Research Article

Fricative Contrast and Coarticulation in Children With and Without Speech Sound Disorders

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Purpose: The purpose of this study was, first, to expand our understanding of typical speech development regarding segmental contrast and anticipatory coarticulation, and second, to explore the potential diagnostic utility of acoustic measures of fricative contrast and anticipatory coarticulation in children with speech sound disorders (SSD).

Method: In a cross-sectional design, 10 adults, 17 typically developing children, and 11 children with SSD repeated carrier phrases with novel words with fricatives (/s/, /ʃ/). Dependent measures were 2 ratios derived from spectral mean, obtained from perceptually accurate tokens. Group analyses compared adults and typically developing children; individual children with SSD were compared to their respective typically developing peers.

Results: Typically developing children demonstrated smaller fricative acoustic contrast than adults but similar coarticulatory patterns. Three children with SSD showed smaller fricative acoustic contrast than their typically developing peers, and 2 children showed abnormal coarticulation. The 2 children with abnormal coarticulation both had a clinical diagnosis of childhood apraxia of speech; no clear pattern was evident regarding SSD subtype for smaller fricative contrast.

Conclusions: Children have not reached adult-like speech motor control for fricative production by age 10 even when fricatives are perceptually accurate. Present findings also suggest that abnormal coarticulation but not reduced fricative contrast is SSD-subtype-specific.

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Speech production involves a complex motor skill that requires rapid and precise articulator movement patterns. Successful speech communication depends, in part, on this motor skill to produce adequate contrasts and transitions between speech sounds. Given the complex nature of speech production, it is not surprising that speech motor development lasts well into the school years (e.g., Nittrouer, 1995; Smith & Zelaznik, 2004). It is also not surprising that some children have difficulty acquiring adequate speech motor skills. Although speech motor control is presumed impaired in children with childhood apraxia of speech (CAS; e.g., Nijland et al., 2002), it is not clear whether such impairments are specific to CAS or whether they also occur in children with other speech sound disorders (SSD), such as phonological disorders (PD). In addition, it is not clear

whether different aspects of speech motor control, such as implementing adequate contrasts between speech sounds and transitioning between speech sounds, are affected differentially in different types of SSD.

The present study was designed to examine speech motor control in children with and without speech disorders, with a specific focus on segmental contrast and anticipatory consonant–vowel (CV) coarticulation. Segmental contrast is defined as the ability to differentiate speech sounds, and anticipatory coarticulation is defined as the ability to plan and transition into subsequent speech sounds (e.g., Lane, Matthies, Perkell, Vick, & Zandipour, 2001; Nittrouer, Studdert-Kennedy, & McGowan, 1989). Segmental contrast and coarticulation both represent aspects of speech production that require fine motor control, and as such, may provide a window into the development and disorders of complex speech motor skills. Further, segments do not occur in isolation. The phonetic context of a speech sound may affect the ability to achieve adequate contrast and, vice versa, the ability to achieve distinct contrast may affect the transitions between sounds (coarticulation). It is also possible that these two aspects of speech motor control represent distinct underlying skills, which may develop and be impaired differentially. For these reasons, the present study examined both contrast and coarticulation via acoustic

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measures. Sibilant fricatives served as the vehicle to study these aspects of speech motor control for several reasons. First, these speech sounds require relatively fine control over tongue placement (e.g., Nittrouer, 1995) and therefore were expected to reveal differences even in children in the elementary school age range. Second, this speech sound contrast is important for intelligibility. For example, Kent et al. (1990) showed that it was among the contrasts most related to intelligibility in speakers with dysarthria. Third, well-established acoustic measures are available to capture fricative production.

The long-term goal of this research is to develop clinically useful, validated, and sensitive diagnostic measures that can be used to identify, and differentiate between, underlying impairments in children with SSD. The primary aim of the current study was to explore the potential utility of two acoustically based measures for distinguishing different types of SSD. A secondary aim was to advance our understanding of typical speech motor development with respect to segmental contrast and anticipatory coarticulation. In the next sections, we first briefly provide relevant background regarding typical development of fricative articulation, followed by background regarding fricative production in children with SSD.

Typical Speech Motor Development

Speech motor development is a complex process that takes place over a period of up to 14 years (e.g., Smith & Zelaznik, 2004). Two critical aspects of speech motor control to be acquired are the ability to implement language-specific contrasts between speech sounds (articulatorily, acoustically, perceptually), and the ability to transition efficiently between successive speech sounds. We discuss each in turn below.

Fricative Contrast

As noted, one critical aspect of speech motor control is the ability to produce contrasts between different speech sounds so that a listener can identify the intended target. For sibilant fricatives, the spectral mean or center of gravity, also referred to as the first moment or *m1* (Forrest, Weismer, Milenkovic, & Dougall, 1988; Jongman, Wayland, & Wong, 2000), is considered one of the main acoustic cues for perceptual discrimination of place of articulation, with higher spectral means for /s/ than for /ʃ/ in adult productions (e.g., Newman, Clouse, & Burnham, 2001). Spectral mean is thought to reflect primarily aspects of articulation related to the size of the cavity in front of the constriction as well as the shape of this constriction, with lower values for larger cavities (Heinz & Stevens, 1961; Nittrouer, 1995; Nittrouer et al., 1989). Thus, it is expected that postalveolar /ʃ/ has lower spectral means than alveolar /s/ because /ʃ/ involves a more posterior constriction than /s/ and typically involves lip rounding, both of which serve to increase the cavity anterior to the constriction.

A number of studies have reported age-related differences in acoustic measures of fricative contrast across

development (e.g., Nissen & Fox, 2005; Nittrouer, 1995; Nittrouer et al., 1989). For example, Nittrouer et al. (1989) examined acoustic fricative contrast in typically developing (TD) children between ages 3 and 7 years, in the context of reduplicated syllables (/ʃiʃi/, /ʃuʃu/, /sisi/, /susu/). On the basis of spectral means from the midpoint and offset of the second (intervocalic) fricative, they reported higher spectral means for /s/ than for /ʃ/ for all age groups, indicating that even young children differentiated these fricatives. However, the difference between fricatives in terms of spectral mean was smaller in children than in adults, suggesting that children are still acquiring and refining the motor skill required for production of these fricatives. Other studies have replicated the finding of an increase in spectral mean contrast with age (e.g., Fox & Nissen, 2005; Holliday, Reidy, Beckman, & Edwards, 2015; Nissen & Fox, 2005; Nittrouer, 1995), although some reported that 3-year-old children may not discriminate these fricatives using spectral means (Nissen & Fox, 2005).

In summary, available evidence suggests that although children (at least as young as 5 years) differentiate fricatives in their productions in terms of spectral mean, this differentiation is smaller than in adults up to at least age 7 years. This smaller differentiation suggests that children up to age 7 years have not yet mastered the motor control required to produce articulatory configurations that implement these fricatives in an adult-like manner. The present study aims to replicate these findings and expand them in several ways. First, we include a group of children between ages 8 and 10 years to determine whether children acquire adult-like acoustic fricative contrast by this age. Second, to investigate the possibility that children are capable of reaching adult-like acoustic contrast but achieve this contrast later in the fricative, we examine the contrast at three points in the fricative (onset, middle, offset). Third, we examine trial-to-trial variability associated with fricative production, in terms of temporal (fricative duration) and spatial (spectral mean) aspects.

