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The Development of Alveolar and Alveopalatal Fricatives in French-Speaking Monolingual and Bilingual Children

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ABSTRACT

Purpose: This study conducted a transcription-based and spectral moments' analysis of alveolar and alveopalatal fricatives in monolingual and bilingual French-speaking children, aged 2;6–6;10 (years;months). We measured the percent accuracy of fricatives and investigated whether young children could distinguish alveolar and alveopalatal fricatives on the basis of spectral moments. In addition, we examined which child- (i.e., age, gender, bilingualism, and alveopalatal fricative inventory size) and word/sound-related (i.e., place-of-articulation [PoA], voicing, vowel quality, and word position) factors influenced spectral moments and fricative duration.
Method: Children (*N* = 89) participated in a picture-naming task in which they produced words containing alveolar /s, z/ and alveopalatal /ʃ, ʒ/ fricatives in word-initial, -medial, and -final positions. The words were transcribed and analyzed acoustically, and the first and third spectral moments (i.e., centroid and skewness) and the duration of fricatives were calculated. The data were subject to mixed-effects linear regression.
Results: Percent accuracy results indicated effects of age on alveopalatal fricatives and effects of word position on voiced fricatives. Statistical models indicated that age, gender, and alveopalatal fricative inventory size influenced spectral moments. Age and inventory size interacted significantly with PoA. Children as young as age 2;6 distinguished alveopalatal and alveolar fricatives on the basis of centroid but not skewness values. The distinction between the two sets of fricatives increased with age. Bilingual children who spoke languages with greater numbers of alveopalatal fricatives distinguished alveopalatal and alveolar fricatives less well than monolinguals and bilinguals who spoke languages with fewer numbers of alveopalatal fricatives. Girls had higher centroid and lower skewness values than boys. Models also revealed a significant influence of word/sound-related factors (voicing, vowel quality, and word position) on spectral moments and fricative duration.
Conclusions: Findings indicated that multiple factors influence the spectral moments and duration measures of children's alveolar and alveopalatal fricatives. In particular, we found that spectral moments were sensitive to gender and bilingualism effects.

Alveopalatal fricatives are difficult to produce. In French, the language of focus in this study, they are one of the last sets of sounds to be acquired and are among the sounds most frequently targeted in speech sound intervention (Aicart-de Falco & Vion, 1987). In this study, we investigate the production of alveopalatal /ʃ, ʒ/ fricatives by French-speaking children, aged 2;6–6;10, and contrast their production with those of alveolar fricatives /s, z/. In particular, we conduct a spectral moments' analysis that details the spectral characteristics of segments in terms of multiple statistical moments. Previous studies with English-speaking children indicate that the spectral differences between alveolar and alveopalatal fricatives are not

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well defined at 3 years and become so only around the age of 5 years (Nissen & Fox, 2005). We investigate whether this is the same in French. We also examine the influence of age and gender on spectral moments as well as other factors that may influence fricative production such as voicing, vowel quality, and word position. In addition to measuring spectral moments, we measure fricative duration to determine whether it is influenced by the same set of factors. The study is conducted in Geneva, Switzerland, where a large number of bilingual families reside; hence, another aim is to examine whether monolingual and bilingual children differ in their spectral realization of fricatives. We start by reviewing the literature on the development of alveolar and alveopalatal fricatives and focus on studies that have conducted spectral moments' analyses on fricatives in children.

Acquisition of Alveolar and Alveopalatal Fricatives

Fricatives are among the last sounds to be acquired in children's speech sound inventories (MacLeod et al., 2011; Stoel-Gammon, 1985). They are sounds produced by air passing through a narrow constriction in the vocal tract. In comparison with stops, they require careful tongue body configuration and aerodynamic control (Kent, 1992). Alveopalatal fricatives, as opposed to alveolar fricatives, require motor differentiation of the blade versus tongue tip: /ʃ/ and /ʒ/ have a wider tongue groove resulting in a larger cross-sectional area than /s/ and /z/, and the constriction for /ʃ/ and /ʒ/ is further back in the vocal tract than for /s/ and /z/. Both alveolar /s/ and /z/ and alveopalatal /ʃ/ and /ʒ/ are also referred to as sibilants, sounds that are characterized by high amplitude high-frequency energy (Ladefoged & Maddieson, 1996).

