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A cross-sectional age group study of coarticulatory resistance: the case of late-acquired voiceless fricatives in English

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Purpose: As a class, fricatives are more "resistant" to consonant-vowel coarticulation than other English sounds. The current study investigates the relative coarticulatory resistance of /θ, s, ʃ/ in child and adult speech to better understand the acquisition of individuated speech sounds.

Method: Ten 5-year-old children, seven 8-year-old children, and 9 college-aged adults produced [əFV] sequences in carrier phrases, where F was /θ/, /s/, or /ʃ/ and V was /æ/, /i/, or /u/. In Experiment 1, coarticulation was perceptually indexed: 65 adults predicted the target stressed vowel based on forward-gated AV speech samples for a subset of 4 speakers from each age group. In Experiment 2, dynamic spectral measures of the /əFV/ sequences were analyzed using SSANOVA to again test for vowel effects on fricative articulation across age groups.

Results: The perceptual results indicated that fricatives blocked vowel-to-vowel coarticulation across speaker age groups. Contrary to expectation, vowels were most accurately predicted when F was /s/, and not when it was /ʃ/ or /θ/ across age groups. Acoustic results indicated the expected biomechanically-motivated /ʃ/ > /s/ > /θ/ coarticulatory resistance hierarchy in adults' speech. By contrast, /ʃ/ > /s/ were similarly influenced by context in 8-year-olds' speech, and the results from 5-year-olds' speech suggested an influence of order-of-acquisition in that /θ/ was surprisingly resistant to coarticulation.

Conclusion: The study results are taken to suggest that a temporal constraint on fricative articulation interacts with biomechanical constraints during development to influence patterns of coarticulation in school-age children's speech.

Keywords: speech development; segmental articulation; anticipatory coarticulation; fricative acquisition

Introduction

Speech sound acquisition is typically approached from a phonemic perspective (e.g., Prather, Hedrick, & Kerns, 1975; Smit, Hand, Freilinger, Bernthal, & Bird, 1990; Dodd, Holm, Hua, & Crosbie, 2003). Studies focus on how children do or do not achieve the same sound across syllable positions and on how these sounds compare to those obtained by the adult. Motivated by a developmentally sensitive theory of speech production (Redford, 2015; 2019), we advocate for studies that supplement the phonemic approach with one that focuses on context and on the dynamics of speech sound articulation (Howson & Redford, 2021). Such an approach assumes that coarticulation is central to understanding the emergence of segment-sized articulatory targets (Nittrouer, Studdert-Kennedy, McGowan, 1989; Studdert-Kennedy, 1991; Davis & Redford, 2019); an assumption that takes seriously the well-known positional effects on consonant acquisition (see Inkelas & Rose, 2007; Theodore, Demuth, & Shattuck-Hufnagel, 2010; 2012). Here, we adopt this approach to investigate school-aged children's production of the voiceless fricatives [θ, s, ʃ] – a subset of the so-called late 8 sounds of English (Sander, 1972; Smit et al., 1990; Shriberg, 1993). The overarching goal is to identify the constraints and strategies that underpin the development of speech sound production.

The late 8 sounds in English include the aforementioned voiceless coronal fricatives, [θ, s, ʃ], the voiced variants of these fricatives [ð, z, ʒ], and liquids [l, ɹ] (see, e.g., Shriberg, 1993:121). A major reason cited for the late acquisition of these sounds is their articulatory complexity (Sander, 1972; Locke, 1983). Consider the coronal fricatives: these require independent control over the tongue tip/blade and body to achieve constrictions that facilitate a turbulent airstream (Stevens, 1971; Shadle, 1985, 1990; Proctor, Shadle, & Iskarous, 2010). Previous research has found that medial grooving of the anterior tongue body is also critical for the production of sibilant fricatives (Narayanan, Alwan, & Haker, 1995; Stone & Lundberg, 1996; Narayanan & Alwan, 2000); meanwhile, pharyngeal cavity volume, controlled by tongue root advancement and laryngeal height, distinguishes voiced from voiceless fricatives (Proctor, Shadle, & Iskarous, 2010). At the same time, the glottis must be appropriately modulated to maintain a transglottal pressure drop, despite the oral constriction, so that airflow across the constriction is sufficient to create an audible turbulence (Stevens, 1971; Shadle, 1990).

Importantly, the vocal tract adjustments needed to produce fricatives must be sustained through time for aerodynamic (Shadle, 1985; 1990) and perceptual reasons (see Jongman, 1989).

In this way, fricatives differ from most of the other speech sounds in English, which allow for continuous movement into and out of targeted vocal tract configurations. Continuous movement is possible because most sounds are based in articulations that exploit physical or biomechanical saturation effects, which give rise to stable acoustics (see Stevens, 1989; Perkell et al., 1997). In contrast, the sustained configuration required for fricative articulation represents a disruption of movement into and out of adjacent targets. This disruption explains the reduced coarticulation of fricatives with other sounds (Byrd, 1996). We suggest that the disruption may also contribute to their generally stronger coarticulatory "resistance" compared to stop and liquid consonants (Farnetani & Recasens, 1993). Either way, the articulatory targets for these sounds are likely specified more precisely than for other sounds: MacNeilage (1970:193) made the observation, repeated in Byrd (1996: 232), that ''targets for fricatives are specified with more precision than targets for stop consonants because the acoustic result is more dependent on precise articulator position in the former case.'' We suggest that when children successfully sustain a vocal tract configuration in service of the acoustic goal, fricatives are naturally disambiguated from their articulatory context, leading to the acquisition of a narrowly-defined speech motor target. In the current study, we investigate the implications of this developmental hypothesis for the coarticulation of voiceless fricatives with a subsequent vowel.

Fricative-Vowel Coarticulation in Children's Speech

In order for children to achieve the sustained fricative constriction that will direct airflow to produce audible turbulence, they must abandon preferred articulatory strategies that condition vowel-to-vowel coarticulation and tight consonant-vowel coarticulation in running speech (e.g., a tongue-body first strategy; see Howson & Redford, 2021). This suggests that children may pass through a stage where they produce fricatives that are especially decoupled from their immediate context. But the few studies on fricative-vowel coarticulation in children's speech paint a more complicated developmental picture than this hypothesis would suggest. We aim to make sense of this picture by focusing on segment-dependent differences in fricative-vowel coarticulation in child and adult speech.

In a classic early study, Nittrouer, Studdert-Kennedy, and McGowan (1989) examined the acoustics of /s, ʃ/ in two vowel contexts, /i, u/, in speech elicited from adults and children, who were divided into 5 age groups ranging from pre-school aged (3 and 4 years) to school-aged (5 and 7 years). Elicitations were reduplicated FVFV disyllables, used to maximize the opportunity for coarticulation. Acoustic analysis of the fricative spectra for F1 at locations least likely to be influenced by vowel articulation (i.e., 100 millisecond prior to the onset of the first vowel) indicated that the youngest children's production of /s/ and /ʃ/ were much less distinct than adult productions, consistent with the later acquisition of these sounds (Sanders, 1972; Smit et al., 1990; Shriberg, 1993). Nonetheless, there was also an effect of vowel context on the mean centroid frequency for /s/ across all age groups. This effect was found to decrease with age, suggesting greater fricative-vowel coarticulation in younger children than in older children, and greater fricative-vowel coarticulation in all children compared to adults. Careful acoustic reasoning led the authors to argue that this effect was not due to lip rounding or to differences in constriction shape; instead, they argued that the results suggested greater overlap in the production of fricatives and vowels in children's speech compared to adult speech.