Anticipatory Coarticulation

A second critical aspect of speech motor control is the ability to transition between successive articulatory configurations. The focus here is on anticipatory coarticulation, in which a later-occurring speech sound influences a preceding one, and relates to the ability to plan ahead and transition into subsequent speech sounds (Lane et al., 2001; Nittrouer et al., 1989; Whalen, 1990). As such, anticipatory coarticulation offers a window into speech motor planning because such influences can only arise if the speaker knows what the subsequent speech sound will be.

With respect to typical speech development, there are conflicting findings in the literature regarding whether children show greater, comparable, or smaller anticipatory coarticulation than adults. In the same study described above involving /s/ and /ʃ/, Nittrouer et al. (1989) reported that children between ages 3 and 7 years showed greater anticipatory coarticulation than adults when examining

second formant (F2) ratios (i.e., higher F2 in fricative before /i/ than before /u/; see also Nittrouer, Studdert-Kennedy, & Neely, 1996; Siren & Wilcox, 1995). This greater coarticulation was interpreted as reflecting larger phonetic planning units in children than in adults, with a subsequent emergence of smaller, phoneme-sized units (Nittrouer et al., 1989). According to this view, greater coarticulation would be expected if children's planning units include both the consonant and the vowel, because then the identity of the subsequent vowel is an integral part of the planning of the consonant. In contrast, if planning involved separate consonant and vowel units, the vowel may be less likely to influence the preceding consonant.

However, a number of studies have failed to replicate these findings of greater coarticulation in children than in adults when using F2 ratios, instead reporting no differences as a function of age (e.g., Katz, Kripke, & Tallal, 1991; Munson, 2004; Sereno, Baum, Marean, & Lieberman, 1987). Furthermore, on the basis of a perceptual identification experiment, Katz et al. (1991) found that adult listeners were able to identify the upcoming vowel from excised fricatives produced by adults and children between ages 5 and 8 years, but not those produced by 3-year-old children, suggesting smaller coarticulation in younger children than in older children and adults, and thus perhaps the use of segment-sized planning units (as in adults) with less efficient transitioning abilities.

A number of methodological differences may lie at the root of these discrepancies, and one of the complications with the above studies is the difficulty in identifying vowel formants in children's speech, given their high fundamental frequency. For this reason, use of measures that circumvent the problem of high fundamental frequencies might be more tractable and feasible. Given that fricative spectral means reflect to some degree the shape and location of constriction, and that different vowels (such as /i/ and /u/) involve different tongue and lip positions in the anterior–posterior dimension, it stands to reason that spectral means should be capable of detecting coarticulatory influences of subsequent vowels if such coarticulation is present. Although comparisons based on spectral mean vowel ratios (e.g., m_{1i} / m_{1u}) have not revealed clear age-related differences (Katz et al., 1991; Nittrouer et al., 1989), only a small number of studies have examined spectral mean ratios as a measure of coarticulation (Katz et al., 1991; Nittrouer et al., 1989; Waldstein & Baum, 1991), and the numerical pattern reported by Nittrouer et al. (1989) was in the direction of higher ratios (greater coarticulation) for children than for adults.

The present study followed up on these prior studies and examined spectral mean ratios as a measure of coarticulation in TD children. We expand on previous work by including children between 8 and 10 years old, and by examining spectral mean ratios at three timepoints in the fricative (onset, middle, offset) to characterize potential changes over time during the fricative (e.g., whether children take longer to anticipate upcoming vowels).

Speech Sound Disorders

SSD are relatively common in children, with prevalence estimates varying from approximately 10%–15% of preschoolers (Gierut, 1998; McLeod & Harrison, 2009) and 4%–10% for school-age children (Gierut, 1998; Shriberg, Tomblin, & McSweeney, 1999). Moreover, children with SSD account for the single largest portion of the caseload for school-based speech-language pathologists in the United States (ASHA, 2014; Mullen & Schooling, 2010).

It is generally agreed that not all SSD are the same, in terms of overt features or underlying impairment (e.g., Terband, Maassen, & Maas, 2016), and a number of different classification schemes have been proposed in the literature (e.g., Dodd, 2014; Shriberg, Austin, Lewis, McSweeney, & Wilson, 1997; Shriberg, Lohmeier, Strand, & Jakielski, 2012; see also Waring & Knight, 2013). Such classification schemes are validated to the extent that the proposed categories differ on relevant measures. One of the complicating factors is that there is considerable overlap in symptoms between different SSD types (Terband et al., 2016), and symptoms are not always operationalized. As noted above, a long-term goal of our research is to develop diagnostic measures that are capable of identifying and differentiating between different types of speech impairments.

Fricative Contrast

Although a number of studies have examined fricative spectra in children with SSD (e.g., Daniloff, Wilcox, & Stephens, 1980; Glaspey & MacLeod, 2010; Karlsson, Shriberg, Flipsen, & McSweeney, 2002), to the best of our knowledge no published studies have examined acoustic fricative contrast in children with SSD. Acoustic studies of other segmental contrasts generally indicate a reduced contrast in children with SSD compared to TD children (e.g., Edwards, Fourakis, Beckman, & Fox, 1999; Forrest, Weismer, Elbert, & Dinnsen, 1994; Forrest, Weismer, Hodge, Elbert, & Dinnsen, 1990; Nijland et al., 2002; Sussman, Marquardt, & Doyle, 2000), even for perceptually adequate segmental contrasts in children with SSD (Forrest et al., 1990; Nijland et al., 2002).

The present study extends previous research on segmental contrast in children with SSD by examining fricative contrast for perceptually adequate voiceless sibilants, at three points in the fricative (onset, middle, offset). We examine children with a variety of speech impairment profiles to begin to explore whether reduced contrast is specific to certain SSD profiles.

Anticipatory Coarticulation

With respect to anticipatory coarticulation, available evidence suggests that children with CAS have atypical coarticulatory patterns (e.g., Nijland et al., 2002, 2003; Sussman et al., 2000). For example, Nijland et al. (2002) asked children with CAS to repeat a carrier phrase with novel CV words that varied systematically in consonant and vowel. Nijland et al. (2002) examined F2 ratios (e.g.,

$F2_i / F2_u$) at several points during the utterance (for perceptually accurate tokens only), and reported that children with CAS showed idiosyncratic differences from typically developing children, with some children producing greater coarticulation and others producing less coarticulation. These findings have been influential in that the ASHA technical report on CAS (ASHA, 2007) lists abnormal coarticulatory transitions as one of three potential diagnostic features, largely on the basis of these acoustic studies. However, as noted by Nijland et al. (2002) as well, the lack of a non-CAS SSD group in these studies means that the specificity of abnormal coarticulation is uncertain. Perhaps abnormal coarticulation is an aspecific feature of SSD regardless of subtype, as has been suggested in a small number of studies that examined acoustic correlates of coarticulation in children with other SSD, including articulation disorders (e.g., Daniloff et al., 1980) and PD (e.g., Hewlett, 1988; Tyler, Figurski, & Langsdale, 1993). All of these studies also report abnormal coarticulation in these children.

Thus, to the extent that studies have examined acoustic measures of anticipatory coarticulation in children with SSD, none have included children with different types of SSD, and review of between-studies findings indicate that abnormal coarticulation may be present in CAS as well as in PD or articulation disorders. As a result, the potential value of abnormal coarticulation to distinguish between SSD subtypes and identify underlying impairments is unclear. Last, no studies have used spectral moments to examine fricative coarticulation in children with SSD. The present study examined anticipatory coarticulation in children with different SSD types based on spectral means obtained from voiceless fricatives in order to begin to explore any potential differential effects as a function of SSD.

