel. Children's articulatory skill should predict both of these abilities. Past work has attempted to control for age-related articulatory skill changes by modeling chronological age as a covariate, but including a diagnostic of articulatory skill, as we do here, may better estimate any effect of preschoolers' articulation upon their coarticulation.

We additionally anticipate an effect of speech discrimination ability upon coarticulation because discrimination and categorization abilities continue to evolve throughout early- and mid-childhood (Hazan and Barrett, 2000). This evolution facilitates the distinction between phonemic contrasts during children's speech production (Lee *et al.*, 1999; Nittrouer *et al.*, 1989). As a result, children with stronger speech discrimination abilities during perceptual tasks may be more adept at articulating differences between fricative contrasts like /s/ and /ʃ/, and between consonants and vowels, like these fricative-vowel sequences, rendering different coarticulation patterns in their speech.

III. METHODS

A. Participants

Participants in this study were 28 children with CIs (16 girls; 12 boys) and 44 children with NH (26 girls; 18 boys). The children with CIs were chronological and hearing age matched using the R package `Matching` (Sekhon, 2011) to two groups of children with NH, controlling for parent-reported gender and socioeconomic status across groups (Table I). All children were monolingual English speakers and were participating in a larger, longitudinal research program studying phonological development and vocabulary growth. To facilitate matching while controlling for the variables across hearing conditions, n=6 children with NH contributed data from two timepoints at which they were studied, two years apart: at approximately age 3 (for hearing age matches) and age 5 (for chronological age matches). An additional n=2 children with NH contributed the same data, from the same time point, to the hearing and chronological age-matched groups.[1] Some of these repeated participant observations were necessary to ensure gender, maternal education, and age balance between the hearing conditions.

The children with NH all passed a hearing screening in at least one ear at 25dB at 1, 2, and 4kHz prior to study participation. Most children with NH had no reported speech or hearing delays, although N=4 caregivers reported that their child was a late talker.[2] The children with CIs had profound deafness in both ears. N=23 children had bilateral CIs, N=4 children had a bimodal device configuration (one hearing aid and one CI), and one child had a unilateral CI. The average age of CI activation was 18.96 months (SD=10.68; range=6-45). See Appendix A for additional audiological information.

Socioeconomic status, interpreted as mother's education level, was reported by the children's caregivers. Maternal education was divided into seven levels to facilitate participant matching: (1) less than high school degree, (2) high school degree equivalent (e.g. General Education Development [GED]), (3) high school degree, (4) technical-associate's degree, (5) some college (2+ years)/trade school, (6) college degree, and (7) graduate degree.

TABLE I. Participant demographic information for matching

	Age(months) M(SD), range	Gender girls, boys	Maternal Education Level M(SD)
Children with CIs (chronological age)[a]	54.66(9.27), 37-72	16, 11	5.81(1.08)
Chronological age matches	54.41(8.61), 37-69	16, 11	5.89(1.05)
Children with CIs (hearing age)	37.20(9.16); 24-56	15, 10	5.96(0.98)
Hearing age matches	37.64(9.33), 28-57	15, 10	5.96(0.98)

[a] After controlling for gender and maternal education, hearing age matches could only be made for 25/28 children with CIs and chronological-age matches for 27/28 children with CIs.

B. Stimuli & Procedure

Target syllables were elicited during a picture-prompted real word repetition task that each child completed. Target sequences were [ʃ-V] and [s-V], balanced for vowel backness by place of articulation (see Appendix B for stimuli list). Syllable targets always fell in stressed, word-initial position. We chose to measure coarticulation within fricative-vowel sequences because the majority of past research on child coarticulation also used this phonetic environment. Furthermore, coarticulation measures are sensitive to segmentation decisions and fricative offsets/vowel onsets are relatively objective.

The lexical stimuli were selected from lists such as the "Toddler Says" portion of the MacArthur Bates Communicative Development Inventory (Fenson *et al.*, 2007), to ensure familiarity to children in this age range. The decision was made to analyze real words instead of nonce words or syllables, even though nonce items were also collected in a separate task, because the children with CIs often could not repeat a sufficient number of correct nonce tokens. For similar reasons, we decided to conduct a word repetition task, instead of only prompting the children with pictures.

Two young, female, native speakers, one a speaker of African American English and another of Mainstream American English, recorded the word stimuli for the tasks. Stimulus recordings were digitized at a sampling rate of 44.1 kHz with a Marantz PMD671 solid-state recorder. Stimulus items were normalized for amplitude. The accompanying visual stimuli were color photographs of the objects.

At least two experimenters guided each child through the word repetition task. All in-lab tasks were completed at the University of Wisconsin, Madison or the University of Minnesota, Twin Cities. Children received the task in their native dialect (N=1 speaker of African American English who contributed data to the hearing age condition (at age 2;5) and chronological age condition (at age 5;4) and N=71 speakers of American English spoken in the Midwest). For the task, the child was seated in front of a computer screen and presented with a photo and accompanying audio stimulus over external speakers which the child was instructed to repeat. Children were encouraged to respond on the first trial, though we analyzed second or third repetitions if the child whispered, shouted, or produced the first repetition incorrectly. First repetitions comprised 99.46% of the words produced by children with CIs, 98.09% of the words produced by chronological age matches, and 97.31% of the words produced by hearing age matches. After each trial, the experimenter manually advanced to the next trial. Stimuli were presented in a different random order for each child using E-prime software (Schneider *et al.*, 2012). The task lasted approximately 20 minutes.

Participants additionally completed a series of standardized speech-language assessments (descriptive statistics listed in Table IV in Results). Vocabulary size was measured with the Expressive Vocabulary Test, 2nd edition (EVT-2) (Williams, 2007). For this task, participants were presented with an image that they had to name or provide a synonym for. N=2 participants, one child with CIs and one chronological age-matched child, did not complete the vocabulary test. Consonant articulation skill was assessed with the Goldman-Fristoe Test of Articulation-Second Edition (GFTA-2) (Goldman and Fristoe, 2000) where singleton consonants in words (initial, medial, and final position) and consonant clusters in words (initial position) were elicited from children from image prompts. N=6 participants, 3 chronological age-matches and 3 hearing age-matches, did not complete the articulation task.

Speech discrimination was measured using a two-alternative forced-choice minimal pair task that assessed 15 minimal pairs (see Appendix C for stimuli list). For each trial, two images depicting words with confusable contrasts were presented side-by-side (e.g. *peas* and *keys*) while the target audio stimulus for one item played. Children then pointed to the correct image and responses were automatically scored (+/- correct). The proportion of trials correct was used in the statistical modeling. To control for vocabulary knowledge and word-picture matching skills, we presented each picture one at a time with the accompanying auditory stimulus prior to the discrimination component. Speech discrimination was not assessed in the older, chronological age-matched children. An additional n=8 hearing age-matched children did not complete the task; all children with CIs completed it.

Finally, participants completed one at-home, daylong audio recording using the Language ENvironment Analysis (LENA) system (Greenwood *et al.*, 2011). For the recording, children wore a small (2"x3") digital language processor, similar to a small audio recorder, inside of a specialized vest pocket throughout an entire day (up to 16 hours). Children's caregivers were instructed to turn the recorders on in the morning when the child awoke and record throughout a typical day. LENA's proporiety diarization algorithm then tracked how frequently the child vocalized throughout the recording. At-home recordings were not collected from chronological-age matches so results with this variable are only reported for the children with CIs and their hearing age matches. N=3 children with CIs and n=7 hearing age matches did not complete an at-home recording. Additionally, the at-home recordings from n=5 children with CIs were excluded, as these recordings were completed more than 3 months after the in-lab testing procedures. This left a total of n=20 recordings from children with CIs and n=17 from the hearing age matches. From the remaining at-home recordings, we computed the average number of child vocalizations per hour by dividing the total number of child vocalizations by the length of the audio recording, in hours. The children with CIs' recordings were an average of 15.81 hours long (SD=0.42, range=14.42-16) and the hearing age matches were an average of 15.49 hours (SD=0.76, range=13.66-16).

C. Acoustic Analysis

Recordings from the word elicitation task were segmented into Praat TextGrids (Boersma and Weenink, 2020), force-aligned to the phone level (McAuliffe *et al.*, 2017), and then hand-checked by one of two trained phoneticians, both native speakers of American English. Hand-checking was carried out using the visual representation from the waveform and spectrogram and auditory analysis. To ensure uniform measurement between children, only words repeated entirely correctly were selected to undergo acoustic analysis. This was necessary to ensure uniform measurement over each consonant and vowel pair between children. Items that were yelled or produced with a breathy voice were additionally removed as it was not possible to measure their coarticulation. At this point, data from one child with NH (a hearing age match) was removed entirely from analysis, as the child repeated less than 50% of the words correctly. Overall, from the remaining participants, acoustic analysis was performed on 84.87% of potential words available for use produced by children with CIs;

95.47% of words from chronological age matches; and 86.88% of words from hearing age matches. The larger percentage of missing data from the hearing age matches is anticipated given their younger age.