Nittrouer et al.'s (1989) general conclusion that children's speech is more coarticulated than adults' speech, though based only on /sV/ sequences, has been supported in a number of subsequent developmental studies on consonant-vowel articulation (Zharkova, Hewlett, & Hardcastle, 2011; Noiray, Abakarova, Rubertus, Krüger, & Tiede, 2018; Rubertus & Noiray, 2018; Howson & Redford, 2021). A number of these studies also confirm the effect of segment identify on coarticulatory strength. For example, Katz & Bharadwaj (2001) used electromagnetic articulography (EMA) to study tongue tip (TT) and tongue body (TB) movements during production of /s/ and /ʃ/ in the context of /i/ and /u/ in 5- and 7-year-old children's speech compared to adults' speech. They found that TT and TB movement diverged earlier as a function of vowel context during /s/ production in children's speech compared to adults' speech; no differences were found for /ʃ/ production. And, in a head-to-head comparison of /s/-vowel and /ʃ/-vowel versus /t/-vowel and /p/-vowel coarticulation in speech produced by children between the ages of 3 and 13 years old, Zharkova (2018) reports vowel-dependent differences in the location of tongue bunching during /pV/ production for all age groups. Fewer vowel-dependent differences for location were found for the other CV sequences, though differences for /tV/ sequences were found by age 9 years and differences for /sV/ were found by age 13 years. Another measure performed only on the coronal consonants, degree of tongue curvature, showed vowel-dependent differences during /tV/ production for children aged 3 through 13 years, similar differences during /sV/ production for children aged 5 through 13 years, and similar differences during /ʃV/ production for children aged 7 through 13 years.

Zharkova (2018) interpreted the apparent interaction between segment and age on degree of coarticulation to suggest an interaction between biomechanical constraints and an order-of-acquisition hierarchy: "(t)he consonants that are generally acquired later were demonstrated in this study to take longer to develop mature coarticulatory patterns, with those consonants that have more articulatory demands on the tongue showing the most protracted development of vowel-related coarticulation" (p. 268). Although Zharkova is referring to the findings for stops versus fricatives, one might also hypothesize that a similar interaction between order of acquisition and production constraints may also define a degree of coarticulation hierarchy for these segments.

Degree of Coarticulation Hierarchies

Recall that our developmental hypothesis is that the sustained constriction needed to achieve fricative articulation contributes to especially reduced fricative-vowel coarticulation during early accurate production of these sounds. This hypothesis is broadly consistent with Zharkova's (2018) finding of reduced coarticulation of fricative-vowel sequences relative to stop-vowel sequences in younger children's speech. The temporal constraint hypothesis is less obviously consistent with the finding of segment-specific differences in fricative-vowel coarticulation, such as that /s/-vowel sequences are more coarticulated earlier than /ʃ/-vowel sequences (Nittrouer et al., 1989; Zharkova, 2018; but see Zharkova et al., 2011, 2012). We suggest that this difference is due to an order-of-acquisition effect on coarticulation. In particular, /s/ may be acquired especially early compared to the other articulatory complex sounds of English (Shriberg, 1993:121-122). In fact, McLeod & Crowe (2018) treat the voiceless alveolar fricative as a middle-acquired sound rather than a late-acquired one based on a comprehensive survey of the literature on children's acquisition of consonant across 27 languages.

McLeod & Crowe (2018) also show that the voiceless interdental fricative /θ/ is among the last acquired sounds in English: whereas /s/ is acquired between ages 3 and 5 years, /θ/ is typically acquired between 5- and 7-years-old (p. 1559). Although they do not explain why /θ/ is acquired so late, we speculate that it is because of its weak acoustic profile and relatively low frequency compared to the sibilant fricative. A weak acoustic profile results in a less salient acoustic target from which to reverse engineer articulation; lower frequency sounds are practiced less during the course of normal acquisition than higher frequency sounds. In combination with the temporal constraint on fricative articulation, these characteristics of /θ/ are expected to have consequences for its degree of coarticulatory resistance in younger children's speech. In particular, the prediction is that /θ/ will be more resistant than /s/ to coarticulation. An especially strong effect of order-of-acquisition on coarticulation predicts that /θ/ will also be more resistant than /ʃ/ to coarticulation when both are produced accurately in young children's speech.

An order of acquisition coarticulatory resistance hierarchy is contrary to the segment-dependent pattern of resistance predicted by adult-based models of coarticulation that reference spatial-temporal constraints on articulation (e.g., Bladon & Al-Bamerni, 1976; Bladon & Nolan, 1977; Recasens, 1985; Recasens, Pallarès, Fontdevila, 1997; Recasens & Espinosa, 2009). Consider the well-established degree of articulatory constraints (DAC) model of lingual coarticulation (Recasens et al., 1997; Recasens & Espinosa, 2009). According to this model, the tongue body involvement in articulation of /ʃ/ renders this sound more resistant to consonant-vowel coarticulation than /s/, which depends more on the tongue blade for its articulation. The alveolar fricative is in turn hypothesized to be more resistant to coarticulation than the interdental fricative, which is also articulated with the tongue blade (Recasens & Rodríguez, 2016). The rationale is that /s/ requires more precision to achieve its constriction than /θ/, where the more ballistic tongue-fronting movement associated with interdental articulation can be achieved with minimal demands on the tongue body. The DAC model thus predicts a /ʃ/ > /s/ > /θ/ resistance hierarchy that is compatible with results from adult speech data: Rodríguez & Recasens (2017), who examine the voiced interdental, /ð/, rather than the voiceless variant, showed that it was less resistant than /s/ or /ʃ/ to consonant-vowel coarticulation.

Current Study

The literature indicates segment-specific differences in the degree to which children coarticulate consonant-vowel sequences, including fricative-vowel sequences. Although consonant-vowel sequences are often substantially more coarticulated in younger children's speech compared to older children's and adults' speech (Zharkova et al., 2011; 2012; Noiray et al., 2018; Rubertus & Noiray, 2018; Howson & Redford, 2021), fricative articulation requires that a narrow constriction be sustained through time for aerodynamic and perceptual reasons. We hypothesize that this requirement provides a temporal constraint on fricative articulation that interacts with an order-of-acquisition effect to predict especially minimal /θ/-vowel coarticulation compared to /s/-vowel coarticulation in young school-aged children's speech. Further, we note that an especially strong, independent effect of order-of-acquisition on segmental articulation predicts less /θ/-vowel coarticulation than /ʃ/-vowel coarticulation in children's speech. Overall, order of acquisition is expected to result in patterns of coarticulatory resistance in children's speech that differs from those predicted by the adult-based DAC model of lingual coarticulation (Recasens et al., 1997; Recasens & Espinosa, 2009). The DAC model predicts that /θ/-vowel coarticulation will be greater than /s/-vowel coarticulation and that /s/-vowel coarticulation will be greater than /ʃ/-vowel coarticulation. The current study tests for an order of acquisition effect on coarticulatory resistance. Specifically, the analyses test for the effect of context on fricative-vowel coarticulation as a function of place-of-articulation within and across 3 age groups: 5-year-olds, 8-year-olds, and adults. Child and adult speakers produced sentences with phrase-medial monosyllabic target words that had /θ, s, ʃ/ in onset position and /i, æ, u/ in the vowel nucleus. The target words were preceded by an unstressed vowel (i.e., schwa in "the"). Fricative resistance to coarticulation was measured in two different experiments: (1) a gated audio-visual (AV) speech prediction task that focused on the extent to which vowel-to-vowel coarticulation was blocked by different voiceless fricatives in child and adult speech; and (2) an acoustic comparison of dynamic formant and center-of-gravity spectral measures by vowel context to investigate the influence of context on different fricatives within each age group. Detailed methods follow, beginning with the general methods that applied to both experiments.

General Method

Overview

The experiments reported below are based on the same speakers and same speech materials. These are introduced here to provide an appropriate background for the methods detailed under Experiment 1 and 2.

Participants

Audiovisual speech data were collected from 26 native English speakers in three age groups: 5-year-old children, 8-year-old children, and college-aged adults. There were ten 5-year-olds (4 female and 6 male), seven 8-year-olds (3 female and 5 male), and 8 adults (4 female and 4 male). Adults were recruited by word-of-mouth and through the Linguistics and Psychology human subjects pool; they were college-aged and ranged from 18.9 – 22.11 years (*M* = 20.22, *SD* = 1.07). Children were recruited using a developmental database maintained by the Psychology

Department at the University of Oregon. The 5-year-olds ranged in age from 67 to 77 months (M = 70.4, SD = 3.17); 8-year-olds ranged in age from 94 to 103 months (M = 97.63, SD = 2.97).