Method

Participants

This study reports findings from a total of 38 participants. Participants include 10 women, 17 TD children, and 11 children with SSD (see Tables 1 and 2). Both TD and SSD groups were divided into two age groups, one between 5 and 7 years old (TD6, $n = 8$; SSD6, $n = 8$) and one between 8 and 10 years old (TD9, $n = 9$; SSD9, $n = 3$). An additional 16 children (three TD6, one TD9, 11 SSD6, and one SSD9) were recruited but excluded from this study for various reasons (malocclusion, high error rates, significant language impairment, incomplete data, recording/analysis concerns).

All participants were monolingual native speakers of American English and passed a hearing screening at 0.5, 1.0, 2.0, and 4.0 kHz at 20 dB (ASHA, 1997) in both ears. Adults reported no history of speech, language, or cognitive disorders or neurological history. In addition, all children met the following inclusion criteria: (a) adequate oral structure and function, on the basis of an oral mechanism

exam (Robbins & Klee, 1987); (b) normal or near-normal language skills as determined by the Clinical Evaluation of Language Fundamentals Screening Test (CELF; Semel, Wiig, & Secord, 2004)¹; and (c) receptive vocabulary within normal limits as determined by standard scores ≥ 85 on the Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4; Dunn & Dunn, 2007). Additional tests were administered for descriptive purposes to most children, including the Expressive Vocabulary Test–Second Edition (EVT-2; Williams, 2007), the nonverbal subtests of the Reynolds Intellectual Assessment Scales (RIAS; Reynolds & Kamphaus, 2003), and the Dynamic Evaluation of Motor Speech Skill (DEMSS; Strand, McCauley, Weigand, Stoeckel, & Baas, 2013).

Children were designated as TD or as having an SSD, on the basis of clinical judgment by an experienced speech-language pathologist. Children in the TD groups demonstrated speech skills within the normal range, based on a percentile rank > 16 on the Goldman-Fristoe Test of Articulation–Second Edition (GFTA-2; Goldman & Fristoe, 2000) and clinical judgment. Children in the SSD group demonstrated speech skills below the normal range, based on a percentile rank of < 16 on the GFTA-2 and/or clinical judgment based on all speaking tasks conducted as part of the assessment, including conversational speech.² Children ranged in severity and nature of their speech sound error profile, and represented a relatively heterogeneous group. For this reason, we present individual data for each child and do not report group-level analyses involving children with SSD. Based on clinical judgment, children's speech error profiles were characterized as PD, articulation disorder (Artic), and/or CAS. The designation PD was on the basis of the presence of relatively consistent error patterns operating on speech sound classes or structures, such as stopping, velar fronting, or weak syllable deletion. The label Artic refers to the presence of relatively consistent distortions of a small number of speech sounds, such as a frontal lisp. The label CAS was based on presence of inconsistent errors on vowels and consonants, difficulty transitioning between speech sounds, and/or abnormal prosody (ASHA, 2007). As can be seen in Table 2, several children exhibited clinical evidence of multiple SSD types. Given the difficulties in diagnosing SSD subtypes due to lack of validated tests for CAS (e.g., McCauley & Strand, 2008), possibility of co-occurrence of multiple disorder types

¹All but two children met the criterion score for their age on the CELF Screening Test (Semel et al., 2004). In both cases (participants 304 and 316), the below-criterion score was affected considerably by low intelligibility for productive tasks on the screener, and as such may represent an underestimate of their language abilities. Both children demonstrated receptive and expressive vocabulary scores within the normal range.

²Some children received percentile ranks > 16 on the GFTA-2 but were classified as SSD based on clinical judgment, as the GFTA-2 only includes evaluation of consonants. Some children's speech difficulties were observed on vowels and suprasegmental aspects of speech.

Table 1. Participant group information.

Group	<i>n</i>	Sex	Age (y;m) (SD)	PPVT-SS (SD)	EVT-SS (SD)	GFTA-SS (SD)	GFTA percentile (SD)	NIX-T (SD)
Adult	10	10F, 0M	20;10 (0;11)	111 (11)	111 (13)	—	—	—
TD6	8	7F, 1M	6;6 (0;11)	118 (16)	113 (11)	108 (3)	60 (11)	63 (13)
TD9	9	3F, 7M	9;1 (0;9)	111 (11)	113 (12)	104 (3)	38 (11)	60 (4)
SSD6	8	2F, 6M	6;3 (0;6)	106 (14)	103 (15)	79 (22)	14 (12)	64 (4)
SSD9	3	0F, 3M	9;11 (1;7)	115 (14)	109 (4)	89 (9)	9 (2)	62 (4)

Note. PPVT = Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007); EVT = Expressive Vocabulary Test–Second Edition (Williams, 2007); GFTA = Goldman-Fristoe Test of Articulation–Second Edition (Goldman & Fristoe, 2000); NIX-T = Nonverbal Intelligence Quotient *T*-score (Reynolds & Kamphaus, 2003); SS = standard score; TD6 = typically developing children between 5 and 7 years old; TD9 = typically developing children between 8 and 10 years old; SSD6 = children with SSD between 5 and 7 years old; SSD9 = children with SSD between 8 and 10 years old; SSD = speech sound disorders; F = female; M = male.

and overlap in symptoms (e.g., Terband et al., 2016), it should be emphasized that these labels are based on clinical impression rather than specific test scores, and as such should be interpreted as descriptive labels to facilitate exploration of relations between SSD characteristics and performance on the experimental measures. Additional information for each child in the SSD6 group is provided in Table 3. The three SSD9 children all had relatively mild SSD and were more homogeneous in that they all were diagnosed only with an articulation disorder. Participant 201's errors were restricted to rhotic sounds (derhotacization of /l, æ, ʌ/), whereas both 307 and 312 produced occasionally dentalized /s/ and /z/.

The SSD6 and TD6 groups differed only in articulation scores (GFTA-SS), $F(1, 14) = 13.23, p = .003$, but not in nonverbal cognition (NIX-T), $F < 1$, n.s.; expressive vocabulary (EVT-SS), $F(1, 14) = 2.50, p = .136$; receptive vocabulary (PPVT-SS), $F(1, 14) = 2.69, p = .123$; or age (in months), $F < 1$, n.s. For the SSD9 and TD9 groups, significant differences were noted only for articulation skills (GFTA-SS), $F(1, 10) = 22.11, p < .001$; no differences were observed for receptive or expressive vocabulary or nonverbal cognition, $F_s < 1, p_s > .40$, or age, $F(1, 10) = 1.52, p = .245$.

Adults were recruited from the University of Arizona student population and received course credit or monetary compensation (\$10/hr) for their participation. Children were recruited from the University clinic, local schools, and local speech-language pathologists, and received small toys for their participation. All participants and parents provided informed consent, and all procedures were approved by the local Institutional Review Board.

Materials

Materials included nine novel /CVb/ words, with $C = /s, z, ʃ/$ and $V = /i, a, u/$. Novel words were embedded in the carrier phrase “It’s the ____ again!” (e.g., “It’s the *soob* again!”). These materials and carrier phrase were selected in part to be comparable to those of Nijland et al. (2002, 2003). Each novel word was paired with a color drawing of an “alien” creature (Ohala, 1999), set on a background representing a planet far away. Each target utterance was prerecorded for the repetition task by an adult female native speaker of American English. The focus of the present article is on the voiceless sibilants /s ʃ/ and the vowels /i u/ (i.e., *seeb, soob, sheeb, shoob*).

Table 2. Individual participant information for children with SSD.