Acoustic measures are sensitive to segmentation decisions so we set a number of alignment conventions. The onset and offset of fricatives corresponded to the presence of high-frequency energy in the spectrogram. Vowel offset/glide onset was delimited at the steady state formant. When no steady-state formant was identifiable, the sequence was equally divided between the glide and the vowel. Vowel onset was marked by periodicity and formant structure in the waveform and spectrogram. The start of the first consonant in the second syllable of each word marked the vowel offset. In the case of second syllables that began with plosives, the lack of formant structure and closure marked vowel offset. For second syllables with nasal onsets, the presence of antiformants marked vowel offset. And for second syllables with fricative onsets, a concentration of high-frequency energy in the spectrogram marked vowel offset.

The second phonetician independently re-aligned an approximately 10%-subset of the first phonetician's alignments. The difference between average CV duration in the target sequences was 20.18 ms. The average difference in target vowel duration was 10.24 ms. Pearson correlations between the coders' measurements were strong and significant: CV sequences: $r=0.89$: $p<.001$, 95% CI=[0.83, 0.93] and vowels: $r=0.92$ $p<.001$, 95% CI=[0.88, 0.94], suggesting high fidelity to the coding conventions.

Coarticulation is often measured acoustically using formant transitions or, for high-frequency sounds, the center of gravity or Peak $\mathrm{ERB_N}$. Previous work in this research program has instead used a measure of acoustic distance, which is suitable for all manners of articulation: the Euclidean distance between averaged Mel-frequency log-magnitude spectra from adjacent phones, henceforth the Mel spectral distance. For this measure, calculated automatically using Librosa packages (McFee *et al.*, 2015), each phone is segmented into 25.6 ms frames, with a 10 ms step, and the ensuing spectra of each phone are averaged. Coarticulation is the Euclidean distance between the Mel spectral vectors averaged over adjacent phones (e.g. [s-V]) (see Cychosz *et al.* (2019); Gerosa *et al.* (2006) for detail).

IV. RESULTS

The primary objective of this study is to examine whether auditory feedback experience drives children's coarticulatory development. The results compare a cross-sectional sample of children with CIs of differing hearing ages to cohorts of their hearing and chronological age-matched peers. Should we see an effect of hearing age on the children with CIs' coarticulation, but not an effect of chronological age; and should the children with CIs resemble their hearing age-matched peers more than chronological age-matched peers, this would suggest that the absence of early auditory feedback has affected the children's phonetic development. On the other hand, there may be a greater effect of chronological age than hearing age, and/or the children with CIs may pattern more like their chronological age-matched peers. Either of these results would suggest that the children with CIs have been able to compensate for the absence of auditory feedback.

All analyses were conducted in the RStudio computing environment (version: 1.3.1073; Team 2020). Data visualizations were created with `ggplot2` (Wickham, 2016). Coarticulation modeling was conducted using the `lme4` (Bates *et al.*, 2015) and `lmerTest` packages (Kuznetsova *et al.*, 2017). The significance of potential model parameters was determined using a combination of log-likelihood comparisons between models, AIC estimations, and p-values procured from model summaries. In all models, continuous predictors were mean-centered to facilitate model interpretation. Code to replicate these analyses can be found in the Github repository associated with this work (`https://github.com/megseekosh/ci_feedback`).

A. Results by hearing age and hearing condition

We first computed coarticulation, or the Mel spectral distance between phones, by hearing status, within each target CV sequence, where a larger distance indicates less coarticulatory overlap. Descriptive statistics in Table II show differences in coarticulation by hearing status: children with CIs coarticulate more within [s-V] and [ʃ-V] sequences than both groups of children with NH. A linear mixed effects model was fit to predict the Mel spectral distance between phones in each target CV sequence (model summary in Table III). The baseline model included random effects for **Word** and **Speaker**. **Word duration** was additionally added to control for the effect of speaking rate on coarticulation and **Child Chronological Age** was added to control for age-related changes in coarticulation unrelated to the other variables of interest. The effect of **Hearing Status** improved upon this model fit: children with CIs coarticulated significantly more within CV sequences than their chronological age-matched peers. They tended to coarticulate more than their hearing age matches as well (Figure 2), but this effect was not significant under an alpha value of .05, suggesting that children with CIs pattern coarticulatorily closer to their hearing age matches. Neither **Place of Articulation** ([s] versus [ʃ]) nor its interaction with **Hearing Status** improved upon model fit.

TABLE II. Spectral distance between C-V by hearing status and consonant

	Spectral distance	
Hearing status	[s-V]	[ʃ-V]
Chronological age matches	11.95 (4.26) 2.15 - 30.24	11.9 (3.46) 3.11 - 31.81
CIs	10.93 (2.95) 5.46 - 29.15	10.95 (3.4) 2.64 - 30.1
Hearing age matches	11.92 (3.98) 6.32 - 29.27	11.48 (3.8) 5.6 - 28.77

We next evaluated the role of hearing versus chronological age upon the children with CIs' coarticulation. A linear mixed effects model, with random effects of **Word** and **Speaker** and a fixed effect of **Word duration**, was fit to predict the degree of coarticulation for the children with CIs. There was a significant effect of **Hearing Age** (β=0.04, t=2.03, p=0.05), but not **Chronological Age** (model comparison with and without **Chronological age**: χ^2=0.88, df=1, p=0.35). **Hearing Age** and **Chronological Age** are highly correlated and so they were fit sequentially in the models. This result indicates that it was the children with CIs' increased *hearing* experience, and not other chronological age-related maturity such as physiological development or domain general fine motor control, that best predicted

TABLE III. Model predicting Mel spectral distance by hearing status

Intercept	10.86***
	(8.64, 13.09)
	t = 9.57
	p = 0.00
Hearing age matches	0.83
	(−0.18, 1.85)
	t = 1.61
	p = 0.11
Chronological age matches	0.90*
	(0.09, 1.72)
	t = 2.18
	p = 0.03
Child chronological age	0.003
	(−0.03, 0.04)
	t = 0.15
	p = 0.89
Word duration	1.97
	(−0.09, 4.03)
	t = 1.87
	p = 0.07
Log Likelihood	−3,082.78
Akaike Inf. Crit.	6,181.55
Bayesian Inf. Crit.	6,222.02
Note:	*p<0.05; **p<0.01; ***p<0.001

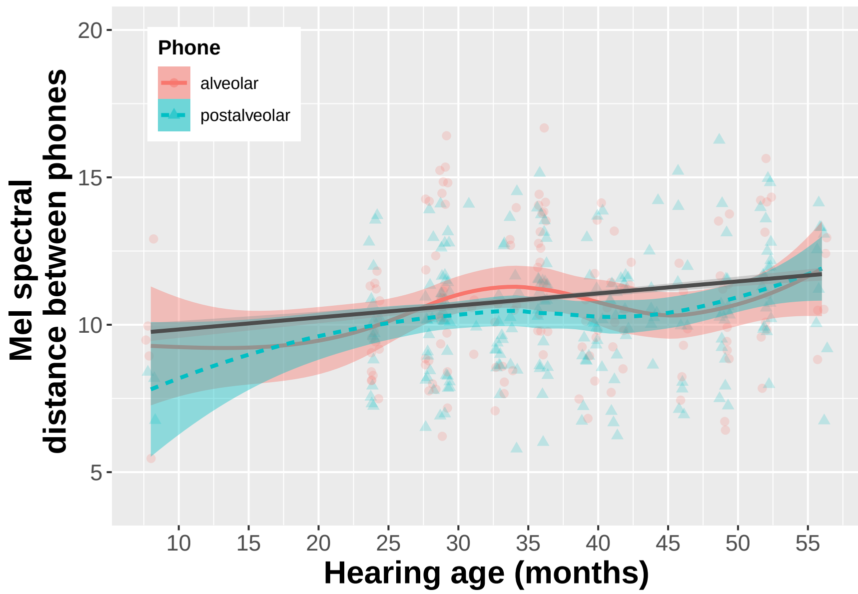

FIG. 1. CV coarticulation (spectral distance between phones) by hearing age in children with CIs. Colored points and local regression lines represent original data. Dark gray linear regression line represents predicted model values. In both cases, ribbons represent 95% confidence intervals.

the degree of their coarticulation (Figure 1). There was again no significant effect of **Place of Articulation**.