The college-aged adults had no self-reported history of speech or hearing therapy. Typical speech, language, and hearing development in children was determined based on standardized speech-language assessments performed in the laboratory. All children had standardized scores within 1 standard deviation of the mean on the articulatory subtest from the Diagnostic Evaluation of Articulation and Phonology (DEAP; Dodd et al., 2002) and on the core language subtests from the Clinical Evaluation of Language Fundamentals – Fifth Edition (Semel et al., 2013). Children also passed a hearing screen. They were given a 1000 Hz tone at 20 dB in the right ear. If this elicited the appropriate response, they were then tested on tones at 1000, 2000, and 4000 Hz at 20 dB in each ear (at a time), following the guidelines set by the American Academy of Audiology Childhood Hearing Screening Guidelines (2011).

We acquired verbal and written consent from caregivers and the child participants as well as from the adult participants for the assessment and elicitation and also to show audiovisual clips of the participants' speech to other university students (see Experiment 1). All procedures were reviewed and approved by the Institutional Review Board at the University of Oregon. Families and college-aged adults were financially compensated for their time. Children also selected a small prize from a prize drawer upon study completion.

Speech Materials and Elicitation

Speakers were audiovisually (AV) recorded during the elicitation task using a Panasonic AJ-PX270 audio-video camcorder. Lighting was provided by two Genaray SP-E-240B Spectro LED Essential 240 Bi-color LED lights. Each of the stimulus sentences were to be produced in the carrier phrase "I bought the *target* hat." The target was a word that contained one of the three voiceless fricatives in onset position, followed by one of three vowels, /i, æ, u/. Table 1 summarizes all the target stimuli.

Table 1. Summary of target stimuli used in this experiment.

	/s/	/ʃ/	/θ/
/i/	sea	she	thief
/æ/	sap	shack	thatch
/u/	sue	shoe	thew

Target words were associated with pictures as a memory aid to be used during elicitation (e.g., a shack with a hat on it for "*shack* hat"). Participants were first taught the picture-word association (e.g., "This shack has a hat on it. We are going to call the hat a *shack hat*."). Next, the full target sentence was elicited: the experimenter would produce the sentence and then the participant would repeat it after the experimenter. During the actual elicitation phase, participants were shown the relevant pictures and then prompted with an audio recording: "You bought the *target* hat today. What did you do today? Please tell me." The targeted response was: "I bought the *target* hat today." A repetition was then prompted with: "What did you do today?"

Target words were elicited once per block in a randomized order. Three blocks resulted in a total of 6 repetitions of each target phrase and so in a total of 54 sentences per speaker. Adults and 8-year-olds produced all sentences fluently and as expected. Younger children occasionally produced the target phrase with a prosodic break between the determiner and target word. When this occurred, the experimenter reminded the child of the full target phrase and the procedure for the item in question was repeated. The sentences with prosodic breaks were not analyzed.

Experiment 1

We used a gated AV speech prediction task to assess the effect of vowel on coarticulation as a function of the different fricatives of interest and age group. This method for measuring coarticulation, introduced and validated by Redford and colleagues (Redford, Kallay, Bogdanov, & Vatikiotis-Bateson, 2019; Howson, Kallay, & Redford, 2020), leverages a perceiver's implicit knowledge of speech production to detect subtle anticipatory cues in the audiovisual signal. The perceiver's task is to predict a segment of interest (e.g., an upcoming vowel) at various gates given the information up to the particular gate. The accuracy with which they can do so has been shown to reflect the amount of anticipatory information available in the speech stream at that gate. Because the method leverages both auditory and visual information, it can be used to detect more information across larger temporal domains than acoustics alone (Redford et al., 2018).

The gated AV speech method for measuring coarticulation has also been validated for children's speech and for data collection in the online environment (Howson et al., 2019). Moreover, like the Redford et al. (2018) study, the Howson et al. study with children showed that coarticulatory cues to an upcoming stressed vowel are available as early as the onset of the definite article, *the*, used to created the /ə/ context for /əCV/ sequences. The Redford et al. study showed that these cues vary in a manner consistent with the expected degree of coarticulatory resistance of the C in question: perceivers identified an upcoming vowel earlier and more accurately in /hV/ sequences compared to /gV/ sequences; identification was also earlier and more accurate for /gV/ sequences compared to /sV/ sequences.

In Experiment 1, we use the gated AV speech method to test for expected age-related differences in anticipatory coarticulation as a function of the voiceless fricative in question. The perceiver's task was to predict the stressed vowel in a target word given AV clips that were cut to provide speech information up until different points (i.e., gates) in the overall speech stream. Above chance accuracy at gates that preceded the vowel target implies the presence of coarticulatory cues to vowel identity; higher accuracy indicates greater coarticulation than lower accuracy. Analyses focused on the extent to which prediction accuracy varied with segment identity and age group. Perceivers were expected to predict the stressed vowel earlier and more accurately for /əsV/ sequences than for /əθV/ sequences in children's speech, assuming an effect of order of acquisition on coarticulatory resistance. Depending on the independent strength of this effect, perceivers were also expected to predict the stressed vowel earlier and more accurately for /ə/ʃ V/ sequences than for /əθV/ sequences in children's speech. By contrast, prediction accuracy was expected to be highest for /əθV/ sequences in adults' speech followed by /əsV/ sequences and then /ə/ʃ V/ sequences in keeping with the DAC model of coarticulation.

Methods

Perceivers

For the gated AV speech prediction task, 65 college students (aged 20 to 24 years old) were recruited through the University of Oregon, Psychology and Linguistics Human Subjects Pool to serve as perceivers. The students received course credit for their participation. Data collection was hosted through the online data collection platform, Testable (www.testable.org). Participants were given a link for participation and assigned to one of three conditions, defined by the onset fricative in the target word: /θ/, /s/, or /ʃ/. Participants signed up for just one condition and were not permitted to participate in the other conditions. 23 participants completed the /s/ condition, 21 participants completed the /ʃ/ condition, and 21 participants completed the /θ/ condition.

Stimuli

To create the gated stimuli, 2 male and 2 female speakers from each age group were selected randomly for a total of 12 speakers. The smaller number of speakers allowed us to design the experiment so that age group and vowel context were within-perceiver factors. The second repetition of each target phrase elicitation in each of the 3 blocks of repetitions was used to generate the gated AV speech stimuli for a total of 3 repetitions per target phrase. Recall that these target phrases were embedded in the carrier sentences: "I bought the FV(C) hat today." The full sentences were extracted from the overall recording and then cut at the following gate locations: (1) the closure of /b/ in *bought*; (2) vowel midpoint in *bought*; (3) consonantal closure for /ð/ in *the*; (4) vowel midpoint in *the*; (5) fricative offset for the target word, and (6) vowel midpoint of the target word (e.g., *I bought the she hat*; aj b|^1 ɑ|^2 tθ|^3 ə|^4 ʃ|^5 i|^6 hæt; see Figure 1). These cuts generated a total of 6 short AV clips for each sentence, which provided progressively more information about the identity of the target vowel (= /i/, /æ/, or /u/). The 12 speakers by 3 repetitions by 6 cuts by 3 voiceless fricatives by 3 target vowels resulted in 1,944 gated stimuli. Again, the stimuli were blocked by fricative onset and presented in separate conditions to perceivers (i.e., 648 stimuli per condition).