Group	Participant ID	Age (y;m)	Sex	PPVT-SS	EVT-SS	GFTA-raw	GFTA-SS	GFTA-%ile	NIX-T	Diagnosis ^a
SSD6	104	6;7	M	96	97	22	72	7	69	PD + Artic
	107	6;2	M	106	94	18	83	12	59	PD
	300	5;6	M	117	120	14	96	29		CAS
	304	5;7	M	106	91	51	44	1		PD + CAS
	316	6;10	M	89	90	34	49	1	63	PD + CAS
	317	6;6	F	113	118	6	100	24	65	CAS
	319	6;1	M	90	90	8	99	30	63	PD + Artic
	320	6;8	F	128	122	11	90	10		CAS + Artic
SSD9	201	8;1	M	130	112	11	79	7	65	Artic
	307	10;9	M	103	104	3	96	11	62	Artic
	312	10;11	M	113	110	4	93	9	58	Artic

Note. PPVT = Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007); EVT = Expressive Vocabulary Test–Second Edition (Williams, 2007); GFTA = Goldman-Fristoe Test of Articulation–Second Edition (Goldman & Fristoe, 2000); NIX-T = Nonverbal Intelligence Quotient *T*-score (Reynolds & Kamphaus, 2003); SS = standard score; SSD6 = children with SSD between 5 and 7 years old; SSD9 = children with SSD between 8 and 10 years old; SSD = speech sound disorders; F = female; M = male; PD = phonological disorder; Artic = articulation disorder; CAS = childhood apraxia of speech.

^aDiagnoses are based on clinical expert speech-language pathologist judgment.

Table 3. Individual participant information for SSD6 children.

ID	Diagnosis ^a	Processes ^b (%)	Not in phonological inventory ^c			Notes
			Initial	Medial	Final	
104	PD + Artic	LS: 29	/l, θ, s, z/	/f, θ, s, z, ð/	/f, θ, s, z/	/l/ → /w/ initial position & clusters. Dentalized /s, z/. /l, ɹ/ → /w/ initial and medial; /θ/ → /f/ all positions; /ð/ → /d/ medial; /ə, ɜ/ derhotacized.
107	PD	LS: 74	/l, ɹ, θ/	/l, ɹ, θ, ð/	/θ/	
300	CAS	LS: 58	/ɹ, dʒ/	/ɹ/	/ɹ/	Segmented speech; equal/excess stress; intermittent hypernasality; distortion errors; no frank vowel errors. Occasional dentalized /s, z/. /ɹ/ derhotacization, all positions and clusters; /l/ distortions in clusters.
304	PD + CAS	ST: 55 CS: 73 LS: 23 VF: 42	/p, w, h, g, k, f, j, ʃ, tʃ, ɹ, θ, z, ð/	/g, f, d, ʃ, tʃ, dʒ, θ, v, s, z, ð/	/f, d, ʃ, tʃ, l, dʒ, θ, v, s, z/	Inconsistent distortion errors; occasional initial groping; intermittent hypernasality and voicing errors; more errors on longer words/phrases; no frank vowel errors. /h/ → /w/, initial consonant deletion (both inconsistent).
316	PD + CAS	LS: 65 VF: 21	/l, ɹ, θ, s, z, ð/	/l, ɹ, s, z, ð, dʒ, v/	/l, ɹ, θ, s, ɹ, z/	/l, ɹ/ → /w/ in all positions and clusters. Difficulties with longer words; sequencing errors; segmented speech; occasional vowel distortions. Dentalized /s, z/.
317	CAS	LS: 58	/ɹ/		/ɹ/	Vowel and diphthong errors; difficulty with longer words, sequencing errors. /ɹ, ə, ɜ/ derhotacized.
319	PD + Artic		/θ, v/	/f, tʃ, θ, v, s/	/θ/	/v/ → /b/ initial & medial; /t/ → /θ/ medial. Visible tongue thrust on alveolars & palatals but rarely audible.
320	CAS + Artic	LS: 48	/ɹ, θ/	/θ, s, ð/	/ɹ/	Difficulty with longer words; occasional vowel distortions. /ɹ, ə, ɜ/ derhotacized.

Note. SSD6 = children with SSD between 5 and 7 years old; PD = phonological disorder; Artic = articulation disorder; LS = liquid simplification; CAS = childhood apraxia of speech; ST = stopping of fricative/affricates; CS = cluster simplification; VF = velar fronting; SSD = speech sound disorders.

^aDiagnoses are based on clinical expert speech-language pathologist judgment. ^bBased on the Khan-Lewis Phonological Analysis–Second Edition (Khan & Lewis, 2002). Listed are only those processes occurring 20% or more. ^cBased on the Goldman-Fristoe Test of Articulation–Second Edition (Goldman & Fristoe, 2000). Only singletons missing from the inventory are listed.

Task and Procedures

Phrases were elicited via a repetition task. Participants repeated the carrier phrases after a prerecorded model, presented over speakers at a comfortable listening level. The task was administered over three separate sessions of three blocks each, for a total of nine trials per target. Targets were presented in random order within each block. The first session began with an introduction to the aliens (picture of the alien accompanied by an introduction phrase in the same voice, e.g., “This is a seeb”). The task instructions were to repeat what the voice said, and there was no time constraint for productions. Participants were tested individually in a quiet room. All productions were recorded (44.1 kHz, 16 bit) on a Marantz CDR-420 recorder via an M-Audio Aries condenser microphone placed on the desk approximately 30 cm from the speaker’s mouth. Presentation of stimuli was controlled by E-Prime (v. 2; Psychology Software Tools, Inc., Sharpsburg, PA).

Data Processing and Acoustic Analysis

The focus of this study was on fricative contrast and anticipatory CV coarticulation, as indexed by acoustic

measures obtained from the first spectral moment (m1) at three points during the fricative (onset, midpoint, offset). Acoustic measures were based on tokens in which both fricative and vowel were perceptually accurate. Accuracy was judged from audio recordings by a native English listener and verified by the first author (a near-native speaker with 20+ years of phonetic training). Acoustic analyses were performed using Praat (Boersma & Weenink, 2008).

Data preprocessing proceeded through three steps. In Step 1, prior to acoustic analysis, all errors were discarded except final consonant errors, which were not expected to affect fricative spectral means. Perceptually evident errors were excluded because errors may arise for different reasons (e.g., lexical selection, phonological planning) and thus may not shed light on speech motor control. Thus, our goal was to examine acoustic measures of segmental contrast and anticipatory coarticulation in the context of speech sounds that were at least perceptually on-target (similar to previous studies; Nijland et al., 2002). A total of 12.6% of trials (173/1,368) was removed due to presence of errors, and error rate was analyzed as a secondary dependent variable in a preliminary analysis (see Supplemental Material S1 for details). In Step 2, trials with recording and/or analysis problems were removed (e.g., clipped waveform,

recording failure), resulting in an additional data loss of 5.7% (78/1,368). In Step 3, targets with fewer than three trials remaining per participant were removed from further acoustic analysis. This led to exclusion of *seeb* for two participants (SSD6 104, SSD6 316), *soob* for five participants (SSD6 104, SSD6 107, SSD6 316, SSD6 319, SSD9 312), and *sheeb* and *shoob* for one participant (SSD6 304). Acoustic analyses were thus based on a minimum of three perceptually accurate and analyzable tokens per participant (see Supplemental Material S2 for details). Acoustic analyses were based on fricative spectra. A Praat script (Munson, 2004) was used to label onsets and offsets of fricatives, using both waveform and spectrogram views. The visible range for the spectrogram was 0–16 kHz, the time step for analysis was fixed at 0.001 seconds, and the dynamic range was typically 45 dB, although analysts occasionally varied the dynamic range to obtain a better view. The waveform scaling was generally set to a fixed height of 2, although occasionally analysts changed the height to increase resolution of the waveform. The visible window from which onsets and offsets were determined included the entire fricative and part of the preceding and following vowels, and generally ranged from 300 to 400 ms. Following Munson (2004), fricative onset (offset) was defined as the beginning (end) of high-frequency aperiodic frication noise; analysts confirmed this with the spectrogram but relied primarily on the waveform. As in Munson (2004), these onsets and offsets were selected regardless of whether there was intrusion of voicing from the vowel into the fricative. Interrater reliability based on a randomly selected participant's data ($1/38 = 2.6\%$) was high, with correlations of $r > .9999$ (for onsets and offsets), average absolute differences of 1.2 ms for onset ($SD = 1.4$; range = 0–4.9) and 1.4 ms for offset ($SD = 1.1$; range = 0–4.4 ms).