B. Additional predictors of coarticulation

To further evaluate the role of hearing status on coarticulation, we examined the interaction of hearing status with two known predictors of child coarticulation—vocabulary size (EVT-2) and speech practice at home (average number of times per hour that the child vocalized in their at-home recording)—and two novel measures that we anticipated might predict coarticulation: articulation skill (GFTA-2) and minimal pair discrimination ability. Descriptive statistics of these predictors by hearing status are listed in Table IV. Note that it is not anticipated that the children with CIs will match to the children with NH along these metrics as they have less experience. For the vocabulary scores, we report growth scale values, which are transformations of raw scores that grow linearly with age. For the articulation scores, we report standard scores that are normalized for child sex and age.

TABLE IV. Task statistics by hearing status

	Hourly voc. count	EVT-2 GSVs	EVT-2 Standard Score	GFTA-2 Standard Score	Discrim. prop. correct
Hearing status	mean (SD) range	mean (SD) range	mean (SD) range	mean (SD) range	mean (SD) range
Chronological age matches	NA	146.31 (11.94) 126-165	122.81 (16.42) 90-151	95.29 (13.59) 69-113	NA
CIs	248.7 (89.15) 50.12-387.33	117 (25.69) 42 - 148	94.69 (20.48) 43-126	70.78 (18.47) 39-104	0.69 (0.15) 0.38-0.97
Hearing age matches	213.86 (95.13) 31.25-376.25	126.21 (18.99) 85-160	119.42 (18.98) 84-160	88.57 (12.96) 73-116	0.69 (0.15) 0.43-0.93

As before, we followed a forward-building model procedure to predict coarticulation within CV sequences with a baseline model containing random effects of **Speaker** and **Word** and fixed effects of **Word duration** and **Chronological Age**. As only the children with CIs and their hearing age matches completed LENA recordings and the minimal pair discrimination task, models evaluating **Hourly Child Vocalization Count** and the **Minimal Pair Discrimination Ability** only include those children. We did not find effects of **Articulation Skill** or **Minimal Pair Discrimination Ability**, or their interaction with hearing condition, upon children's coarticulation, so we excluded those variables from further analysis. For models with vocabulary size, the interaction of **Vocabulary Size** with **Hearing Status** improved upon the baseline model fit, indicating that the relationship between expressive vocabulary and coarticulation varied by hearing group (Figure 2). There

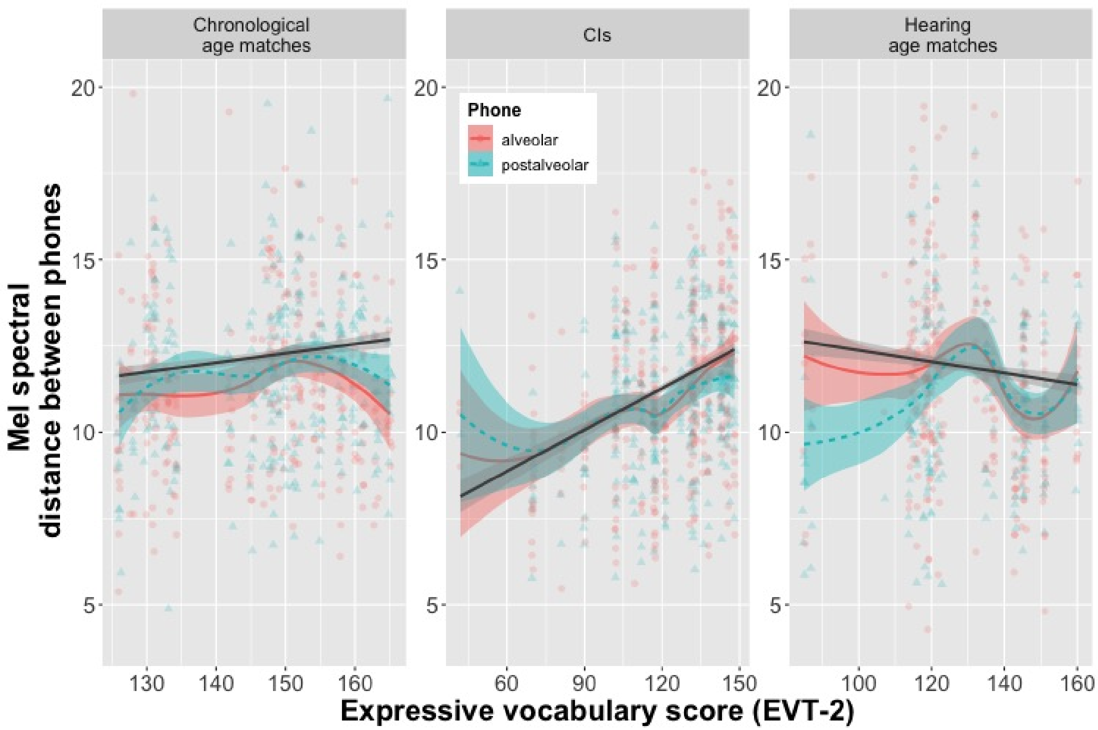

FIG. 2. CV coarticulation (spectral distance between phones) by expressive vocabulary score (EVT-2) and hearing status. Colored points and local regression lines represent original data. Dark gray linear regression line represents predicted model values. In both cases, ribbons represent 95% confidence intervals. Note the free scale on the x-axis.

was a significant, positive relationship between expressive vocabulary and degree of coarticulation for the children with CIs (EVT-2 score: β=0.03, t=2.13, p=0.04), but no reliably significant effects of vocabulary on coarticulation for either group with NH, perhaps due to their limited vocabulary score ranges. We elaborate upon this result in the Discussion.

Hourly Child Vocalization Count from the LENA recordings did not improve upon the baseline model: there was no effect of daily speech practice upon the degree of coarticulation for children with CIs or their hearing age-matched peers. This null result was unexpected given the effect of child vocalization frequency upon coarticulatory development that we found in our previous work on 4-year-olds with NH. For the children with NH in this study, we hypothesize that the null result could stem from a limited number of hearing age matches or from the smaller range of hourly child vocalizations, a point that we return to in the Discussion.

For children with CIs, we hypothesized that there could be another source of the null result. Post-implantation, it may take time to learn to incorporate self-auditory feedback into speech routines and, as such, we might not see an effect of vocal output frequency upon speech production outcomes immediately or even several months after implantation. We explored this idea by performing a median split upon the children with CIs by their hearing age (median hearing age = 36 months). We then fit the model as before but with the interaction of the binary variable **Hearing Age Group** (<>35 months hearing experience) and **Hourly Child Vocalization Count**. (Models with the **Hearing Age Group** parameter did not include **Chronological Age** as the parameters are not independent.) While the **Hearing Age Group*Hourly Child Vocalization Count** interaction was not significant in the model, **Hourly Child Vocalization Count** was significant with the reference level "> 35 months hearing experience" (β=0.01, t=2.2, p=0.045), but not significant with the reference level "<= 35 months hearing experience," indicating that the effects of vocal output upon degree of coarticulation tend to appear in the children with more than three years hearing experience, but not children with less than three years experience.

V. DISCUSSION & CONCLUSION

This study measured the coarticulation patterns of a cross-sectional cohort of children with CIs and their hearing and chronological age-matched peers to evaluate if auditory feedback could explain the relationship between speech practice and phonetic development. We found several pieces of evidence suggesting that auditory feedback does play such a role. First, among the children with CIs, results showed a negative relationship between degree of coarticulation and hearing age, but no relationship with chronological age, articulation ability, or phonemic discrimination ability. Second, children with CIs coarticulated more overall than their hearing and chronological age-matched peers, but differed significantly only from the chronological age matches, suggesting that hearing experience was more important for coarticulatory outcomes than age-related maturity. Finally, an exploratory median split analysis conducted over the children with CIs suggested that the effect of speech practice on coarticulation outcomes may take years post-implantation to manifest.

A. Differences by hearing condition

We predicted that if the children with CIs patterned like their chronological age-matched peers, this would indicate that they were able to compensate for the absence of auditory information pre-implantation and/or that age-appropriate coarticulation can develop somewhat independently of auditory feedback experience. The fact that the children with CIs patterned closer to their hearing age-matched peers suggests that auditory feedback—from caregiver input and the children's own vocalizations—is important for age-appropriate coarticulatory development and that the absence of this feedback mechanism may inhibit typical phonetic development, at least for a time. Without the ability to (1) establish robust acoustic-auditory categories from caregiver language spoken around them and then (2) compare their own vocal output to those early acoustic-auditory categories (Guenther, 2006), children with reduced auditory feedback experience are unable to update their speech-motor commands resulting in immature phonetic development.