[Figure 1 about here]

Procedure

All perceivers judged the 648 gated stimuli associated with a particular voiceless fricative onset. The task was to identify the target vowel based on the gated stimuli; that is, it was a 3-way forced choice identification task with the possible responses of /i/, /æ/, or /u/. Judgment accuracy at gates that preceded the vowel onset (= Gate 6) depends on the presence and strength of coarticulatory cues to the stressed vowel at those gates. Participants would watch the AV clip and then make their response by selecting from among 3 buttons, labeled "e", "a", and "u" for /i/, /æ/, or /u/, respectively. Participants were also given the target words that correspond to each of the three vowel choices with the final video frame (e.g., *sap*, *sea*, *sue*). The final frame of the video would remain on the screen until a response was made. Speakers were blocked within condition so that perceivers made responses on all stimuli associated with a single speaker before moving on to the next speaker. Stimuli within each block were randomized as was the order of the speakers. The entire experiment was conducted online using the platform Testable (www.testable.com).

Analyses

Raw accuracy measures were converted into the Rand Index (ACC; Rand, 1971) using the fossil package (Vavrek, 2011) in R (R Core Team, 2019). The Rand Index measures the similarity between two data clusters. In the present case, the similarity metric is the comparison between the responses made by the participant and the correct response for each set of stimuli. The result is a bias-corrected measure of prediction accuracy, the ACC measure, which indicates the presence and strength of coarticulatory cues to the (variable) stressed vowel target at each Gate for each Participant, and for each Fricative and Age Group. ACC was compared statistically using a linear mixed effects (LME) model with the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) and p-values were calculated using Satterthwaite's Method (Satterthwaite, 1946) with the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017). The R^2 value (Devore, 2011) was calculated with the MuMin package (Barton, 2018). The linear model included the fixed effects of Gate (6 levels: 1-6), Fricative (3 levels: /θ, s, ʃ/), and Age Group (3 levels: 5-year-olds, 8-year-olds, and Adults). The model included a random by Fricative slope with a random intercept for each Participant. We also included a random intercept for each Speaker (i.e., the speaker that the Participant was seeing in each clip). A random by Fricative slope with a random intercept for Speaker was omitted because it resulted in a singular fit. Post-hoc tests were done using Tukey HSD (Tukey, 1949) in the emmeans package (Lenth, 2018). Data visualization used the ggplot2 package (Wickham, 2018). See Table 2 in the appendix for a confusion matrix for each vowel.

Results

The overall LME model had an R^2 of 0.50 and the model achieved convergence with a relative gradient below the acceptable limits (< 0.001). The model results indicated a significant simple effect of Gate [$F(5, 4603) = 604.65$, $p < 0.001$], a significant Gate by Fricative interaction [$F(10, 4603) = 6.10$, $p < 0.001$], and an interaction between Gate by Age Group [$F(10, 4603) = 1.84$, $p = 0.049$. Contrary to expectation, prediction accuracy did not vary systematically with the simple effect of Age Group [$F(2, 11) = 1.13$, $p = 0.357$] nor with the interaction of Age Group and Fricative [$F(4, 4555) = 1.03$, $p = 0.388$], or Age Group, Fricative, and Gate [$F(20, 4603) = 0.90$, $p = 0.584$]. Nonetheless, the results shown in Figure 2 hint at the possibility of age-related differences in the availability of coarticulatory cues as a function of fricative articulation. These results can be seen in Figure 2, where the rand index derived from correct vowel prediction is plotted as a function of Gate, Fricative condition, and Age Group. Note that the rand index, used to generate a bias corrected measure for accuracy and in this dataset, converts the three-way choice of vowels into either a correct or incorrect measure taking into account any bias in answering that participants may have had to choose one vowel over the others. As a result, chance is 0.5 instead of 0.33 because the three-way choice is transformed into a correct or incorrect response (i.e., 2 choices).

[Figure 2 about here]

The data in Figure 2 indicate that the effect of Gate was due to the expected increase in prediction accuracy with proximity to the target vowel (= Gate 6, V). Post hoc mean comparisons indicate that the rand index at every gate was significantly different from every other gate ($p < 0.05$) except for the difference between the first two gates (Gate 1, [b]: M = 0.477, SD = 0.140; Gate 2, [ɑ]: M = 0.488; SD = 0.141; $p = 0.578$) and the gates associated with the onset and vowel midpoint of the determiner "the" (Gate 3, [ð]: M = 0.510, SD = 0.128; Gate 4, [ə]: M = 0.518, SD = 0.141; $p = 0.881$).

Although there was no overall difference in prediction accuracy as a function of Fricative identity [$F(2, 47) = 0.17$, $p = 0.841$], the significant interaction between Gate and Fricative is in line with the expectation that anticipatory cues to vowel identity would vary systematically with the fricative. In the present data, the interaction was due to the different levels of prediction accuracy obtained at the fricative gate (= Gate 5, F; see Figure 3). Post hoc comparisons indicate that perceivers were better able to judge the identity of the subsequent vowel when the fricative was /s/ (M = 0.602, SD = 0.132) compared to when it was /ʃ/ (M = 0.551, SD = 0.146) or /θ/ (M = 0.527, SD = 0.137). Intriguingly, perceivers were equally poor at predicting the upcoming vowel at the offset of /ʃ/ and /θ/ regardless of a speaker's age.

Post hoc mean comparisons were also used to explore the Gate by Age Group interaction. These comparisons did not reveal any significant difference between the Age Groups at each Gate ($p > 0.05$); however, the tests revealed that Gate 1 was significantly different than Gate 2 ($p = 0.015$) for 5-year-olds, but not for 8-year-olds ($p = 0.396$) or Adults ($p = 0.251$). The tests also indicated a significant difference between Gate 2 and Gate 4 for 5-year-olds ($p = 0.010$), but not 8-year-olds ($p = 0.994$) or Adults ($p = 0.141$). These findings suggest that perceivers were able to make above chance predictions about the vowel context prior to the onset of the fricative in 5-year-olds' speech compared to 8-year-olds' or adults' speech. Figure 3 shows this effect more clearly by presenting overall accuracy by Gate for the different age groups.

[Figure 3 about here]

Discussion

The significant Gate by Fricative interaction in the present experiment indicate fricative-dependent differences in the perceivers' ability to predict an upcoming vowel. These differences index the realitve coarticulatory resistance of the different fricatives. More specifically, the results indicate that anticipatory coarticulatory cues were strongest for /s/ and equally weak for /θ/ and /ʃ/. The coarticulatory resistance hierarchy based on these data is thus /θ/ = /ʃ/ > /s/. Although the DAC model predicts higher resistance for /ʃ/ than for /s/, this model does not predict that resistance for /θ/ would be higher than for /s/. Only the order-of-acquisition hypothesis makes this prediction. The strongest version of this hypothesis might even predict that coarticulatory resistance would be stronger for /θ/ than for /ʃ/ in children's speech. Of course, the hypothesis also predicts an effect of age on the resistance hierarchy. But, despite some suggestion to the contrary in the data presented in Figure 2 (i.e., some visible differences by age group at Gate 5, F), the expected interaction between Age Group and Fricative was not significant. Instead, there was a significant Gate by Age Group interaction that was consistent with previous research findings that show stronger coarticulatory effects in younger children's speech compared to older children's and adults' speech (e.g., Zharkova et al., 2022; 2012; Noiray et al., 2018; Zharkova, 2018). But unlike in those studies, this effect was limited to vowel-to-vowel coarticulation; it was not observed for consonant-vowel coarticulation.

The surprising finding that /θ/ and /ʃ/ were equally opaque to coarticulatory effects could suggest that the voiceless interdental fricative is special in English. We had assumed that its supraglottal articulatory dynamics are highly similar to [ð] in the Rodríguez & Recasens (2017) study or Proctor (2009) study, but this may not be the case. After all, unlike English /θ/, Catalan (Rodríguez & Recasens, 2017) and Spanish (Proctor, 2009) [ð] are an intervocalic allophone of /d/. Its allophonic status could have implications for its articulation. For example, the intervocalic /d/ in both Catalan and Spanish could exhibit greater coarticulation because they are in essence a lenited allophone of the underlying segment /d/. On the other hand, it could be that English /θ/ is in fact a "strong" articulation, rendering it more resistant than allophonic [ð] to coarticulation with an adjacent vowel. It should also be noted that [ð] is often realized as an approximate and thus has laminar airflow, instead of turbulent airflow. With regards to English, Shadle, Proctor, & Iskarous (2008) were able to demonstrate a great deal of variability in the coarticulatory patterns for English /θ/. They examined 5 speakers' production of /θ/ in four vocalic environments /i, a, ə, u/ using MRI data. They found that 2 of the 5 speakers had significant variability in the posterior tongue position based on vocalic environment, while three speakers showed only small variations in tongue position. This might suggest that for some speakers, the tongue tip movement for /θ/ may require significant bracing of the tongue body to achieve and then sustain its interdental position, thus limiting pre-posturing for the upcoming vowel during articulation.