Following labeling onsets and offsets, a second Praat script was used to compute fricative durations, as well as spectral moments based on fast Fourier transform obtained from 40-ms Gaussian analysis windows placed at three points in the fricative: (a) onset, centered on 30 ms into the fricative (i.e., excluding the first 10 ms), (b) midpoint, centered on the middle of the fricative, and (c) offset, centered on 30 ms before the end of the fricative. Prior to computing the spectral moments, the spectrum was filtered using a pass band Hanning filter between 500 and 10000 Hz (50 Hz smoothing). Lower frequencies were excluded to eliminate possible influences of intruding voicing on spectral measures. The focus in this study was on spectral means (first moment or m_1); median values (for m_1 and duration) were computed per participant per target and used in statistical analyses.

To capture fricative contrast and anticipatory CV coarticulation and minimize influences of differences in vocal tract size (see Nijland et al., 2002; Nittrouer et al., 1989), we derived two primary dependent measures from the median m_1 values, the F -ratio and the V -ratio. The F -ratio quantifies fricative contrast and is defined as $(\text{median } m_{1s} / \text{median } m_{1j})$ (Nittrouer et al., 1989; Perkell et al., 2007). F -ratios > 1 indicate higher spectral mean for /s/ than for /ʃ/, F -ratios < 1 indicate the reverse, and F -ratios = 1 indicate

no difference between fricatives. The V -ratio indexes anticipatory CV coarticulation and is defined as $(\text{median } m_{1i} / \text{median } m_{1u})$ (Nittrouer et al., 1989). V -ratios > 1 indicate higher spectral mean for fricative preceding /i/ than for fricatives preceding /u/, V -ratios < 1 indicate the reverse, and V -ratios = 1 indicate no difference.

Statistical Analysis

Primary dependent variables were F -ratio (contrast) and V -ratio (coarticulation). In the comparison between adults and TD children, we also examined intraspeaker variability of duration and spectral means as secondary dependent variables, indexed by the coefficient of variation ($CoV = \text{standard deviation} / \text{mean}$). Error rate, duration, and raw spectral means were also analyzed prior to analysis of primary and secondary dependent variables. However, few group effects were observed, and hence we focus on the primary and secondary dependent measures below. For space considerations we refer the interested reader to Supplemental Material S1 for details of these analyses³ and Supplemental Material S2 for group and individual data for all variables.

Data from adults and TD children were analyzed at the group level with analyses of variance (ANOVAs) and Tukey follow-up tests to identify the locus of significant effects. In addition, for V -ratio and F -ratio, we evaluated whether the ratio was significantly different from 1 using one sample t tests at each timepoint. Last, we examined the correlations between F -ratios and V -ratios to test whether these ratios capture independent constructs.

To compare the TD6 and SSD6 groups for error rate, we conducted a $3 (\text{Group}) \times 2 (\text{Fricative}) \times 2 (\text{Vowel})$ ANOVA. For all other variables, due to missing data for different targets for different children and resulting imbalance across targets, group-level analyses were not considered appropriate. Instead, we compared children with SSD to TD groups by presenting descriptive data and individual comparisons. We compared medians of each child with SSD to their respective TD group using Crawford, Garthwaite, and Porter's (2010) single-case Bayesian analysis methods, testing for differences for each target (using SingleBayes_ES.exe; http://homepages.abdn.ac.uk/j.crawford/pages/dept/Single_Case_Effect_Sizes.htm; Crawford et al., 2010). These single-case analyses take into account the means, standard deviations, and sample size of the control sample to determine whether an individual's score falls outside the normal range. For all analyses we report significant effects ($\alpha < .05$, two-tailed); we also report trends (marginal effects), defined as effects with p values between

³For error rate TD6 children made more errors than adults, and there were more errors on /s/ than on /ʃ/. SSD6 children made more errors than TD6 children, in particular for /s/. For duration, there were no group effects, only longer duration for /ʃ/ than for /s/, and children with SSD did not differ from TD children for any target except /s/ in *seeb* for SSD6 304. For spectral mean, adults had higher m_1 for /s/ than for both children's groups, which did not differ; no other group effects were significant. There were no differences in m_1 in any context for any of the SSD children compared to TD children.

.05 and .10. For space considerations, detailed information about individual children (precise *p* values and effect sizes with 95% credible intervals) is provided in Supplemental Material S3.

Results

Part 1: Adults Versus Typically Developing Children

F-Ratio

Group data for *F*-ratios are given in Table 4 and Figure 1. The 3 (Group) $\times$ 2 (Vowel) $\times$ 3 (Timepoint) ANOVA on *F*-ratios revealed a significant main effect of Group, $F(2, 24) = 4.14, p = .028$, indicating greater acoustic contrast for adults (1.473) than for TD9 children (1.338). The TD6 children (1.371) did not differ from adults or TD9 children. There was also a significant effect of Timepoint, $F(2, 48) = 27.74, p < .001$, that indicated smaller contrast at fricative onset (1.341) than at fricative midpoint (1.428) or offset (1.424); the latter two did not differ. There was a marginal effect for Vowel, $F(1, 24) = 4.09, p = .054$, suggesting numerically greater contrast in the /u/ context (1.420) than in the /i/ context (1.375). No other effects were significant, all *F*s $< 1.06, ps > .35$, except Group $\times$ Vowel, $F(2, 24) = 1.77, p = .191$. For all three groups, *F*-ratios significantly exceeded 1 at all timepoints for both vowel contexts (see Table 4).

V-Ratio

Data for *V*-ratios are presented in Table 4 and Figure 2. The 3 (Group) $\times$ 2 (Fricative) $\times$ 3 (Timepoint)

ANOVA on *V*-ratios revealed only a main effect of Timepoint, $F(2, 48) = 7.01, p = .002$, indicating that the *V*-ratio at fricative offset was greater (1.056) than at either fricative onset (1.034) or midpoint (1.035). There was also a trend for a Fricative effect, $F(1, 24) = 3.02, p = .095$, suggesting numerically greater *V*-ratio for /ʃ/ (1.056) than for /s/ (1.027). There were no other significant effects, all *F*s $< 1.11, ps > .35$, except Group $\times$ Fricative, $F(2, 24) = 1.92, p = .1681$.

In comparing *V*-ratios to 1 (see Table 4), adults' *V*-ratios significantly exceeded 1 at all timepoints for /ʃ/ but not for /s/. *V*-ratios in the TD6 group significantly exceeded 1 only for /ʃ/ at fricative offset, with trends in the same direction at onset and midpoint, and no differences from 1 for /s/. For the TD9 group, only the *V*-ratio for /s/ at fricative offset significantly exceeded 1; there were trends in the same direction for /ʃ/ at fricative offset, and for both /s/ and /ʃ/ at onset.