Although the children with CIs patterned closest to their hearing age matches, they still coarticulated more than them. Why might children with CIs coarticulate this much? First, it is important to stress that the children with CIs only *tended* to coarticulate more than the hearing age matches: our modeling did not show a significant effect of hearing status between the two groups. Nevertheless, this trend by hearing condition warrants exploration. The children with CIs were matched to their hearing age matches by auditory feedback experience, but as discussed in Section II, the two groups differed along other dimensions. For example, the children with CIs were chronologically older so they had more somatosensory experience than the hearing age matches (although this increased experience is unlikely to explain why the children with CIs would coarticulate *more* than the hearing age matches). For similar reasons, the children with CIs also likely had more established audiovisual synchrony abilities than their hearing age matches (Bergeson *et al.*, 2003). But again, this increased experience does not predict that the children with CIs would coarticulate more than the hearing age matches.

At least two explanations remain for the phonetic differences between the children with CIs and their hearing age matches. Most obviously, even post-implantation children with

CIs experience a degraded audio signal: electrical hearing breaks spectral information into channels and information about spectral distinctions within each channel is lost. The current spread across electrodes distorts the signal further. High-frequency spectral contrasts—such as /s/ and /ʃ/—are especially impacted. (And the current study measured coarticulation within [s-V] and [ʃ-V] sequences.) Thus, although the children with CIs were hearing age-matched to the children with NH, the two groups still had distinct auditory feedback experiences.

Another explanation for the heightened coarticulation of children with CIs could be the differing language learning environments of children with and without CIs. For one thing, since the children with CIs are chronologically older than their hearing aged peers, their caregivers could use a less child-directed speech register (Liu *et al.*, 2009). Among other consequences, this could mean that some phonemic contrasts are less distinguished in the children's input (Cristia and Seidl, 2014). Additionally, recent research suggests that, compared to children with NH, children with hearing loss, and those fitted with CIs in particular, hear fewer conversational turns and fewer words from adult caregivers in their environments (Ambrose *et al.*, 2015; DesJardin and Eisenberg, 2007; Dilley *et al.*, 2020; Holt *et al.*, 2012; Kondaurova *et al.*, 2020). These patterns may continue post-implantation as families of children with severe hearing loss maintain early-established communicative patterns (Nittrouer *et al.*, 2019). Children who hear less speech in their environments, and engage in fewer turns with adult caregivers, have less exposure to adult-like speech models, including the auditory-acoustic categories that are supposed to form the basis for phonemic categorization. Furthermore, since they are interacting with caregivers less, children with CIs may have less opportunity to vocalize and integrate self-auditory feedback into their speech-motor routines. Thus, another explanation for the heightened degree of coarticulation in the children with CIs' speech could be quantity and quality of adult language around them.

B. Practice effects

The primary motivation for this work was to evaluate if the auditory feedback children experience as they vocalize could explain the previously documented speech practice effect (vocalization frequency) on coarticulatory development (Cychosz *et al.*, to appear). Consequently, it is important to acknowledge that we only replicated the relationship between vocalization frequency and coarticulation for the children with CIs who had three or more years of hearing experience. We did not replicate the finding at all in the subset of children with NH who completed daylong recordings. We attribute the null finding in the children with NH to differences between this NH population and the population previously studied: the children with NH who completed recordings in this study were (1) younger (M=33 months [SD=3.05] compared to M=44.86 months [SD=3.57] previously studied), (2) smaller in number (n=18 participants compared to n=80 previously studied), and (3) produced a smaller range of vocalizations in their recordings (31.25-376.25 vocalizations versus 12.1-495.8 in the group previously studied). Nevertheless, going forward it will be important to try to replicate the results of Cychosz *et al.* in children with NH.

For the children with CIs, we believe that there are straightforward explanations for why the effects of vocalization frequency upon phonetic outcomes do not manifest until several years post-implantation. First, auditory feedback comes not just from infants' and children's own vocal play, but in response to stimulants in the environment (a caregiver cooing to an infant or posing a question to a toddler). But for the families of children with CIs, it takes time to establish parent-child communicative routines post-implantation (Kondaurova *et al.*, 2020). Second, auditory feedback experience builds upon itself, over time, in development. For example, as consonants emerge in the speech of infants with NH, the infants begin to pay attention to consonants in the ambient speech signal that they are not yet producing which encourages their phonological repertoires to further expand (DePaolis *et al.*, 2011). Another example of the cumulative effects of auditory feedback comes from infants with CIs who rarely produce repetitive vocalizations pre-implantation, but quickly acquire this skill post-implantation (Fagan, 2014). Consonant emergence and repetitive babbling are major milestones in early phonological development—where the effects of auditory feedback experience can quickly be observed. Other low-level phonetic outcomes, like we studied here, may be slower to incorporate feedback which could explain why the effects of vocalization frequency take time to emerge.

It should be noted that we only uncovered the effects of vocalization frequency upon coarticulation for the children with CIs during a post-hoc exploration of the data, by conducting a median split over those children based on hearing age. We did not attempt to fit a function to explain the relationship between hearing age, vocalization frequency, and coarticulation. So we do not make unequivocal statements about the developmental timecourse of a relationship between vocalization frequency and coarticulation, that it will only manifest after 36 months hearing experience for example. We instead conclude that the effects of vocal and speech practice may take several years to manifest in phonetic outcomes.

C. Implications

The children with CIs in this study had an average hearing age of 37.64 months (range=28-57), and relatively young average age of CI activation (18.96 months, range=6-45)—a crucial predictor of speech-language outcomes for pediatric CI recipients (Niparko *et al.*, 2010). Thus, finding that children with CIs, with this amount of hearing experience, have not attained age-appropriate speech development has numerous implications. First, it is well known that the speech intelligibility of children with NH improves with age (Hustad *et al.*, 2020). It is unknown how well the coarticulation measure that we used correlates with speech intelligibility, but this coarticulation measure is clearly an indicator of speech clarity and speech motor skill more broadly. The lack of clarity in the speech of these children with CIs could pose some problems for communication. Poor speech intelligibility in a three-year-old (with NH) is anticipated, and adults have even been shown to modify their speech to accommodate young children's perceived phonetic ability (Julien and Munson, 2012). However, that same degree of unintelligibility in a five-year-old child, who happens to have CIs, may appear exceptional to an adult interlocutor who does not anticipate that level of speech immaturity in an older child. This could render child-adult communication difficult, only exacerbating tendencies for children with hearing loss to be exposed to less speech from adult models in their environments (Ambrose *et al.*, 2015; DesJardin and Eisenberg, 2007; Dilley *et al.*, 2020; Holt *et al.*, 2012; Kondaurova *et al.*, 2020).

Another implication of these findings concerns the classification of children's speech throughout development. Speech production tends to be measured by what sounds children can produce correctly, especially for pediatric speech sound disorders. However, results from this work and others suggest that phoneme production accuracy should not be the only way to evaluate speech development. For example, previous work has shown that even years post-implantation, children with CIs are less intelligible, distinguish less reliably between consonant contrasts, and speak slower than NH peers (Allen *et al.*, 1998; Flipsen, 2008; Freeman and Pisoni, 2017; Reidy *et al.*, 2017; Tobey *et al.*, 2003). With the amount of hearing experience that the children with CIs in this study had, their speech errors tend not to be phonemic in nature anymore, but instead sub-phonemic, demonstrating the importance of moving beyond binary [+/- correct] distinctions. The fact that articulatory ability (GFTA-2) did not predict individual differences in children's coarticulation in this study is further evidence of this. Finding that a diagnostic test like the GFTA-2 does not predict coarticulation does not mean that articulatory maturity or fine motor control do not matter for spoken phonetic outcomes—they clearly do. Rather, this finding demonstrates how subtle differences in motor control may go unnoticed in broader tests. A test that involves categorical distinctions cannot capture some of children's less skilled, sub-phonemic productions.

Finally, finding that the children with CIs patterned more closely to their hearing age matches suggests that, for all children, speech intelligibility improves with auditory feedback, not just physiological maturation. So pediatric guidelines which currently encourage parents to talk to their children to facilitate phonological, lexical, and perceptual development (LoRe *et al.*, 2018), may need to be expanded to encourage caregivers to talk to their children to *elicit* speech. Turn-taking between caregivers and their children, above and beyond the quantity of adult speech that children hear, may be crucial for the development of mature speech production. This guideline may be especially pertinent for caregivers of children with limited early auditory feedback experience.