An alternative explanation for the surprising finding that the target vowel was equally difficult to predict in /θV/ and /ʃV/ sequences may have to do with the high visual salience of an interdental articulation. It could be that seeing the tongue tip beween the teeth distracts perceivers from attending to the more subtle cues associated with anticipatory vowel articulation, which are conveyed by jaw height, lip shape, and soft tissue deformations in the neck (due to changes in pharyngeal volume). Support for this methodological explanation of the finding comes from the unanticipated effect of the sentence frame on findings reported in Redford et al. (2018). In that study, the metrical context for a determiner noun phrase was manipulated by with the verb: in one condition the plain verb "pack" was used; in the other, the phrasal verb "pack up" was used. The task was to predict whether the rhyme of the target noun was "oop" (= [uːp]) or "ack" (= [æk]). When the bilabial stop was adjacent to the onset of the determiner (i.e., the "pack up" condition), perceivers were strongly biased towards an "oop" response; no such bias existed in the "pack" condition. Although we used a bias-corrected accuracy measure here (as well as in the Redford et al. study), the results could still indicate that perceivers are influenced by processing factors that are extraneous to the construct of interest (i.e., coarticulation).

Experiment 2

The perplexing result of equivalent perceiver performance across the /θ/ and /ʃ/ conditions in Experiment 1 may be an epiphenomenon of the perceptual method used to measure anticipatory coarticulation. This possibility leads us wonder whether the absence of an effect of age group on prediction accuracy in Experiment 1 may also be due to methodological factors. Two such factors comes to mind: the increment of measurement and the small number of speakers within each age group.

In Experiment 1, gates were mostly aligned to the midpoint of a segment, except for the fricative gate where it was placed at the release of the fricative constriction and before the onset of the voiced resonances for the upcoming vowel. The target vowel was not reliably predicted until this fricative gate in older children and in adults. This suggests that the coarticulatory action of specific interest to us is taking place somewhere during the articulation of the fricative. In Experiment 2, we investigate this action in greater detail by testing for context-induced differences on dynamic spectral changes in the fricative in the context of different /əFV/ sequences. We also address the extremely small sample problem by measuring all 6 repetitions produced by all 26 speakers who were recorded. The results from Experiment 1 lead us to predict no effect of the target vowel on the spectral dynamics of schwa. The predictions for the spectral dynamics of the fricative depend on the constraints that create a coarticulatory resistance hierarchy, including developmental ones. If resistance to fricative-vowel coarticulation is due only to biomechanical conflict, and the phonemic English interdental is indeed articulated very similarly to the allophonic Catalan interdental, then the spectral dynamics of the fricative are expected to show stronger effects of the target vowel when the fricative is /θ/ than when it is /s/; the target vowel effect on fricative spectra should also be stronger for /s/ than for /ʃ/. But, if children's acquisition of fricatives depends on their being able to disengage from the vowel context, then we would expect to see effects of the target vowel on the spectral dynamics of the fricative that vary with the order of fricative acquisition; that is, the effect of target vowel should be stronger on early acquired /s/ and /ʃ/ than on the later acquired /θ/, especially in the youngest children's speech.

Methods

The participant characteristics, speech materials, and elicitation procedure used are described in detail under General Methods above. Here, we note that in addition to collecting AV data, audio-only data was also obtained using a wireless Shure ULX1-M1 microphone that was attach to a hat that participants wore. The wireless microphone sent audio information to Marantz Professional Solid State PMD660 where it was recorded at 44,100 Hz and 16-bit.

Measurement and analyses

Praat was used to segment the schwa preceding the fricative, the fricative, and the vowel following the fricative. Onset of the schwa was determined to be the end of aperiodic noise associated with the preceeding /ð/ in "the" and the onset of periodic noise and formant structure associated with the schwa. The offset was taken to be the dissipation of formant structure and an increase in the presence of aperiodic noise associated with the fricative onset in the target word. The offset of the schwa vowel was used as a marker for the onset of the fricative. The offset of the fricative was determined to be the end of aperiodic noise and the onset of formant structure and periodic noise associated with the stressed vowel in the target word. The offset of the fricative was used as the onset to the stressed vowel. The offset of the stressed vowel was determined in one of two ways, depending on if there was a following consonant or not. If there was a following stop/affricate consonant, offset of the vowel was determined by the onset of closure associated with the stop or stop portion of the affricate and the dissipation of formants structure. If there was no following consonant, the dissipation of intensity and formant structure in the waveform was used to identify vowel offset. Formants (F1-F3) were extracted at 10 equally spaced intervals for both vowels; center of gravity (COG) was extracted at 10 equally spaced intervals for fricatives. Formant tracking for F1, F2, and F3 were adjusted manually for each of the segmented vowels to ensure accurate tracking and then Hz values were extracted. For COG, a window of 0.03s was selected with each interval at the center of the selection and then COG was extracted. Statistical comparisons were performed in R (R Core Team, 2019) using smooth spline (SS)ANOVA (Gu, 2002). The technique has been used to analyze the effect of context on lingual trajectories based on ultrasound data (Davidson, 2006) as well as the effect of context on formant trajectories based on acoustic data (e.g., Howson & Redford, 2021). Here, we use the technique to analyze both formant and COG trajectories as a function of the target vowel context. Since the smoothing functions themselves are not interpretable from model outputs alone (Flego & Forrest, 2021), best fit contours and confidence intervals are visualized to identify context-dependent differences in the given trajectories. Statistically significant areas of differences can then be observed where the confidence intervals do not overlap on the SSANOVA plot.

We also calculated the root mean square error (RMSE) across COG trajectories to index vowel-dependent variability in fricative articulation within speaker in order to directly test for systematic differences due to Fricative and Age Group and the interaction of these two fixed effects. The RMSE was chosen because it compares to input vectors and provides a summary measure for how different the two vectors are from each other, with a larger number indicating more difference. Thus, we operationalize the difference between vocalic environments and use this as an indicator for coarticulatory resistance (i.e., higher RMSE = less resistance/more variability; lower RMSE = more resistance/less variability). COG values at each interval of measurment was averaged across repetitions within fricative, vowel context and speaker. We then used the rmse() function in the Metrics package (Hamner & Michael, 2018) in R (R Core

Team, 2021) to calculate RMSE, which is equal to the total difference in mean COG values across contour comparisons within speaker and so to variability in fricative articulation as a function of vowel context. Lower RMSE values indicate less vowel-dependent variability, or FV coarticulation, than higher RMSE values. The RMSE values were then entered as the dependent variable in a linear model that tested for the fixed effects of Age Group 3 levels: 5-year-olds, 8-year-olds, and Adults), Fricative (3 levels: /θ, s, ʃ/), and Context Comparison (3 levels: /Fi/ versus /Fæ/; Fi/ versus /Fu/; and /Fæ/ versus /Fu/). We included a random by participant intercept. Data visualization was performed with ggplot2 (Wickham, 2016).

Results

The results are presented by speaker age group. Within each age group, we present the SSANOVA plots with best fit contours for each segment in the /əFV/ sequences. The plots for /əθV/ are presented first, followed by the plots for /əsV/, and then /əʃV/. The contours and confidence intervals displayed in each plot are examined to identify vowel-dependent differences in fricative articulation. The extent of these differences gives rise to a description of segment-dependent coarticulatory resistance that is provided by way of summary for the results from each age group, prior to the detailed results. The results for adult speakers are presented first, followed by those from 8-year-old speakers, and then 5-year-old speakers. The order of presentation allows us to directly compare resistance hierarchies as a function of age, beginning with the mature hierarchy. Following the SSANOVA results, we present the results of the RMSE analysis.