Relationship Between V-Ratio and F-Ratio

The *V*-ratio and *F*-ratio capture conceptually distinct constructs (coarticulation vs. contrast), but both are based on the same spectral mean measures. To further evaluate whether these ratios are independent, we correlated both measures (averaged across vowel contexts for *F*-ratio and averaged across fricative contexts for *V*-ratio) in each of the three groups, at each timepoint (see Table 5 for correlation coefficients). None of the correlations approached significance (all *ps* $> .15$).

Duration Variability

Analysis of intraspeaker duration variability (CoV_{dur}) revealed a significant effect of Group, $F(2, 24) = 11.20$,

Table 4. Group data for *F*-ratio and *V*-ratio, with *t* values from comparisons of ratios to 1 (for adult and TD groups only).

Ratio	Group	Context	<i>n</i>	Onset	<i>SD</i>	<i>t</i>	Mid	<i>SD</i>	<i>t</i>	Offset	<i>SD</i>	<i>t</i>
F	Adult	/i/	10	1.39	0.12	10.42***	1.50	0.11	15.13***	1.47	0.09	15.64***
		/u/	10	1.42	0.09	14.78***	1.52	0.11	15.43***	1.54	0.12	14.56***
	TD6	/i/	8	1.24	0.15	4.62**	1.37	0.12	8.97***	1.34	0.12	7.68***
		/u/	8	1.36	0.22	4.53**	1.45	0.16	7.91***	1.47	0.18	7.18***
	TD9	/i/	9	1.30	0.06	14.73***	1.35	0.08	12.42***	1.37	0.09	12.75***
		/u/	9	1.30	0.12	7.24***	1.36	0.20	5.54***	1.35	0.18	5.92***
	SSD6	/i/	6	1.13	0.11		1.19	0.14		1.13	0.13	
		/u/	4	0.94	0.23		1.17	0.09		1.12	0.07	
	SSD9	/i/	3	1.27	0.11		1.33	0.12		1.39	0.17	
		/u/	2	1.28	0.04		1.38	0.03		1.44	0.11	
V	Adult	/s/	10	1.01	0.05	0.83	1.03	0.07	1.12	1.01	0.09	0.46
		/ʃ/	10	1.04	0.02	5.01***	1.03	0.04	2.47*	1.06	0.05	3.90**
	TD6	/s/	8	0.99	0.08	-0.28	1.01	0.09	0.30	1.03	0.06	1.19
		/ʃ/	8	1.08	0.11	2.12 [^]	1.06	0.08	2.31 [^]	1.12	0.09	3.68**
	TD9	/s/	9	1.04	0.06	2.12 [^]	1.04	0.09	1.18	1.07	0.08	2.85*
		/ʃ/	9	1.04	0.06	2.04 [^]	1.04	0.08	1.55	1.05	0.06	2.29 [^]
	SSD6	/s/	4	1.31	0.31		1.08	0.07		1.05	0.18	
		/ʃ/	7	1.07	0.05		1.04	0.02		1.07	0.02	
	SSD9	/s/	2	1.01	0.15		0.98	0.02		0.99	0.03	
		/ʃ/	3	1.04	0.09		1.04	0.05		1.05	0.05	

Note. TD6 = children who are typically developing between 5 and 7 years old; TD9 = children who are typically developing between 8 and 10 years old; SSD6 = children with SSD between 5 and 7 years old; SSD9 = children with SSD between 8 and 10 years old; TD = typically developing; SSD = speech sound disorders.

p* $< .05$. *p* $< .01$. ****p* $< .001$. [^]*p* $< .10$.

Figure 1. *F*-ratio by timepoint (left = /i/ context, right = /u/ context). Top: Group data. Middle: TD6 group versus individual SSD6 children. Bottom: TD9 group versus individual SSD9 children. Error bars represent standard error. TD6 = children who are typically developing between 5 and 7 years old; TD9 = children who are typically developing between 8 and 10 years old; SSD6 = children with SSD between 5 and 7 years old; SSD9 = children with SSD between 8 and 10 years old; SSD = speech sound disorders.

$p < .001$, which indicated that both TD groups exhibited greater trial-to-trial variability (TD6 $\text{CoV}_{\text{dur}} = 0.155$; TD9 $\text{CoV}_{\text{dur}} = 0.133$) than adults ($\text{CoV}_{\text{dur}} = 0.078$); the two TD groups did not differ from one another. The Fricative $\times$ Vowel interaction was also significant, $F(1, 24) = 4.37$, $p = .047$, indicating a pattern of greater variability for /s/ in the /i/ context (0.133) than in the /u/ context (0.107), with an opposite pattern for /ʃ/ (/i/ context: 0.113; /u/ context: 0.134); none of the pairwise comparisons reached significance.

Spectral Mean (m1) Variability

With respect to intraspeaker variability (CoV_{m1}), analysis revealed a main effect of Group, $F(2, 24) = 7.94$, $p = .002$, indicating greater variability in the TD6 group (0.100) than in adults (0.060); variability for the TD9 group (0.078) fell between TD6 and adults and did not differ

significantly from either group. Group also interacted with Fricative, $F(2, 24) = 4.59$, $p = .021$. This interaction showed that for /s/, the TD6 group (0.103) differed from both the adult (0.068) and TD9 groups (0.065), which did not differ from each other, whereas for /ʃ/ both TD groups differed from adults (0.052) but not from each other (TD6 $\text{CoV}_{\text{m1}} = 0.097$; TD9 $\text{CoV}_{\text{m1}} = 0.091$). A main effect of Timepoint, $F(2, 48) = 8.99$, $p < .001$, indicated greater variability at fricative onset (0.090) than at midpoint (0.076) and offset (0.073); the latter two did not differ. A Vowel $\times$ Timepoint interaction, $F(2, 48) = 4.06$, $p = .024$, revealed that this Timepoint effect reached significance only in the /i/ context (onset > mid = offset: $0.096 > 0.070 = 0.073$) but not in the /u/ context (onset = mid = offset: $0.084 = 0.076 = 0.078$). A Fricative $\times$ Vowel interaction, $F(1, 24) = 10.14$, $p = .004$, indicated a pattern of greater variability in /i/ (0.084) than /u/ context (0.073) for /s/, with the opposite

Figure 2. *V*-ratio by timepoint (left = /s/ context, right = /j/ context). Top: Group data. Middle: TD6 group versus individual SSD6 children. Bottom: TD9 group versus individual SSD9 children. Note different y-axis range for left and right panels. Error bars represent standard error. TD6 = children who are typically developing between 5 and 7 years old; TD9 = children who are typically developing between 8 and 10 years old; SSD6 = children with SSD between 5 and 7 years old; SSD9 = children with SSD between 8 and 10 years old; SSD = speech sound disorders.

pattern for /j/ (/i/ = 0.075; /u/ = 0.085); none of the pairwise comparisons reached significance. A marginal interaction of Group $\times$ Fricative $\times$ Vowel, $F(2, 24) = 2.84$, $p = .078$, suggested that the Group $\times$ Fricative $\times$ Vowel was mainly

driven by the /i/ context. No other effects were significant, all $F_s < 1.6$, $p_s > .15$.

Interim Summary: Adults Versus Typically Developing Children

For *F*-ratios, adults showed greater acoustic contrast than TD9 children, with the TD6 group in between. *F*-ratios were lower at fricative onset than at midpoint and offset. For *V*-ratios, there were no significant group differences, and *V*-ratios were higher at fricative offset than at onset and midpoint. *V*-ratio and *F*-ratio were not correlated with each other at any timepoint in any of the three groups. In terms of variability, both groups of TD children exhibited greater trial-to-trial variability in both the temporal domain (fricative duration) and in the spatial domain (m1), compared to adults. For m1 variability, both children's groups were more

Table 5. Pearson correlation coefficients for correlations between *F*-ratio and *V*-ratio by group and timepoint.