D. Interactions with the developing lexicon

This work additionally explored the interaction of vocabulary size and hearing status upon coarticulation since previous work has found a negative relationship between vocabulary size and the degree of intra-syllabic coarticulation in children with NH (Cychosz *et al.*, to appear; Noiray *et al.*, 2019a). There were strong effects of vocabulary size upon the children with CIs' coarticulation, extending previous findings made on children with NH to a new population. This finding has implications for theorists and clinicians alike. First, it suggests that auditory deprivation—the early absence of self auditory feedback and adult speech models—does not inhibit children post-implantation from growing a lexicon, making generalizations over it, and then reflecting those generalizations in phonetic output (Faes and Gillis, 2016). Second, for clinicians, the developing lexicon is a strong predictor of speech, language, and literacy outcomes, for children with and without hearing loss (Metsala and Walley, 1998; Nittrouer *et al.*, 2016; Storkel and Morrisette, 2002). Consequently, clinicians may note that the widespread phonetic and phonological gains stemming from lexical growth, reported for children with NH, may apply to children with CIs as well.

Although we documented a robust effect of vocabulary size upon the children with CIs' coarticulation, and a trend in the same direction for the chronological age matches, vocabulary was not predictive of coarticulation for the hearing age matches. It is possible that the null effect stems from several of the same participant demographic differences previously outlined (smaller number of children studied, reduced range of vocabulary scores). However, we hypothesize that the role of vocabulary upon phonetic outcomes, particularly outcomes like fricative-vowel coarticulation that require precise articulatory configurations and coordinated lingual-labial gestures (for /ʃ/), might only emerge in older children with a minimum level of articulatory maturity. Past results that found effects of vocabulary size on coarticulation were made either on older children aged 4;6-7;2[3] (the majority of whom were 7-years-old) (Noiray *et al.*, 2019a), or 3;3-4;4 (Cychosz *et al.*, to appear). The hearing age matches here, however, were an average of 3;2 (SD=0;9). We could thus be unearthing a floor effect where effects of the lexicon on phonetic development first require that children reach certain milestones in physiological and/or articulatory development.

We tested this idea by evaluating the interaction of vocabulary size and articulatory skill (GFTA-2 score) upon coarticulation in the hearing age matches. But our exploratory analysis did not reveal an interaction between these factors for coarticulation. This result does not mean that baseline articulatory skills aren't prerequisites for lexical-phonetic effects, and it does not mean that a certain amount of physiological immaturity doesn't explain the results; the GFTA-2 is just one metric of articulatory skill. Future work will clearly be needed to unearth the exact timecourse of the relationship between the lexicon and coarticulation in children's speech as it does not manifest for the youngest children studied here.

E. Future work

Future work on this topic could go in several directions. Additional phonetic outcomes, beyond coarticulation, should be studied in children with CIs' speech as the effects of hearing age and hearing status may vary by outcome (Faes and Gillis, 2016; Reidy *et al.*, 2017). For example, vowel space development may rely even *more* on auditory feedback since many distinct vocal tract configurations can result in similar vocalic output. In that case, for vocalic development, we would expect to see children with CIs pattern even more closely to their hearing age-matched peers than they did for coarticulation. It would likewise be interesting to study these patterns in older children. Since adults and young children coarticulate for different reasons, work with older children could establish when young speakers start coarticulating for adult-like reasons (e.g. reflecting speech planning or lexical statistics).

Another interesting direction for future research would be to compare anticipatory coarticulation patterns by place of vowel articulation in children with CIs and NH. In adult speech, it is well known that consonants exhibit assimilatory effects to adjacent vowels: for example, peak F2 frequencies in fricatives are lower in the sequences [su] and [ʃu] than [si] and [ʃi] (Soli, 1981). Exploratory work in our lab, however, is now showing that younger children, and children with CIs, distinguish less between the fricatives in sequences like [ʃi] and [ʃu] than older children with NH. This "true" coarticulation, where the place of vowel articulation exerts pressure on surrounding consonants, is thus distinct from that reported in most of the child speech literature (Barbier *et al.*, 2020; Nittrouer *et al.*, 1989; Noiray *et al.*, 2019a,b; Zharkova *et al.*, 2011): the underlying causes are distinct and the developmental trajectory differs. "True" coarticulation, for example by place of vowel articulation, would then be a phenomenon that a child must acquire, with age and experience. This would be an interesting developmental phenomenon to study in child speech.

Finally, while this work did not find an effect of children's minimal pair discrimination ability upon coarticulation, this cannot rule out effects of perceptual skill. More fine-grained, sub-phonemic perceptual measures and/or those that take into account response time, might relate to spoken coarticulation. For example, future research could study the potential link between children's spoken coarticulation and their perceptual compensation for coarticulation (Mann, 1980). Are children who coarticulate less in their own speech also better at compensating for coarticulatory patterns, for example in caregiver speech? Researchers interested in this perception-production connection may need to determine a causal mechanism experimentally, however, as there are reports that overall children compensate for coarticulation less than adults (Harrington *et al.*, 2016).

In this study, we elicited words in a repetition task which could result in imitation effects after the model speaker. In this experimental design, where we compare between children but not stimulus items, we are less concerned about potential imitation effects. But other researchers interested in comparing across segment types or individual stimulus items should consider alternatives to word repetition tasks.

In conclusion, this work studied the potential effect of auditory feedback upon spoken coarticulation by comparing the patterns of children with CIs and their hearing and chronological age-matched peers. Overall, children with CIs coarticulated more than children with NH, but patterned most closely to their hearing age-matched peers. We additionally found a negative relationship between children with CIs' hearing age and the degree of their coarticulation. We found no effects of children's articulatory or perceptual skill upon coarticulation in any of the children. Finally, the effects of vocalization frequency on coarticulation, which we were only able to replicate in the children with CIs and not their hearing age-matches, only manifested after several years of hearing experience. Combined, these results suggest that the auditory feedback experienced during vocal output predicts children's coarticulatory outcomes, independent of age-related maturity. In doing so, this work has used data from a population with unique auditory experiences, children with CIs, to shed light on the processes underlying phonetic development.

ACKNOWLEDGMENTS

The authors thank the children and their families for participating in this research. Additional thanks to many members of the Learning to Talk Labs at the University of Wisconsin, Madison and the University of Minnesota, Twin Cities for their help collecting data and to Michele Liquori for help processing the data. This work was supported by National Institute on Deafness and Other Communication Disorders grants T32DC000046 (M.C.) and R01DC02932 (J.R.E., B.M., and Mary E. Beckman).

APPENDIX A:

TABLE V. Audiological information from children with cochlear implants

Participant	Chronological Age	Age at hearing loss	Age at CI activation	Etiology	Device configuration	Activation
808E37FS1	37	0	6	Genetic	Bilateral	simultaneous
308E37FS1	37	0	13	Genetic	Bilateral	simultaneous
803E41FS1	41	0	34	Unknown	Bimodal	n/a
806E42MS1	42	14	34	Genetic	Unilateral	L
307E44MS1	44	0	15	Genetic	Bilateral	R-L
304E48FS2	48	0	12	Genetic	Bilateral	R-L
306E49FS2	49	0	8	Unknown	Bilateral	R-L
302E49FS2	49	0	13	Unknown	Bilateral	R-L
314E50FS2	50	10	17	Unknown	Bilateral	R-L
310E51FS2	51	unknown	23	Genetic	Bilateral	simultaneous
807E51MS2	51	10	22	Mondini malformation	Bimodal	n/a
801E50MS2	51	1.5	15	Unknown	Bilateral	simultaneous
665L52FS4	52	0	12	Genetic	Bilateral	R-L
608L52FS4	55	0.5	9	Connexin 26	Bilateral	simultaneous
605L55MS5	55	0	16	Unknown	Bimodal	n/a
804E56MS2	56	0	7	Genetic	Bilateral	simultaneous
305E56FS2	56	0	22	Unknown	Bilateral	R-L
300E57MS2	57	0	13	Genetic	Bilateral	simultaneous
312E57FS2	57	0	24	Genetic	Bilateral	R-L
679L58MS6	58	0	29	Genetic	Bimodal	n/a
309E59MS2	59	0.5	7	Genetic	Bilateral	simultaneous
311E62MS2	62	9	13	Unknown	Bilateral	L-R
809E64MS2	64	6	8	Meningitis	Bilateral	R-L
800E65MS2	65	30	37	Genetic	Bilateral	simultaneous
303E65FS2	65	6	13	Unknown	Bilateral	simultaneous
805E68MS3	68	24	34	Unknown	Bilateral	R-L
301E69FS3	69	0	45	Unknown	Bilateral	R-L
802E72FS3	72	3	30	Unknown	Bilateral	L-R

APPENDIX B:

TABLE VI. Stimuli used in word elicitation task

Stimulus
sandwich [ˈ**sæ**ndwɪtʃ]
scissors [ˈ**sɪ**zɚz]
share/sharing [ˈ**ʃe**ɹ]/[ˈ**ʃe**ɹɪŋ]*
sheep [ˈ**ʃi**p]
shoe/shoes [ˈ**ʃu**]/[ˈ**ʃu**z]
shorts [ˈ**ʃo**ɹts]
shovel [ˈ**ʃʌ**vl]
shower [ˈ**ʃaʊ**ɚ]
sick/sink [ˈ**sɪ**k]/[ˈ**sɪ**nk]
soup [ˈ**su**p]
sun [ˈ**sʌ**n]

* Where two words are noted, the item left of the slash was elicited from children 48 months and younger and the item right of the slash was elicited from children older than 48 months.