Adult Speakers

The results from adult speakers indicate a coarticulatory resistance hierarchy that is consistent with expectations from the DAC model: /ʃ/ > /s/ > /θ/. More specifically, the COG trajectories for the interdental fricative vary substantially with the target vowel; those for the alveolar fricative vary much less with the target vowel; and, COG trajectories for the palatoalveolar fricative do not vary with vowel context. The results also suggest that fricative articulation blocks vowel-to-vowel coarticulation, regardless of fricative type: contours that are best fits of schwa formant trajectories did not vary with the target stressed vowel for any fricative. Detailed results follow.

Interdental fricative. Figure 4 presents the SSANOVA plots for the /əθV/ sequences produced by adult speakers. Best fit contours that correspond to formant or COG trajectories, depending on the segment, are color-coded by target vowel: /i, æ, u/. From left to right, the plots show formant trajectories for /ə/, followed by COG trajectories for the fricative, and then formant trajectories for the target vowel. The best fit contours clearly indicate the expected difference in F1, F2, and F3 trajectories for the target vowels, /i, æ, u/. There were also very clear differences in the COG trajectories as a function of this vowel: COG was highest for /u/, followed by /i/, and then /æ/. The markedly higher COG in the /u/ context suggests a retracted tongue tip during the fricative articulation in this context. If this is the case, then coarticulation with the following /u/ may have resulted in voiceless fricative articulation that was more akin to [s̪] than to [θ]. A more dental articulation would result in more airflow hitting the upper incisors causing more turbulent airflow and the higher COG that is observed for /θ/ in this context. This contrasts the typical articulation where the tongue is between the teeth (c.f., Narayanan, Alwan, & Haker, 1995), resulting in a more sibilant-like articulation. However, it is also possible that jaw height plays a significant role in shaping the COG of /θ/. The relative jaw height for each of the vowels /u/ > /i/ > /æ/ also reflects the COG levels from highest to lowest, respectively.

[Figure 4 about here]

Figure 4 indicates that the trajectory dynamics also differed by context: in the /u/ context, the COG trajectory increased across a greater number of intervals compared to in either the /i/ or /æ/ context; the early rise in the COG trajectory was steeper in the context of /i/ compared to /æ/. As expected based on the results from Experiment 1, /ə/ formant trajectories did not vary as a function of the target vowel.

Alveolar fricative. Figure 5 presents the SSANOVA plots for the /əsV/ sequences produced by adult speakers. Again, trajectories are color-coded by stressed vowel context. As before, the rightmost panel presents the best fit contours and confidence intervals for the F1, F2, and F3 measures, and – as expected – these differ with target vowel quality. The middle panel presents the best fit contours for /s/ measures. These indicate a significant effect of the target vowel on COG trajectories, even though this effect was weaker than for /θ/ (*cf.* middle panel in Figure 2 above). The /s/ COG trajectory was highest in the /æ/ context, followed by the /i/ and then the /u/ context. The dynamics of the /s/ trajectories were roughly similar across vowel contexts: a quick increase in COG was followed by a relatively steady COG until a quick fall at the end of articulation. Again, the target vowel had no effect on /ə/ formant trajectories, consistent with /s/-blocking of anticipatory vowel-to-vowel coarticulation.

[Figure 5 about here]

Palatoalveolar fricative. Figure 6 presents the SSANOVA plots for the /əʃV/ sequences produced by adult speakers. Contours color-coded by target vowel show the expected differences in formant trajectories for the vowels: /i, æ, u/. Unlike for /əθV/ or /əsV/, the middle panel shows no effect of target vowel on the COG trajectories. Unsurprisingly, the effect of target vowel is also not evident: the color-coded contours for schwa F1, F2, and F3 are entirely overlapped (leftmost panel).

[Figure 6 about here]

8-year-old Speakers

The results from 8-year-old speakers indicate a coarticulatory resistance hierarchy that is inconsistent with expectations from the DAC model: /ʃ/, /s/ > /θ/. Again, the interdental fricative varied more substantially with the target vowel than did the alveolar fricative, but this difference was smaller than in adult speech. The best fit contours for the alveolar and palatoalveolar fricative indicated differences in COG trajectories as a function of vowel context: /s/ and /ʃ/ were articulated differently before /i/ than before /æ/ or /u/. Detailed results follow.

Interdental fricative. Figure 7 presents the SSANOVA plots for the /əθV/ sequences produced by 8-year-old speakers. We again see the expected differences in formant trajectories by target vowel (rightmost panel). The effect of vowel on /θ/ trajectories was smaller than in the adults' data (*cf.* Figure 3), but there was nonetheless evidence of anticipatory fricative-vowel coarticulation: the COG trajectory was lower in advance of an /æ/ target compared to an /i/ or /u/ target; the COG trajectories also diverged beginning at fricative midpoint in advance of /i/ and /u/. Intriguingly, the formant trajectories for schwa (left) suggest some effect of the target vowel on schwa.

[Figure 7 about here]

Alveolar fricative. Figure 8 presents the SSANOVA plots for the /əsV/ sequences produced by 8-year-old speakers. The effect of target vowel on formant trajectories is clearly visible in the rightmost panel. Some effect of vowel was also evident during /s/ articulation: the COG trajectory was higher in advance of /i/ compared to /æ/ or /u/. Overall, though, the effect of vowel on /s/ was smaller than the effect of vowel on /θ/ in 8-year-olds' speech (*cf.* Figure 7 above); it was also smaller than the effect of vowel on /s/ in adults' speech (*cf.* Figure 5 above). There was no significant effect of target vowel on schwa formant trajectories: confidence intervals around the best fit lines overlap. The possible exception to this description is in the contours associated with the F1 measurements at schwa offset. There, F1 was slightly higher in the context of a low front vowel than in the context of either high vowel.

[Figure 8 about here]

Palatoalveolar fricative. Figure 9 presents the SSANOVA plots for the /əʃV/ sequences produced by 8-year-old speakers. The target vowel formants are again shown as best fit contours in the rightmost panel. There is a clear effect of this stressed vowel on /ʃ/ (middle panel), which is at odds with the adult data, in particular, COG was higher when the preceeding vowel was /i/ across the entire fricative interval. The effect of vowel on /ʃ/ is therefore stronger than the effect of vowel on /s/ in 8-year-olds' speech (see Figure 8). There is no effect of vowel target on schwa formant trajectories.

[Figure 9 about here]

5-year-old Speakers

The results from 5-year-old speakers indicate even more minimal fricative-vowel coarticulation than in older children's and adults' speech. Unlike in 8-year-olds' and adults' speech, the interdental fricative is at least as resistant as /s/ to the influence of the following vowel, and perhaps more so. The palatoalveolar fricative is again the most resistant to coarticulation, and so the hierarchy is: /ʃ/ > /θ/ ≥ /s/. This hierarchy suggests the influence of both biomechanical constraints and an order-of-acquisition effect on fricative-vowel coarticulation. Detailed results follow.

Interdental fricative. Figure 10 presents the SSANOVA plots for the /əθV/ sequences produced by 5-year-old speakers. The overlapping best fit contours in the leftmost panel again indicate no effect of target vowel on schwa formant trajectories. The expected difference in target vowel formant trajectories are shown in the rightmost panel. The stressed vowel had a very minimal effect on the preceding fricative: the confidence intervals around the best fit line indicate largely overlapping COG trajectories during /θ/ articulation as a function of vowel context. That said, the trajectories do separate somewhat beginning at the middle of the fricative in advance of /u/ versus /æ/.

[Figure 10 about here]

Alveolar fricative. Figure 11 presents the SSANOVA plots for the /əsV/ sequences produced by 5-year-old speakers. There was a significant difference in COG trajectories for /s/ when preceding /u/: the contour indicates an overall lower COG peak and shallower trajectory overall. There were no observed differences in the preceding /ə/ for any context.