McLeod and Crowe (2018) conducted a cross-linguistic analysis of consonant acquisition across 27 languages, consulting findings from 64 studies. They found that, across all languages, /s, z, ʃ/ were acquired with 90% accuracy between ages 4;0 and 4;1, whereas /ʒ/ was acquired with the same degree of accuracy 1 year later. Focusing specifically on English, McLeod and Crowe (2018) report that eight studies were consistent with /s, z, ʃ/ being classified as middle sounds and /ʒ/ as a late sound.

Turning to French, MacLeod et al. (2011), on the basis of a normative study with over 150 French Canadian preschool children, indicate that /z/ is an early sound being acquired (i.e., produced accurately by 75% of the children in three word positions) before age 3;0, whereas /s, ʃ, ʒ/ are late sounds being acquired after age 4;5. Similarly, Aicart-de Falco and Vion (1987), in a study of 75 European French-speaking children, aged 3–6 years, report late acquisition of alveolar and alveopalatal fricatives. They note that over 60% of all consonant errors concern the sounds /s, z, ʃ, ʒ/ and that errors continue through to 6 years. Overall, the findings concur that sibilant fricatives, particularly alveopalatal fricatives, pose difficulty for children in acquisition across various languages, including French.

Spectral Moments' Analyses

A common way to examine the acoustic properties of fricatives is to conduct a spectral moments' analysis, which computes mathematical moments from the power spectrum (i.e., the distribution of energy across frequency). Four spectral moments are generally considered. The first is the center of gravity or mean (also referred to as the centroid),[1] which calculates the average energy concentration. The second is the standard deviation, which is used to distinguish a flat diffuse spectral shape from a peaky compact one. The third is skewness, which indicates whether noisy energy is centered around the mean or is concentrated in the right or left tail of the distribution. The fourth is kurtosis, which measures the peakedness of a distribution. The spectral moments most useful for distinguishing alveolar and alveopalatal fricatives are the first and the third (Li et al., 2009). The first spectral moment is related to the location of constriction in the oral cavity. The point of constriction for /s, z/ is more anterior than for /ʃ, ʒ/, resulting in a shorter frontal cavity and higher mean energy. The third spectral moment (skewness) is also correlated with place of articulation (PoA). /ʃ, ʒ/ have positive values with a greater concentration of energy in the lower frequencies, whereas /s, z/ have negative values with greater concentration in the higher frequencies.

Factors That Influence Spectral Moments' Analyses

Both child- and word/sound-related factors influence spectral moments' analysis. Child-related factors include age, gender, and bilingualism, whereas word- and sound-related factors include PoA, voicing, vowel quality, and word position. Studies that have conducted spectral moments' analyses in children have been interested in whether children are able to distinguish PoA (alveolar vs. alveopalatal fricatives) on the basis of spectral moments and whether this ability changes across age. We summarize these studies and then examine research on other child- (gender and bilingualism) and word/sound-related (voicing, vowel quality, and word position) factors. We concentrate the discussion on findings with the first and third spectral moments.

[1]We use the terms *centroid, center of gravity,* and *spectral mean* interchangeably to refer to the first spectral moment.

Influence of PoA and Age

Several studies report age-related differences in spectral moments (Nissen & Fox, 2005; Nittrouer, 1995). Children have smaller oral cavities than adults, resulting in higher mean frequencies for fricative spectra. As already discussed above, PoA influences spectral moments: Alveolar /s, z/ have a higher center of gravity and more negative skewness than alveopalatal /ʃ, ʒ/ fricatives. Studies tend to show that younger children differentiate fricatives according to PoA less well than older children and adults. Nittrouer (1995) measured spectral moments in voiceless word-initial fricatives produced in consonant–vowel syllables by English-speaking children, aged 3–7 years, and adults. She observed a significant main effect of PoA for the first spectral moment indicating that both children and adults distinguished /s/ and /ʃ/: The mean energy for /s/ was higher than for /ʃ/. However, there was also a significant Age × PoA interaction: The difference between the spectral moments for /s/ and /ʃ/ was greater for adults than for children. The authors also found a significant PoA main effect for the third spectral moment; the /ʃ/ spectrum was more positively skewed than /s/, but there was no significant Age × PoA interaction, meaning that the distinction between /s/ and /ʃ/ across adults and children was similar.