APPENDIX C:

TABLE VII. Stimuli used in speech discrimination task

Contrast	Type of contrast	Words
/b ∼ k/	consonant	bee - key
/b ∼ p/	consonant	big - pig
/k ∼ dʒ/	consonant	car - jar
/tʃ∼ k/	consonant	cheese - keys
/k ∼ h/	consonant	cold - hold
/g ∼ dʒ/	consonant	goose - juice
/h ∼ p/	consonant	hen - pen
/dʒ∼ m/	consonant	juice - moose
/k ∼ p/	consonant	keys - peas
/s ∼ θ/	consonant	mouse - mouth
/k ∼ t/	consonant	sick - sit
/l ∼ w/	consonant	sleep - sweep
/ɔɹ∼ aʊ/	vowel	horse - house
/u ∼ aʊ/	vowel	moose - mouse
/ɑɹ∼ ɔɹ/	rhotic vowel	star - store

APPENDIX D:

TABLE VIII. Effect of hearing status and vocabulary on Mel spectral distance

Intercept	11.35^{***}
	(10.38, 12.32)
	t = 22.89
	p = 0.00
EVT-2 score	0.03^{*}
	(0.002, 0.05)
	t = 2.13
	p = 0.04
Chronological age matches	0.21
	(−0.93, 1.35)
	t = 0.36
	p = 0.72
Hearing age matches	0.45
	(−0.68, 1.59)
	t = 0.79
	p = 0.44
Child chronological age	0.003
	(−0.04, 0.05)
	t = 0.15
	p = 0.89
Word duration	1.97
	(−0.10, 4.04)
	t = 1.86
	p = 0.07
EVT-2 score*Chrono age match	−0.004
	(−0.06, 0.05)
	t = −0.14
	p = 0.89
EVT-2 score*Hearing age match	-0.04^{*}
	(−0.09, −0.005)
	t = −2.19
	p = 0.03
Note:	$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

[1] All reported results were replicated with the repeated child observations removed.

[2] The caregiver-reported late talkers all scored at or above an age-appropriate level on the Expressive Vocabulary Test, 2nd edition (EVT-2) (Williams, 2007) (greater than or equal to 85) and the Goldman-Fristoe Test of Articulation, 2nd edition (GFTA-2) (Goldman and Fristoe, 2000) (greater than or equal to 70)

[3] Overall average age of children not provided.

Allen, M., Nikolopoulos, T., and O'Donoghue, G. (**1998**). "Speech intelligibility in children after cochlear implantation," Otology & Neurotology **19**(6), 742–746.

Ambrose, S. E., Walker, E. A., Unflat-Berry, L. M., Oleson, J. J., and Moeller, M. P. (**2015**). "Quantity and Quality of Caregivers' Linguistic Input to 18-Month and 3-Year-Old Children Who Are Hard of Hearing:," Ear and Hearing **36**(1), 48S–59S, doi: 10.1097/AUD.0000000000000209.

Barbier, G., Perrier, P., Payan, Y., Tiede, M. K., Gerber, S., Perkell, J. S., and Ménard, L. (**2020**). "What anticipatory coarticulation in children tells us about speech motor control maturity," PLoS ONE **15**(4), e0231484, doi: 10.1371/journal.pone.0231484.

Bates, D., Maechler, M., Bolker, B., and Walker, S. (**2015**). "Fitting linear mixed-effects models using lme4," Journal of Statistical Software **67**(1), 1–48.

Bergeson, T. R., Pisoni, D. B., and Davis, R. A. O. (**2003**). "A Longitudinal Study of Audiovisual Speech Perception by Children with Hearing Loss Who have Cochlear Implants," The Volta review **103**(4), 347–370.

Boersma, P., and Weenink, D. (**2020**). "Praat: Doing phonetics by computer" .

Callan, D. E., Kent, R., Guenther, F. H., and Vorperian, H. K. (**2000**). "An auditory-feedback-based neural network model of speech production that is robust to developmental changes in the size and shape of the articulatory system," Journal of Speech Language and Hearing Research **43**, 721–736.

Caudrelier, T., Ménard, L., Perrier, P., Schwartz, J.-L., Gerber, S., Vidou, C., and Rochet-Capellan, A. (**2019**). "Transfer of sensorimotor learning reveals phoneme representations in preliterate children," Cognition **192**, 103973, doi: 10.1016/j.cognition.2019.05.010.

Cristia, A., and Seidl, A. (**2014**). "The hyperarticulation hypothesis of infant-directed speech," Journal of Child Language **41**(4), 913–934, doi: 10.1017/S0305000914000105.

Cychosz, M., Edwards, J. R., Munson, B., and Johnson, K. (**2019**). "Spectral and temporal measures of coarticulation in child speech," The Journal of the Acoustical Society of America-Express Letters **146**(6), EL516–EL522, doi: 10.1121/1.5139201.

Cychosz, M., Munson, B., and Edwards, J. R. (**to appear**). "Practice and experience predict coarticulation in child speech," Language Learning and Development doi: 10.31234/osf.io/vwhtk.

DePaolis, R. A., Vihman, M. M., and Keren-Portnoy, T. (**2011**). "Do production patterns influence the processing of speech in prelinguistic infants?," Infant Behavior and Development **34**(4), 590–601, doi: 10.1016/j.infbeh.2011.06.005.

DesJardin, J. L., and Eisenberg, L. S. (**2007**). "Maternal Contributions: Supporting Language Development in Young Children with Cochlear Implants:," Ear and Hearing **28**(4), 456–469, doi: 10.1097/AUD.0b013e31806dc1ab.

Dilley, L., Lehet, M., Wieland, E. A., Arjmandi, M. K., Kondaurova, M., Wang, Y., Reed, J., Svirsky, M., Houston, D., and Bergeson, T. (**2020**). "Individual Differences in Mothers' Spontaneous Infant-Directed Speech Predict Language Attainment in Children With Cochlear Implants," Journal of Speech, Language, and Hearing Research **63**(7), 2453–2467, doi: 10.1044/2020_JSLHR-19-00229.

Edwards, J., Beckman, M. E., and Munson, B. (**2004**). "The interaction between vocabulary size and phonotactic probability effects on children's production accuracy and fluency in novel word repetition," Journal of Speech Language and Hearing Research **57**, 421–436.

Eguchi, S., and Hirsh, I. (**1969**). "Development of speech sounds in children," Acta Otolaryngolica **(suppl 257)**, 21–51.

Faes, J., and Gillis, S. (**2016**). "Word initial fricative production in children with cochlear implants and their normally hearing peers matched on lexicon size," Clinical Linguistics & Phonetics **30**(12), 959–982, doi: 10.1080/02699206.2016.1213882.

Fagan, M. K. (**2014**). "Frequency of vocalization before and after cochlear implantation: Dynamic effect of auditory feedback on infant behavior," Journal of experimental child psychology **126**, 328–338, doi: 10.1016/j.jecp.2014.05.005.

Fagan, M. K. (**2015**). "Why repetition? Repetitive babbling, auditory feedback, and cochlear implantation," Journal of experimental child psychology **137**, 125–136, doi: 10.1016/j.jecp.2015.04.005.

Fenson, L., Marchman, V., Thal, D. J., Dale, P., Reznick, J., and Bates, E. (**2007**). *MacArthur-Bates Communicative Development Inventories User's Guide and Technical Manual*, 2nd edition ed. (Singular, San Diego, CA).

Flipsen, P. (**2008**). "Intelligibility of spontaneous conversational speech produced by children with cochlear implants: A review," International Journal of Pediatric Otorhinolaryngology **72**(5), 559–564, doi: 10.1016/j.ijporl.2008.01.026.

Freeman, V., and Pisoni, D. B. (**2017**). "Speech rate, rate-matching, and intelligibility in early-implanted cochlear implant users," The Journal of the Acoustical Society of America **142**(2), 1043–1054, doi: 10.1121/1.4998590.

Gerosa, M., Lee, S., Giuliani, D., and Narayanan, S. (**2006**). "Analyzing children's speech: An acoustic study of consonants and consonant-vowel transition," in *2006 IEEE International Conference on Acoustics Speed and Signal Processing Proceedings*, IEEE, Toulouse, France, Vol. 1, pp. 393–396, doi: 10.1109/ICASSP.2006.1660040.