[Figure 11 about here]

Palatoalveolar fricative. Figure 12 presents the SSANOVA plots for the /əʃV/ sequences produced by 5-year-old speakers. The confidence intervals around the contours indicate no vowel-dependent COG differences on the preceding /ʃ/. A small effect of vowel context was observed on /ə/ formant trajectories directly before articulation of /ʃ/: F1 was somewhat higher in the /i/ context than in the /æ/ or /u/ context. This difference is in the opposite direction of an effect of vowel height on F1 and so suggests the influence of the palatoalveolar fricative: in particular it suggests a slightly more anterior and constricted posture for this fricative in the /i/ context compared to the /æ/ or /u/ context.

[Figure 12 about here]

RSME Analysis

The RSME results revealed a main effect of Fricative [$F(2, 160) = 75.48$, $p < 0.001$] and Context Comparison [$F(2, 160) = 6.39$, $p = 0.002$], but not of Age Group [$F(2, 20) = 1.36$, $p = 0.280$]. The expected interaction between Fricative and Age Group was nonetheless significant [$F(4, 160) = 8.04$, $p < 0.001$]; the interaction between Group and Context Comparison was also significant [$F(4, 160) = 3.18$, $p = 0.015$]. The other interactions were not statistically significant [Fricative × Context, $F(4, 160) = 2.15$, $p = 0.077$; Group × Fricative × Context, $F(8, 160) = 1.39$, $p = 0.204$]. The R^2 metric for the model was 0.605.

Posthoc analyses on RSME values associated with fricatives revealed a significant difference between between /θ/ and /s/ *M* = 1216 (*SD* = 831) vs. *M* = 589 (*SD* = 300); p < 0.001], /θ/ and /ʃ/ *M* = 1216 (*SD* = 831) vs. *M* = 328 (*SD* = 171); p < 0.001], and /s/ and /ʃ/ (p = 0.002). The differences were consistent with a coarticulatory resistance hierarchy where /ʃ/ > /s/ > /θ/: the interdental fricative differed most across the vowel context comparisons in child and adult speech as shown in Figure 13. But posthoc tests also confirmed that /θ/ varied more across vowel contexts in adults' speech than in children's speech [adults vs. 8-year-olds, *M* = 1615 (*SD* = 1166) vs. *M* = 814 (*SD* = 388), *p* < 0.001; adults vs. 5-year-olds, *M* = 1615 (*SD* = 1166) vs. *M* = 1130 (*SD* = 491, *p* = 0.048)].

[Figure 13 about here]

Discussion

As in Experiment 1, the analysis of spectral dynamics indicated that fricative articulation largely blocks vowel-to-vowel coarticulation no matter the age of the speaker. Only a very few small differences in schwa formant trajectories were observed: before /θ/ in 8-year-old children's speech and before /ʃ/ in 5-year-old children's speech; only the adjustment before /θ/ in 8-year-olds' speech was consistent with vowel-to-vowel coarticulation. Also as in Experiment 1, the spectral dynamics indicated that /ʃ/ was more resistant to consonant-vowel coarticulation than /s/. But, unlike in Experiment 1, the finding was that /θ/ was least resistant to coarticulation. The /ʃ/ > /s/ > /θ/ resistance hierarchy was confirmed for all age groups in an analysis of overall difference (RMSE) between trajectories across vowel contexts within fricative. Still, there was an effect of age on /θV/ coarticulation. The best fit contours for the 10 measures taken during the fricative interval were markedly different for /θ/ across vowel contexts in adults' speech; the COG trajectories for /θ/ also varied with vowel context in 8-year-olds' speech, but not across the entire duration of frication; COG trajectories for /θ/ were also less variable across vowel contexts in 5-year-olds' speech compared to adults' speech. The SSANOVA results were confirmed in an analysis of overall vowel-dependent differences: RMSE values for /θ/ were higher in adults' speech than in either group of children's speech.

General Discussion

We studied anticipatory vowel coarticulation as a function of fricative identity in speech produced by school-aged children and college-aged adults to better understand the constraints that influence the development of segmental articulation. The hypothesis was that the spatial-temporal constraint of creating a sustained constriction for fricatives would lead to especially reduced vowel-to-vowel and consonant-vowel coarticulation during their early accurate production. The constraint would manifest as an order of acquisition effect whereby the especially late acquired interdental fricative, /θ/, would be more resistant to vowel coarticulation in young childrne's speech than the earlier acquired alveolar fricative, /s/, and possibly even more resistant than the palatoalveolar fricative, /ʃ/. The predicted /θ/ > /ʃ/ ≥ /s/ resistance hierarchy was not upheld across the different experiments. Instead, a final analysis in Experiment 2 clearly indicated /ʃ/ > /s/ > /θ/ across age groups: the target vowel had the smallest effect on the articulation of /ʃ/, the next smallest effect on /s/, and the largest effect on /θ/. The latter hierarchy is in line with predictions from the DAC model of lingual coarticulation (Recasens et al., 1997; Recasens & Espinosa, 2009), which references biomechanical constraints to explain patterns of coarticulation. According to this model, when tongue body movements are more constrained by the requirements of a constriction, anticipatory vowel-to-vowel and consonant-vowel coarticulation is low; when tongue body movements are less constrained by the requirements of a constriction, coarticulation is high. Palatoalveolar fricatives are thus expected to block anticipatory coarticulation more than alveolar fricatives, which in turn are expected to block anticipatory coarticulation more than interdental fricatives. This is because palatoalveolars are articulated by raising and fronting the tongue blade and predorsum, which requires more involvement of the tongue body (via contraction of the genioglossus) than the raising and fronting of the tongue tip or blade needed for the alveolar or interdental constrictions. Moreover, consonants, like /s/, which require precise control over constriction degree will also require more bracing by the tongue body than consonants, like /θ/, that are more ballistic in their movement, and so, /s/ is expected to block coarticulation more than /θ/.

Although order of acquisition did not upend the resistant hierarchy predicted by DAC, the perceptual and acoustic results nonetheless indicate developmental effects on coarticulation that are somewhat contradictory: the results indicate somewhat more vowel-to-vowel coarticulation in children's speech compared to adults' speech, and somewhat less fricative-vowel coarticulation in children's speech compared to adults' speech. The former result of increased vowel-to-vowel coarticulation is in line with previous findings (Rubertus & Noiray, 2018); the latter result of decreased fricative-vowel coarticulation – due as it is primarily to the interdental fricative – is consistent with the predicted order of acquisition effect. In what follows, we argue that the former result is compatible with holistic speech plans, and the latter with the emergence of segment-sized speech motor targets over developmental time. We begin with fricative-vowel coarticulation.

In the past decade, ultrasound studies of children's speech have largely confirmed Nittrouer and colleagues' interpretation of their /sV/ acoustic findings: younger children's speech is generally more coarticulated than older children's speech, which is more coarticulated than adults' speech (see, e.g., Nittrouer et al., 1989; Zharkova et al., 2011; 2012; Noiray et al., 2018; Rubertus & Noiray, 2018). Nittouer and colleagues framed their interpretation with reference to the whole word production hypothesis, which first arose in the 1970s to account for the patterns observed in child phonology (e.g., Waterson, 1971; Ferguson & Farwell, 1975; Menn, 1983). In speech, one version of the hypothesis is that early speech plan representations are gestural amalgams (Studdert-Kennedy, 1991); another is that speech plan representations are holistic motor and perceptual forms that are integrated during the production process (Redford, 2019). Either way, the hypothesis assumes a differentiation process to explain how children come to acquire segment-like behaviors that characterize adult speech. At the level of speech motor control, this means overcoming biomechanical linkages such as the linkage that exists between the tongue body and tongue tip.