Nissen and Fox (2005) also measured spectral moments of word-initial fricatives produced in monosyllables by English-speaking children, aged 3–6 years, and adults. They found a significant Age × PoA interaction for the first spectral moment; however, in contrast to Nittrouer (1995), they did not find that children, aged 3 and 4 years, distinguished /s/ and /ʃ/. A contrast between /s/ and /ʃ/ was shown by the 5-year-olds, which became more pronounced in the adults. The authors posit that the lack of acoustic differences in the younger children may be due to the small overall size of their vocal tracts; the frontal cavity size differences between /s/ and /ʃ/ are not considerable. In the case of the third spectral moment, there was an effect of PoA and a significant Age × PoA interaction: /ʃ/ was more positively skewed than /s/, and the contrast in spectral skewness was greater for adults than for children. Holliday et al. (2015), when measuring the first spectral moment in productions of real and nonwords by children, aged 2–5 years, and adults, found age effects for /ʃ/ but not for /s/. The centroid for /s/ did not differ between child and female adult speakers (although it did for male adult speakers), whereas the centroid for /ʃ/ was high in the youngest children and decreased with age.

Closer to home, Grandon and Vilain (2020) measured spectral moments in word-initial /s/ and /ʃ/ in European French-speaking children, aged 5;7–10;7. They found a significant PoA difference for the group as a whole and an age interaction with younger children having higher centroid values for /ʃ/ but not for /s/. In summary, a number of studies have revealed main effects of PoA and age on spectral moments and PoA × Age interactions, although the details vary across studies.

Influence of Gender

With regard to gender, females tend to have higher centroid values than males due to smaller oral cavities and different degrees of lip rounding (Jongman et al., 2000; Koenig et al., 2013). Lower values for the third spectral moment have also been reported in females compared with males (Jongman et al., 2000). Nissen and Fox (2005) found isolated gender effects in their acoustic study of spectral moments in children, aged 3–6 years, and adults. For example, child male speakers had higher spectral means for /s/ and lower spectral means for /ʃ/ than child female speakers. Their findings for /s/ differ from what is normally reported for gender-related effects since boys obtained higher spectral means for /s/ than girls. Ford et al. (2018), in a large-scale study of fricative production in Australian English-speaking children (aged 5–13 years), reported gender differences for sibilants /s, ʃ/ that were consistent with adult findings: Girls produced both sibilants with higher spectral means and lower spectral skewness than boys. Similar findings have been reported by Bang et al. (2017). Researchers claim that vocal tract and head circumference growth may explain some aspects of gender differences; however, much of the difference appears to be due to socially influenced and learned articulatory behavior since differences in vocal tract size are small in child speakers (Bang et al., 2017). Li et al.'s (2016) results are consistent with this claim. They documented gender differences in the spectral moments of /s/, which were influenced by gender identity (as measured by the Childhood Gender Identity Questionnaire, a questionnaire that characterizes male- and female-typical behavior) and not by physical measures of body height (which served as a proxy for vocal tract length). Given findings on significant gender effects across a number of studies, we examine the effect of gender in this study.

Influence of Bilingualism

Several studies have compared monolingual and bilingual children on the development of voice onset time (Kehoe et al., 2004; Stoehr et al., 2018), vowel contrasts (Yang & Fox, 2017), consonant inventories (Fabiano-Smith & Barlow, 2010), and syllable structure (Keffala et al., 2018; Kehoe & Havy, 2019), finding evidence for similarities and differences between monolinguals and bilinguals in their acquisition patterns. Few studies have compared monolingual and bilingual children on (alveolar and alveopalatal) fricative production or have measured spectral moments in bilingual children, with the exception of Kehoe and colleagues and Philippart de Foy et al. (2020), to be discussed below, thus suggesting this study is opportune.

Kehoe and colleagues compared monolingual and bilingual French-speaking children, aged 2–6 years, on their production of alveopalatal fricatives by employing phonetic transcription rather than acoustic analysis (Kehoe & Girardier, 2020; Kehoe & Havy, 2019). They investigated whether the size of the alveopalatal/palatal fricative inventory in the child's L1 (i.e., language spoken at home other than French) influenced alveopalatal production in French. Thus, for example, they coded bilingual children, who speak Swedish, which has one alveopalatal consonant, as having a small alveopalatal fricative inventory, and children, who speak Russian, which has eight alveopalatal fricatives and affricates, as having a large inventory. They did not find any influence of alveopalatal fricative inventory size on alveopalatal fricative production in French.