Goldman, R., and Fristoe, M. (**2000**). *Goldman-Fristoe Test of Articulation-Second Edition (GFTA-2)*, second ed. (American Guidance Service, Circle Pines, MN).

Greenwood, C. R., Thiemann-Bourque, K., Walker, D., Buzhardt, J., and Gilkerson, J. (**2011**). "Assessing Children's Home Language Environments Using Automatic Speech Recognition Technology," Communication Disorders Quarterly **32**(2), 83–92, doi: 10.1177/1525740110367826.

Guenther, F. H. (**2006**). "Cortical interactions underlying the production of speech sounds," Journal of Communication Disorders **39**(5), 350–365, doi: 10.1016/j.jcomdis.2006.06.013.

Harrington, J., Kleber, F., and Stevens, M. (**2016**). "The Relationship Between the (Mis)-Parsing of Coarticulation in Perception and Sound Change: Evidence from Dissimilation and Language Acquisition," in *Recent Advances in Nonlinear Speech Processing*, edited by A. Esposito, M. Faundez-Zanuy, A. M. Esposito, G. Cordasco, T. Drugman, J. Solé-Casals, and F. C. Morabito, **48** (Springer International Publishing, Cham), pp. 15–34, doi: 10.1007/978-3-319-28109-4_3.

Hazan, V., and Barrett, S. (**2000**). "The development of phonemic categorization in children aged 6–12," Journal of Phonetics **28**(4), 377–396, doi: 10.1006/jpho.2000.0121.

Hillenbrand, J., Getty, L. A., Wheeler, K., and Clark, M. J. (**1995**). "Acoustic characteristics of American English vowels," The Journal of the Acoustical Society of America **97**(5), 3099–3111, doi: 10.1121/1.409456.

Holt, R. F., Beer, J., Kronenberger, W. G., Pisoni, D. B., and Lalonde, K. (**2012**). "Contribution of Family Environment to Pediatric Cochlear Implant Users' Speech and Language Outcomes: Some Preliminary Findings," Journal of Speech, Language, and Hearing Research **55**(3), 848–864, doi: 10.1044/1092-4388(2011/11-0143).

Hustad, K. C., Mahr, T., Natzke, P. E. M., and Rathouz, P. J. (**2020**). "Development of Speech Intelligibility Between 30 and 47 Months in Typically Developing Children: A Cross-Sectional Study of Growth," Journal of Speech, Language & Hearing Research **63**(6), 1675–1687, doi: 10.1044/2020_JSLHR-20-00008.

Iuzzini-Seigel, J., Hogan, T. P., Guarino, A. J., and Green, J. R. (**2015**). "Reliance on auditory feedback in children with childhood apraxia of speech," Journal of Communication Disorders **54**, 32–42, doi: 10.1016/j.jcomdis.2015.01.002.

Iyer, S. N., and Oller, D. K. (**2008**). "Prelinguistic Vocal Development in Infants with Typical Hearing and Infants with Severe-to-Profound Hearing Loss," The Volta review **108**(2), 115–138.

Julien, H. M., and Munson, B. (**2012**). "Modifying Speech to Children based on their Perceived Phonetic Accuracy," Journal of speech, language, and hearing research : JSLHR **55**(6), 1836–1849, doi: 10.1044/1092-4388(2012/11-0131).

Katseff, S., Houde, J., and Johnson, K. (**2012**). "Partial Compensation for Altered Auditory Feedback: A Tradeoff with Somatosensory Feedback?," Language and Speech **55**(2), 295–308, doi: 10.1177/0023830911417802.

Koester, L. S., Brooks, L. R., and Karkowski, A. M. (**1998**). "A Comparison of the Vocal Patterns of Deaf and Hearing Mother-Infant Dyads during Face-to-Face Interactions," Journal of Deaf Studies and Deaf Education **3**(4), 290–301, doi: 10.1093/oxfordjournals.deafed.a014357.

Kondaurova, M. V., Smith, N. A., Zheng, Q., Reed, J., and Fagan, M. K. (**2020**). "Vocal Turn-Taking Between Mothers and Their Children With Cochlear Implants:," Ear and Hearing **41**(2), 362–373, doi: 10.1097/AUD.0000000000000769.

Koopmans-van Beinum, F. J., Clement, C. J., and Dikkenberg-Pot, I. V. D. (**2001**). "Babbling and the lack of auditory speech perception: A matter of coordination?," Developmental Science **4**(1), 61–70, doi: 10.1111/1467-7687.00149.

Kuznetsova, A., Brockhoff, P., and Christensen, R. (**2017**). "lmerTest Package: Tests in linear mixed-effects models," Journal of Statistical Software **82**(13), 1–26.

Lee, S., Potamianos, A., and Narayanan, S. (**1999**). "Acoustics of children's speech: Developmental changes of temporal and spectral parameters," The Journal of the Acoustical Society of America **105**(3), 1455–1468, doi: 10.1121/1.426686.

Liu, H.-M., Tsao, F.-M., and Kuhl, P. K. (**2009**). "Age-related Changes in Acoustic Modifications of Mandarin Maternal Speech to Preverbal Infants and Five-Year-Old Children: A Longitudinal Study," Journal of child language **36**(4), 909, doi: 10.1017/S030500090800929X.

LoRe, D., Ladner, P., and Suskind, D. (**2018**). "Talk, Read, Sing: Early Language Exposure As an Overlooked Social Determinant of Health," Pediatrics **142**(3), e20182007, doi: 10.1542/peds.2018-2007.

Mann, V. A. (**1980**). "Influence of preceding liquid on stop-consonant perception," Perception & Psychophysics **28**(5), 407–412.

McAuliffe, M., Socolof, M., Mihuc, A., Wagner, M., and Sonderegger, M. (**2017**). "Montreal Forced Aligner" .

McDaniel, J., and Gifford, R. H. (**2020**). "Prelinguistic Vocal Development in Children With Cochlear Implants: A Systematic Review," Ear & Hearing **41**(5), 1064–1076, doi: 10.1097/AUD.0000000000000829.

McFee, B., Raffel, C., Liang, D., Ellis, D., McVicar, M., Battenberg, E., and Nieto, O. (**2015**). "Librosa: Audio and Music Signal Analysis in Python," in *Proceedings of the 14th Python in Science Conference*, Austin, Texas, pp. 18–24, doi: 10.25080/Majora-7b98e3ed-003.

Ménard, L., Perrier, P., Aubin, J., Savariaux, C., and Thibeault, M. (**2008**). "Compensation strategies for a lip-tube perturbation of French [u]: An acoustic and perceptual study of 4-year-old children," The Journal of the Acoustical Society of America **124**(2), 1192–1206, doi: 10.1121/1.2945704.

Metsala, J., and Walley, A. (**1998**). "Spoken vocabulary growth and the segmental restructuring of lexical representations: Precurors to phonemic awareness and early reading ability.," in *Word Recognition in Beginning Literacy* (Lawrence Erlbaum Associates), pp. 89–120.

Moulin-Frier, C., Nguyen, S. M., and Oudeyer, P.-Y. (**2014**). "Self-organization of early vocal development in infants and machines: The role of intrinsic motivation," Frontiers in Psychology **4**, doi: 10.3389/fpsyg.2013.01006.

Munson, B., Edwards, J., and Beckman, M. E. (**2005**). "Relationships Between Nonword Repetition Accuracy and Other Measures of Linguistic Development in Children With Phonological Disorders," Journal of Speech, Language, and Hearing Research **48**(1), 61–78, doi: 10.1044/1092-4388(2005/006).

Nathani, S., Oller, D. K., and Neal, A. R. (**2007**). "On the Robustness of Vocal Development: An Examination of Infants With Moderate-to-Severe Hearing Loss and Additional Risk Factors," Journal of Speech Language and Hearing Research **50**, 1425–1444, doi: 10.1044/1092-4388(2007/099).

Niparko, J. K., Tobey, E. A., Thal, D. J., Eisenberg, L. S., Wang, N.-Y., Quittner, A. L., and Fink, N. E. (**2010**). "Spoken Language Development in Children Following Cochlear Implantation," Journal of the American Medical Association **303**(15), 1498–1506.

Nittrouer, S. (**1993**). "The emergence of mature gestural patterns is not uniform: Evidence from an acoustic study," Journal of Speech Language and Hearing Research **36**, 959–972.

Nittrouer, S., Lowenstein, J. H., and Antonelli, J. (**2019**). "Parental Language Input to Children With Hearing Loss: Does It Matter in the End?," Journal of Speech, Language, and Hearing Research **63**(1), 234–258, doi: 10.1044/2019_JSLHR-19-00123.