We had previously proposed that children adopt a tongue-body first strategy to facilitate sequential production of different speech sounds (Howson & Redford, 2021). This strategy accounts for the higher levels of vowel-to-vowel and stop-vowel coarticulation generally observed in children's speech, as well as our findings of strong anticipatory vowel effects on liquid production in children's speech compared to adults' speech and the finding that young children do not distinguish /l/ from /ɹ/ along the F2 dimension prior to maximal constriction of the vocal tract in contrast to adult speech (Howson & Redford, 2021). The current study asked: How does a child overcome a tongue-body first strategy to produce fricatives, which require a sustained constriction to generate turbulence? We hypothesized that children must pass through a developmental stage where they *disengage* the fricative from the vocalic environment in order to acquire the speech sound (i.e., produce it correctly). This hypothesis predicts that young children who have only recently acquired fricatives should exhibit less fricative-vowel coarticulation than older children and adults, and so that later acquired fricatives should be less coarticulated with surrounding vowels than earlier acquired fricatives. The results from Experiment 1 were inconclusive, but the results from Experiment 2 provide some support for the latter hypothesis: children's fricatives were less influenced by vowel context than adults' fricatives overall; moreover, the interdental fricative – which is typically acquired last of the voiceless fricatives – was more resistant to influences from a subsequent vowel in children's speech than in adults' speech.

But, if children are disengaging the tongue body from the vowel context when producing fricatives, why is it that fricatives did not also fully block vowel-to-vowel coarticulation in the youngest speakers? Recall, that the strongest evidence for vowel-to-vowel coarticulation comes from Experiment 1 where perceivers were at above chance accuracy in predicting the target stressed vowel at the midpoint of the unstressed determiner vowel in 5-year-olds' speech. The accuracy measure was bias-corrected, which meant collapsing across the response options of /i/

or /u/ or /æ/. Given these options, the anticipatory effect on schwa must be understood as an effect of vowel backness or an effect of vowel height or an effect of vowel rounding or as some combination of these effects. Whereas an effect of vowel backness would undermine the disengagement hypothesis for fricative articulation, an effect of vowel rounding would only be consistent with the idea that the child's speech plan is at least the size of a determiner + noun. An effect of vowel height might be understood as either an effect of jaw position or tongue body position, and so is less diagnostic than the other effects.

To better understand what anticipatory vowel postures perceivers detected at the midpoint of the schwa in 5-year-olds' speech, we examined the uncorrected accuracy data shown in Figure 13. These data suggest an overall response bias towards /i/ that is evident across the early gates. Such a bias is consistent with the narrow constriction required for fricative articulation. This bias was marginally reduced in 5-year-olds' speech. At the same time, accuracy for /u/ increased marginally at the determiner gates in 5-year-olds' speech. Together, the data suggest that perceivers detected an effect of anticipatory rounding on schwa production in the youngest children's speech. A similar effect might account for the small context-dependent formant differences observed for schwa in 8-year-olds' speech. Either way, the results do not undercut the disengagement hypothesis used to explain why /θV/ sequences were less coarticulated in children's speech compared to adults' speech.

[Figure 14 about here]

Overall, the present results suggest that the DAC model of coarticulation generalizes to explain coarticulatory patterns in children's speech. The results are also compatible with a developmental scenario for fricative acquisition that includes a stage during which the articulation is disengaged from the vocalic environment. Once the constriction target for a fricative target is well established, movements into and out of its articulation can again be optimized for context. As a consequence, anticipatory posturing for the subsequent vowel increases with speech practice – to the extent allowed by the fricative constriction target itself. The present results suggest that the practice effects may extend for some time after accurate production of a fricative is achieved.

We conclude with separate notes on the mismatch between our perceptual results from Experiment 1 and the acoustic results from Experiment 2 since we believe these to raise new and interesting questions that could be addressed in future studies on fricative-vowel coarticulation.

In Experiment 1, perceivers' performance suggested that /θ/ was as resistant to coarticulation as /ʃ/. But, in Experiment 2, /θ/ acoustics were found to be profoundly influenced by the adjacent vowel in adults' speech and, to a lesser extent, in 8-year-olds's speech. We interpret the mismatch to suggest the importance of visual cues to the perception of /θ/ and the relative unimportance of acoustic cues. After all, the interdental fricative is an especially low intensity and spectrally diffuse sounds, which is easily confused with others. While articulatory complexity and aerodynamic properties of /θ/ likely play a role in delayed acquisition, we assumed that their weak spectral profile also provides part of the explanation for the slow acquisition of /θ/ relative to the other fricatives. But there is also substantial individual differences in the order with which sounds are acquired. Some children no doubt acquire /θ/ early relative to their peers. Others even use /θ/ to substitute for /s/. The mismatch between our perceptual and acoustic results suggest a reason for individual differences: it could be that different orders of acquisition of /θ/ reflects differences in the extent to which children are sensitive to visual information in the acquisition of speech goals.

Other smaller mismatches between the perceptual results in Experiment 1 and acoustic results in Experiment 2, such as the greater effect of vowel context on /ʃ/ in AV speech judgments than on acoustics, also beg the question of how children may exploit visual cues in the acquisition of running speech. Does the presence of visible cues to coarticulation influence the acquisition of coarticulatory patterns? Many of these patterns will be language-specific, suggesting that coarticulation cannot simply emerge as an epiphenomenon of speeded movements into and out of sequential targets. The prolonged acquisition of adult-like fricative-vowel production provides an opportunity to explore these ideas and related questions in future work.

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Appendix

Table 2. Confusion matrix for /i, æ, u/ responses for all stimuli (top left), /θ/ (top right), /s/ (bottom left), and /ʃ/ (bottom right).

ALL

Target	**Response**		
	i	æ	u
i	0.519	0.272	0.207
æ	0.395	0.398	0.205
u	0.352	0.262	0.384

θ

Target	**Target**		
	i	æ	u
i	0.531	0.240	0.228
a	0.413	0.361	0.224
u	0.409	0.244	0.345

s

Target	**Response**		
	i	æ	u
i	0.531	0.240	0.228
æ	0.413	0.361	0.224
u	0.409	0.244	0.345

ʃ

Target	**Response**		
	i	æ	u
i	0.485	0.307	0.208
a	0.347	0.450	0.201
u	0.333	0.287	0.378

Figure Captions

Figure 1. The final frame for each cut from one repetition of a 5-year-old's production of I bought the she hat (aj b$|^{1}$ *a*$|^{2}$ *tθ*$|^{3}$ *ə*$|^{4}$ *ʃ*$|^{5}$ *i*$|^{6}$ *hæt).*

Figure 2. Rand Index (ACC) by gate, fricative condition, and the speakers' age groups. The dotted line on the plot indicates the threshold for being above or below chance.

Figure 3. Rand Index (ACC) by gate and the speakers' age groups. The dotted line on the plot indicates the threshold for being above or below chance.

Figure 4. Trajectories for adult /əθV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /θ/ (center). Color coding is by vowel target.

Figure 5. Trajectories for adult /əsV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /s/ (center). Color coding is by vowel target.

Figure 6. Trajectories for adult /əʃV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /ʃ/ (center). Color coding is by vowel target.

Figure 7. Trajectories for 8-year-old /əθV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /θ/ (center). Color coding is by vowel target.

Figure 8. Trajectories for 8-year-old /əsV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /s/ (center). Color coding is by vowel target.

Figure 9. Trajectories for 8-year-old /əʃV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /ʃ/ (center). Color coding is by vowel target.

Figure 10. Trajectories for 5-year-old /əθV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /θ/ (center). Color coding is by vowel target.

Figure 11. Trajectories for 5-year-old /əsV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /s/ (center). Color coding is by vowel target.

Figure 12. Trajectories for 5-year-old /əʃV/ sequences: formant trajectories for schwa (left) and target vowel (right); COG trajectories for /ʃ/ (center). Color coding is by vowel target.

Figure 13. Boxplots of RMSE for Age Group × Fricative.

Figure 14. Raw accuracy measures for /i/ (left), /æ/ (middle), and /u/ (right), for each fricative /s/ (top), /ʃ/ (middle), /θ/ (bottom). Adults are in blue, 8-year-olds are in green, and 5-year-olds are in red.