It is, nevertheless, possible that phonetic transcription may be less sensitive to fine-grained differences, which result from the interaction between a bilingual's two languages than acoustic analysis. Philippart de Foy et al. (2020) conducted a spectral moments' analysis of 16 bilingual French-speaking children; the children spoke Italian (*n* = 11) or Arabic (*n* = 5) as L1. The children were aged between 1;9 and 3;0 when they were first tested and were recorded longitudinally over a period of 12 months. Philippart de Foy et al. (2020) posited that bilingual children speaking Arabic might have an advantage in sibilant fricative acquisition, because there is a larger number of fricatives in Arabic than in French and because the consonant inventory in Arabic poses articulatory challenges in the form of a larger overall inventory. Bilingual children speaking Italian may have less of an advantage than bilingual children speaking Arabic since their consonant inventory is similar to that of French. Results supported their predictions. The bilingual French–Arabic children had higher centers of gravity and lower values of skewness for /s/ compared with /ʃ/, suggesting a distinction between the two sets of fricatives. In contrast, the French–Italian children exhibited high centers of gravity for both /s/ and /ʃ/, suggesting that, when attempting /ʃ/, they were producing [s]. Philippart de Foy et al. (2020) did not test monolingual children, so we cannot determine whether the spectral moments of the bilinguals differ from those of monolinguals; nevertheless, their findings suggest that a spectral moments' analysis may be sensitive to speech differences, which result from bilingual input. We now turn to other word/sound-related factors that influence spectral moments.

Influence of Voicing

Voicing influences spectral moments' realization. Voiced fricatives have lower centroid values than voiceless fricatives, because the voice source contributes spectral energy in the low-frequency region. Jongman et al. (2000) documented a main effect of voice on all spectral moments in adult speakers, although they note that effect sizes were small. Voiceless fricatives were characterized by higher values for spectral mean and lower values for skewness than voiced fricatives. Petrović (2020) reports centroid values of above 6000 Hz for /s/ and below 6000 Hz for /z/, 5000 Hz for /ʃ/, and 4000 Hz for /ʒ/. We are not aware of any studies on spectral moments of voiced fricatives in children; however, children frequently devoice consonants in early phonological acquisition. Thus, children may differentiate voiced and voiceless cognates on the basis of spectral moments less well than adults.

Influence of Vowel Quality

Vowel quality effects on spectral moments have been frequently reported (Grandon & Vilain, 2020; Jongman et al., 2000; Nittrouer, 1995; Zharkova, 2021). Mean frequency is lower in the vicinity of /u/ than it is for /a/ and /i/ (Jongman et al., 2000). For example, Nittrouer (1995) reported higher centroid values for fricatives before the front vowel /i/ than before the back vowels /u/ and /ɑ/ with similar effects observed for children and adults. Others have reported greater acoustic contrasts in some vowel contexts than others. Zharkova (2021), for example, observed more pronounced differences between alveolar and alveopalatal fricatives before /a/ than before /i/ in 3-year-old children. Six children differentiated the consonants before /a/, whereas only four did so before /i/. Zharkova (2021) accounted for the reduced contrast in the context of /i/ by the effect of the high vowel on the tongue position of /s/. Given the findings on the influence of vowel quality on spectral moments, we control for this variable in this study.

Influence of Word Position

Finally, we consider the influence of word position on spectral moments. Most studies have conducted spectral moments' analyses on word-initial fricatives (Grandon & Vilain, 2020; Holliday et al., 2015; Li et al., 2009; Nissen & Fox, 2005). One of the few studies that have measured spectral moments in other word positions is Shadle and Mair (1996), which reported on spectral moments of fricatives situated in word-final and -medial positions. They found that spectral moments were relatively insensitive to word position. In the case of children, positional effects have often been observed in nonacoustic studies of fricative acquisition (Edwards, 1996), a robust finding being the earlier acquisition of fricatives in word-final position. In this study, we employ stimuli in which fricatives are located in different word positions; thus, we are also interested in whether word position influences spectral moments' analyses.