Group	<i>n</i>	Onset	Middle	Offset
Adult	10	0.381	0.153	0.096
TD6	8	0.226	0.325	0.231
TD9	9	-0.349	-0.495	-0.426

Note. TD6 = children who are typically developing between 5 and 7 years old; TD9 = children who are typically developing between 8 and 10 years old.

variable than adults overall and for /f/, whereas only the TD6 group was significantly more variable than adults for /s/. Onset variability was greater than variability at midpoint and offset.

Part II: TD Versus SSD Children

F-Ratio

Individual data for *F*-ratios are provided in Table 6 and Figure 1. For *F*-ratios, only two children from the SSD6 group (107 and 300) demonstrated significant differences from the TD6 group at one or more timepoint. Participant 107's *F*-ratio was significantly lower at fricative midpoint for the /i/ context (1.0716; $p = .047$) than in the TD6 group (1.3710). Participant 300 revealed significantly lower *F*-ratio at fricative offset for the /i/ context (0.9168; $p = .015$; TD6 group = 1.3389), and at fricative onset for the /u/ context (0.6884; $p = .026$; TD6 group = 1.3588). Participant 300 also showed a trend for lower *F*-ratio at fricative midpoint in the /i/ context (1.0970; $p = .063$; TD6 group = 1.3710). Participant 317 also showed a trend for lower *F*-ratio for the /u/ context at fricative midpoint (1.0831; $p = .069$; TD6 group = 1.4481) and fricative offset (1.0330; $p = .062$; TD6 group = 1.4651).

Among the SSD9 children, there was only a trend toward lower *F*-ratio for participant 201, at fricative onset in the /i/ context (1.1622; $p = .063$; TD9 group = 1.3029). No other differences or trends were observed.

V-Ratio

Individual data for *F*-ratios are provided in Table 6 and Figure 2. For *V*-ratios, only two children (300 and

317) showed significant differences from the TD6 group. For the /s/ context, participant 300 had a *higher* *V*-ratio than TD6 children at fricative onset (1.7411; $p < .001$; TD6 group = 0.9919) but a *lower* *V*-ratio at fricative offset (0.8649; $p = .048$), with no difference at fricative midpoint. Participant 317 exhibited *higher* *V*-ratios than TD6 children in the /s/ context at fricative onset (1.3038; $p = .009$; TD6 group = 0.9919) as well as fricative offset (1.3022; $p = .005$; TD6 group = 1.027), with no difference at fricative midpoint.

For the SSD9 children, there was only a trend for a lower *V*-ratio for participant 201 at fricative onset for the /s/ context (0.9080; $p = .075$; TD9 group = 1.0449). No other comparisons reached significance.

Discussion

The present study investigated segmental contrast and anticipatory coarticulation in children with and without SSD by examining ratios of spectral means obtained from three points in the fricative. Before discussing findings from the children with SSD, we first discuss findings from the TD children.

Typically Developing Children

Fricative Contrast

All three groups (adults, TD6, TD9) differentiated the two fricatives studied here, as indicated by *F*-ratios differing from 1 at all timepoints. In addition, fricative contrast was larger at fricative midpoint and offset than at onset, suggesting that targets are not reached until perhaps

Table 6. Individual data for *F*-ratio and *V*-ratio.

ID	F-ratio					V-ratio				
	Context	<i>n</i>	Onset	Mid	Offset	Context	<i>n</i>	Onset	Mid	Offset
104	/i/	0				/s/	0			
	/u/	0				/f/	4	1.17	1.09	1.08
107	/i/	3	1.12	1.07	1.16	/s/	0			
	/u/	0				/f/	5	1.08	1.03	1.04
300	/i/	3	1.14	<u>1.10</u>	0.92	/s/	3	1.74	0.99	0.86
	/u/	4	0.69	<u>1.16</u>	1.16	/f/	4	1.05	1.05	1.09
304	/i/	0				/s/	4	1.05	1.07	0.99
	/u/	0				/f/	0			
316	/i/	0				/s/	0			
	/u/	0				/f/	6	1.03	1.03	1.06
317	/i/	4	1.15	1.16	1.28	/s/	3	1.30	1.11	1.30
	/u/	3	0.97	<u>1.08</u>	<u>1.03</u>	/f/	8	1.09	1.03	1.05
319	/i/	3	0.95	<u>1.17</u>	<u>1.18</u>	/s/	0			
	/u/	0				/f/	7	1.06	1.05	1.11
320	/i/	7	1.27	1.43	1.12	/s/	7	1.14	1.15	1.05
	/u/	7	1.15	1.26	1.16	/f/	9	1.03	1.01	1.09
201	/i/	6	<u>1.16</u>	1.24	1.20	/s/	6	<u>0.91</u>	0.96	0.97
	/u/	6	<u>1.25</u>	1.35	1.36	/f/	6	<u>0.98</u>	1.05	1.10
307	/i/	6	1.27	1.28	1.46	/s/	8	1.12	0.99	1.01
	/u/	8	1.31	1.40	1.52	/f/	6	1.14	1.09	1.05
312	/i/	3	1.37	1.47	1.52	/s/	0			
	/u/	0				/f/	8	1.00	0.99	1.00

Note. ID = participant number; *n* = smallest number of tokens available for computing ratio. Significant differences from the respective typically developing groups are in **bold**, trends in underlined italics.

the midpoint but are then largely maintained throughout the rest of the fricative. More pertinent to our purpose, both groups of children had lower *F*-ratios than adults, with the TD9 group differing significantly from adults. The lack of a significant difference between adults and the TD6 group was somewhat surprising but may simply reflect larger variability in that group. It is important to reiterate that these analyses were based on perceptually adequate fricative tokens and thus do not simply represent an acoustic measure of perceptually evident errors. In other words, the *F*-ratio was able to identify subtle differences in segmental contrast between children and adults, and these findings suggest that even at age 9 years, children with typical speech development have not mastered adult-like fricative articulation. These findings are consistent with previous research showing a long developmental trajectory of speech motor development (e.g., Fox & Nissen, 2005; Nittrouer et al., 1989; Smith & Zelaznik, 2004). Further, these findings highlight the importance of including age-matched normative groups when examining speech motor skills in children with SSD.

One possible interpretation of these findings is that the target regions that define a specific speech sound (for example as conceptualized in the DIVA model; Guenther, 1995; Guenther, Ghosh, & Tourville, 2006) are larger in children than in adults. In the DIVA model, speech motor control involves target regions in auditory/acoustic space, and children must not only learn the proper motor commands to reach these targets but also the proper boundaries of each speech sound target. The notion of target regions helps account for the fact that speech sounds may vary somewhat and still be perceived as the target, and for speaking rate or style effects. For example, hyperarticulation could be modeled as aiming for the center of a target region, whereas hypoarticulation could be modeled as aiming for the boundaries of target regions (e.g., Perkell et al., 2000). Thus, a reduced acoustic contrast may indicate that children have larger target regions than adults, that adults aim more for the center of regions than children, or that adults are more successful at reaching the center of the target region. This study was not designed to tease these alternative explanations apart, and therefore these explanations remain speculative.