Nittrouer, S., Lowenstein, J. H., and Holloman, C. (**2016**). “Early predictors of phonological and morphosyntactic skills in second graders with cochlear implants,” Research in Developmental Disabilities **55**, 143–160, doi: 10.1016/j.ridd.2016.03.020.

Nittrouer, S., Studdert-Kennedy, M., and McGowan, R. S. (**1989**). “The emergence of phonetic segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children and adults,” Journal of Speech Language and Hearing Research **32**, 120–132.

Nittrouer, S., Studdert-Kennedy, M., and Neely, S. T. (**1996**). “How Children Learn to Organize Their Speech Gestures: Further Evidence From Fricative-Vowel Syllables,” Journal of Speech Language and Hearing Research **39**, 379–389, doi: 10.1044/jshr.3902.379.

Noiray, A., Abakarova, D., Rubertus, E., Krüger, S., and Tiede, M. (**2018**). “How Do Children Organize Their Speech in the First Years of Life? Insight From Ultrasound Imaging,” Journal of Speech, Language, and Hearing Research **61**(6), 1355–1368, doi: 10.1044/2018_JSLHR-S-17-0148.

Noiray, A., Popescu, A., Killmer, H., Rubertus, E., Krüger, S., and Hintermeier, L. (**2019**a). “Spoken Language Development and the Challenge of Skill Integration,” Frontiers in Psychology **10**(2777), 1–17, doi: 10.3389/fpsyg.2019.02777.

Noiray, A., Wieling, M., Abakarova, D., Rubertus, E., and Tiede, M. (**2019**b). “Back From the Future: Nonlinear Anticipation in Adults' and Children's Speech,” Journal of Speech, Language, and Hearing Research **62**(8S), 3033–3054, doi: 10.1044/2019_JSLHR-S-CSMC7-18-0208.

Oller, D. K., and Eilers, R. E. (**1988**). "The Role of Audition in Infant Babbling," Child Development **59**(2), 441–449.

Perkell, J. S. (**2012**). "Movement goals and feedback and feedforward control mechanisms in speech production," Journal of neurolinguistics **25**(5), 382–407, doi: 10.1016/j.jneuroling.2010.02.011.

Perkell, J. S. (**2013**). "Five Decades of Research in Speech Motor Control: What Have We Learned, and Where Should We Go From Here?," Journal of Speech, Language, and Hearing Research **56**(6), 1857–1874, doi: 10.1044/1092-4388(2013/12-0382).

Reidy, P. F., Kristensen, K., Winn, M. B., Litovsky, R. Y., and Edwards, J. R. (**2017**). "The Acoustics of Word-Initial Fricatives and Their Effect on Word-Level Intelligibility in Children With Bilateral Cochlear Implants:," Ear and Hearing **38**(1), 42–56, doi: 10.1097/AUD.0000000000000349.

Rubertus, E., and Noiray, A. (**2020**). "Vocalic activation width decreases across childhood: Evidence from carryover coarticulation," Laboratory Phonology: Journal of the Association for Laboratory Phonology **11**(1), 7, doi: 10.5334/labphon.228.

Rvachew, S., Ohberg, A., Grawburg, M., and Heyding, J. (**2003**). "Phonological Awareness and Phonemic Perception in 4-Year-Old Children With Delayed Expressive Phonology Skills," American Journal of Speech-Language Pathology **12**(4), 463–471, doi: 10.1044/1058-0360(2003/092).

Savariaux, C., Perrier, P., and Orliaguet, J. P. (**1995**). "Compensation strategies for the perturbation of the rounded vowel [u] using a lip tube: A study of the control space in speech production," The Journal of the Acoustical Society of America **98**(5), 2428–2442, doi: 10.1121/1.413277.

Schneider, W., Eschman, A., and Zuccolotto, A. (**2012**). "E-Prime" Psychology Softwre Tools, Inc.

Sekhon, J. S. (**2011**). "Multivariate and Propensity Score Matching Software with Automated Balance Optimization: The {Matching} Package for {R}," Journal of Statistical Software **42**(7), 1–52.

Shiller, D. M., Rvachew, S., and Brosseau-Lapré, F. (**2010**). "Importance of the auditory perceptual target to the achievement of speech production accuracy," Canadian Journal of Speech-Language Pathology and Audiology **34**(3), 181–192.

Smith, A., and Goffman, L. (**1998**). "Stability and Patterning of Speech Movement Sequences in Children and Adults," Journal of Speech Language and Hearing Research **41**(1), 18–30, doi: 10.1044/jslhr.4101.18.

Soli, S. D. (**1981**). "Second formants in fricatives: Acoustic consequences of fricative-vowel coarticulation," The Journal of the Acoustical Society of America **70**(4), 976–984, doi: 10.1121/1.387032.

Stoel-Gammon, C., and Otomo, K. (**1986**). "Babbling development of hearing-impaired and normally hearing subjects," Journal of Speech and Hearing Disorders **51**(1), 33–41.

Storkel, H. L., and Morrisette, M. L. (**2002**). "The Lexicon and Phonology: Interactions in Language Acquisition," Language, Speech, and Hearing Services in Schools **33**(1), 24–37, doi: 10.1044/0161-1461(2002/003).

Team, R. (**2020**). *RStudio: Integrated Development for R* (RStudio, Inc., Boston, MA).

Terband, H., and Maassen, B. (**2010**). “Speech motor development in chldhood apraxia of speech: Generating testable hypotheses by neurocomputational modeling,” Folia Phoniatrica et Logopaedica **62**(3), 134–142.

Terband, H., van Brenk, F., and van Doornik-van der Zee, A. (**2014**). “Auditory feedback perturbation in children with developmental speech sound disorders,” Journal of Communication Disorders **51**, 64–77, doi: 10.1016/j.jcomdis.2014.06.009.

Tobey, E. A., Geers, A. E., Brenner, C., Altuna, D., and Gabbert, G. (**2003**). “Factors Associated with Development of Speech Production Skills in Children Implanted by Age Five:,” Ear and Hearing **24**(Supplement), 36S–45S, doi: 10.1097/01.AUD.0000051688.48224.A6.

Tremblay, S., Shiller, D. M., and Ostry, D. J. (**2003**). “Somatosensory basis of speech production,” Nature **423**(6942), 866–869, doi: 10.1038/nature01710.

van den Bunt, M. R., Groen, M. A., Frost, S., Lau, A., Preston, J. L., Gracco, V. L., Pugh, K. R., and Verhoeven, L. T. W. (**2018**). “Sensorimotor Control of Speech and Children’s Reading Ability,” Scientific Studies of Reading **22**(6), 503–516, doi: 10.1080/10888438.2018.1491583.

von Hapsburg, D., and Davis, B. L. (**2006**). “Auditory Sensitivity and the Prelinguistic Vocalizations of Early-Amplified Infants,” Journal of Speech, Language, and Hearing Research **49**(4), 809–822, doi: 10.1044/1092-4388(2006/057).

Vorperian, H. K., Kent, R., Lindstrom, M. J., Kalina, C. M., Gentry, L. R., and Yandell, B. S. (**2005**). “Development of vocal tract length during early childhood: A magnetic resonance imaging study,” The Journal of the Acoustical Society of America **117**(1), 338–

350, doi: 10.1121/1.1835958.

Walsh, B., and Smith, A. (**2002**). "Articulatory movements in adolescents: Evidence for protracted develop- ment of speech motor control processes.," Journal of Speech Language and Hearing Research **45**(6), 1119–1133.

Whalen, D. H. (**1990**). "Coarticulation is largely planned," Journal of Phonetics **18**, 3–35.

Wickham, H. (**2016**). *Ggplot2: Elegant Graphics for Data Analysis* (Springer-Verlag New York, New York).

Williams, K. (**2007**). *Expressive Vocabulary Test, Second Edition*, second ed. (Pearson Education, San Antonio, TX).

Zharkova, N. (**2016**). "Ultrasound and acoustic analysis of sibilant fricatives in preadolescents and adults," The Journal of the Acoustical Society of America **139**(5), 2342–2351, doi: 10.1121/1.4947046.

Zharkova, N., Hewlett, N., and Hardcastle, W. J. (**2011**). "Coarticulation as an Indicator of Speech Motor Control Development in Children: An Ultrasound Study," Motor Control **15**(1), 118–140, doi: 10.1123/mcj.15.1.118.

Zharkova, N., Hewlett, N., Hardcastle, W. J., and Lickley, R. J. (**2014**). "Spatial and Temporal Lingual Coarticulation and Motor Control in Preadolescents," Journal of Speech Language and Hearing Research **57**(2), 374–388, doi: 10.1044/2014_JSLHR-S-11-0350.