Anticipatory Coarticulation

V-ratios greater than 1 indicate a vowel-related effect on the preceding fricative (i.e., anticipatory CV coarticulation). *V*-ratios numerically exceeded 1 in all cases except for /s/ onset in the TD6 group, but significant differences from 1 were noted only for /ʃ/ in adults at all timepoints, for /s/ at fricative offset in the TD6 group, and for /ʃ/ at fricative offset in the TD9 group. A significant timepoint effect indicated increasing ratios toward the fricative offset, consistent with the notion that tongue position is changing in anticipation of the upcoming vowel. Contrary to the fricative contrast findings, however, the analyses revealed no differences between groups in terms of anticipatory coarticulation as captured by *V*-ratios. Qualitatively, however,

the fact that children only showed significant departures from 1 at fricative offset suggests that perhaps children anticipate the upcoming vowel later than adults. It is important to note here that these time course differences cannot be explained by differences in fricative duration, as there were no differences between groups in terms of fricative duration.

The fact that no group differences were observed for anticipatory coarticulation contrasts with findings based on other acoustic measures (e.g., *F2* values; Nittrouer et al., 1989) but is consistent with previous work that has examined *V*-ratios in children and adults (e.g., Katz et al., 1991; Nittrouer et al., 1989). The *V*-ratios reported in the present study are comparable to those reported in previous studies. One possible interpretation is that *V*-ratios based on spectral means, at least in the present implementation, are simply not sufficiently sensitive to detect age-related differences. Perhaps other spectral measures may provide a more sensitive metric (e.g., spectral peak, spectral slope, other moments; e.g., Koenig, Shadle, Preston, & Mooshammer, 2013; Nissen & Fox, 2005).

Variability

An additional observation is that even though TD children by and large did not differ from adults in fricative duration or absolute spectral means, both TD groups did show greater trial-to-trial variability in both the temporal and spatial domain. These findings are consistent with previous work (e.g., Grigos, 2009; Munson, 2004; Nijland et al., 2003; Smith & Zelaznik, 2004), and suggest that even older children have not achieved adult-like articulation skills. Greater variability may reflect less stable motor programs and/or a greater reliance on auditory or somatosensory feedback to achieve fricative targets (Callan, Kent, Guenther, & Vorperian, 2000; Terband, Maassen, Guenther, & Brumberg, 2009). For example, in the DIVA model, speech motor control involves two control mechanisms that work together to achieve acoustic/auditory target regions for the intended speech sound: a feedback-based control system and a feedforward control system. The feedback control system compares incoming auditory and somatosensory feedback generated by the speaker to the expected, intended auditory and somatosensory feedback, and generates a corrective motor command when the actual feedback differs from the intended feedback to correct this "error." The feedforward control system uses information gleaned from previous attempts, including previous corrective commands from the feedback system, to generate predictive motor commands to achieve intended acoustic/auditory targets. One benefit of the feedforward system is that it is more robust and rapid, as this system does not rely on processing feedback. If children are still developing accurate feedforward commands and rely to a greater extent than adults in feedback-based control, one would expect greater variability in children due to minor online corrections resulting from mismatches between expected and actual feedback. Our findings are consistent with this idea.

Children With Speech Sound Disorders

Fricative Contrast

At the group level (descriptively; see Table 4) the SSD6 children demonstrated lower *F*-ratios than TD6 children at all timepoints in both vowel contexts. Individual participant *F*-ratios were also numerically lower than the TD6 ratios at all timepoints in both vowel contexts for all children except participant 320 for /i/ at fricative onset and midpoint. Of the five SSD6 children who had sufficient data to compute an *F*-ratio in at least one vowel context, two showed a significantly lower *F*-ratio in at least one vowel context (107 and 300) and a third showed a trend for the /u/ context (317). Given the small sample sizes, interpretation must necessarily be cautious, but one relevant observation is that reduced acoustic fricative contrast does not appear to differentiate between clinical SSD subtypes, as two of these three children were diagnosed with CAS (300 and 317) and one with a PD (107).

For the older children with SSD, descriptive group data suggest *F*-ratio values largely within the range of the TD9 group (see Table 4). None of the SSD9 children differed significantly from the TD9 group for either vowel context at any timepoint. Thus, it appears that these older children with SSD, all three with a clinical diagnosis of articulation disorder, have achieved sufficient speech motor skill to implement age-appropriate fricative contrasts as indexed by acoustic measures.

Anticipatory Coarticulation

For the SSD9 group, none of the children differed from TD9 children in terms of *V*-ratio. Thus, there is no evidence for abnormal anticipatory coarticulation for these children. When comparing SSD6 and TD6 children, no clear consistent patterns were evident for *V*-ratios at the descriptive group level (see Table 4). All eight SSD6 children had sufficient data to contribute a *V*-ratio for at least one fricative context. Of these eight children, only two revealed significant differences from the TD6 group (300 and 317), in the /s/ context only. Both children had received a clinical diagnosis of only CAS. Although the absence of differences for the other SSD6 children does not necessarily mean that their coarticulation was age-appropriate, our findings support those of Nijland et al. (2002), in that children with CAS were found to differ from TD children with respect to acoustic measures of anticipatory coarticulation. As in Nijland et al. (2002), the children showed idiosyncratic patterns. Participant 300 showed greater coarticulation at onset and less coarticulation at offset, whereas participant 317 showed greater coarticulation at onset and offset. Our findings, although based on a small number of children, extend the findings of Nijland et al. (2002) by suggesting that abnormal coarticulation may be specific to CAS and not a general feature of SSD. This interpretation is consistent with the idea that CAS is a speech motor planning/programming impairment (e.g., ASHA, 2007; Maas, Gildersleeve-Neumann, Jakielski, & Stoeckel, 2014; Nijland et al., 2002, 2003), as anticipatory coarticulation

is thought to reflect speech motor planning (e.g., Whalen, 1990).

Limitations

The present findings must be interpreted with caution for a number of reasons. First, the sample size was relatively small and heterogeneous, and not all children with SSD produced a sufficient number of tokens that could be analyzed acoustically. This limits power to detect differences as well as generality of these findings (e.g., this approach may be appropriate for children with mild to moderate SSD but not those with severe SSD). Thus, further research is needed to replicate and extend these initial findings. Second, the study used a cross-sectional rather than a longitudinal design, and longitudinal designs are ultimately preferred for examining developmental changes (Terband et al., 2016). Third, it is possible that different acoustic measures may be more sensitive or informative about the nature of fricative production and coarticulation in children with or without SSD. Future work should explore other measures (e.g., spectral peaks, other moments; Koenig et al., 2013; Nissen & Fox, 2005) to address the development of fricative production as well as the potential for identifying and differentiating speech production impairments in children. Fourth, acoustic measures serve as a proxy for speech movements and reflect the integrated action of the many articulators involved, but are incapable of identifying specific articulatory configurations and their contributions to the overall signal (Goffman, Smith, Heisler, & Ho, 2008).

Conclusion

Findings from this study on fricative production indicate that typical speech motor development is protracted, with smaller acoustic fricative contrast for children than adults, even older children. No significant age effects were found for anticipatory coarticulation, which may mean that anticipatory coarticulation is adult-like in these children or that the chosen measure (*V*-ratio) is not sufficiently sensitive to detect age-related differences. With respect to SSD, the present findings should be interpreted cautiously given the small sample size and heterogeneity of error profiles, but suggest that reduced fricative contrast may be present in some younger children with SSD regardless of clinical subtype. In contrast, abnormal coarticulation may be more specific to the CAS subtype. Further research is needed to explore whether additional measures are more sensitive and informative about underlying impairments and hence whether such measures may have clinical utility.

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