Fricative Duration

Apart from measuring spectral moments, we also measure the duration of alveolar and alveopalatal fricatives. Certain word/sound-related factors may influence fricative duration but not spectral moments, thus, suggesting that both spectral and temporal measures are important when considering factors that influence fricative production across age. In general, children's segment durations decrease with age due to increased timing control and speech motor capabilities (Kent & Forner, 1980). Duration has not been found to be a reliable measure to distinguish PoA; however, it does distinguish voiceless from voiced fricatives: Voiceless fricatives are longer than voiced (Crystal & House, 1988; Jongman et al., 2000). Focusing on /s/ and /z/ in word-final position, Song et al. (2013) found that even 2-year-olds produced voiced fricatives longer than voiceless ones. Segment duration may also vary according to word position with final segments being longer than initial, which, in turn, are longer than medial (Oller, 1973). Others report differences in fricative duration according to vowel quality: Nissen and Fox (2005) found reduced duration when fricatives were followed by low vowel [ɑ] versus high vowels [i] or [u]. Thus, we examine whether child- and word/sound-related factors influence fricative duration.

This Study and Main Research Predictions

As discussed above, fricatives are among the last sounds to emerge during phonological development due to their articulatory difficulty (Kent, 1992). They have not received as much research attention as other classes of sounds (e.g., stops and liquids), particularly in languages other than English (Grandon & Vilain, 2020). Given this lack of research, the overarching aim of this study is to present findings on fricative development in French, specifically findings on alveolar and alveopalatal fricatives. The study involves a cross-sectional design, investigating fricative production in children aged 2–6 years. First, we present data on the percent accuracy of alveolar and alveopalatal fricatives at different age ranges, which may serve as preliminary normative data on fricative production in French. Second, we conduct a spectral moments' analysis, focusing on the first and third spectral moments, in order to determine which factors influence spectral moments' realizations. The child-related factors include age, gender, and bilingualism, and the sound/word-related factors include PoA, voicing, vowel quality, and word position. We also examine the influence of these factors on fricative duration. This study extends previous research by comparing monolingual and bilingual children and by examining the effects of different phonetic factors on spectral moments. Based on the preceding literature review, our predictions are as follows:

Child Related

- Age: We predict that age will have a significant effect on spectral moments' realization. Younger children will have higher centroids and lower skewness values than older children.
- Gender: We predict gender effects on spectral moments as has been reported in previous research (Ford et al., 2018): Girls should have higher centroids and lower skewness values than boys.
- Bilingual status: Based on the findings of Philippart de Foy et al. (2020), we predict that bilingualism may have an influence on children's spectral moments. First, we examine whether monolinguals differ from bilinguals as a group. Bilinguals might be able to distinguish alveolar and alveopalatal fricatives more easily than monolinguals, because they have exposure to different types of linguistic complexity across both of their languages, which lead to facilitative effects on the perception and production of fricatives (Grech & Dodd, 2008; Kehoe & Havy, 2019). Alternatively, bilinguals, as a group, may distinguish alveolar and alveopalatal fricatives less easily than monolinguals, because producing sounds across two phonetic inventories, some of which are phonetically similar but not identical, poses perceptive and productive challenges for bilingual children.
  Second, following Kehoe and Havy (2019) and Kehoe and Girardier (2020), we code the complexity of alveopalatal fricatives by counting the number of alveopalatal fricatives in the child's L1. If this effect is significant, it suggests that the influence of bilingualism on fricative production is not a general but a specific effect related to the size of the alveopalatal fricative inventory. The effect may be facilitative: Producing many alveopalatal fricatives in the home language may help the child produce them in French. Alternatively, the effect may be nonfacilitative: Producing many alveopalatal fricatives in the home language may create perceptual and productive challenges, which leads to poorer alveopalatal fricative production in French.

Word/Sound Related

- PoA: Based on previous research, we predict an Age × PoA interaction with greater differentiation between alveolar and alveopalatal fricatives with increasing age. Some studies indicate that children distinguish alveolar from alveopalatal fricatives at an early age (Nittrouer, 1995); others do not (Nissen & Fox, 2005). Thus, we make no firm predictions about whether we will observe significant PoA distinctions in our youngest group of children.
- Voicing: We predict that voicing influences spectral moments. Higher centroid and lower skewness values will be obtained for voiceless as opposed to voiced fricatives (Jongman et al., 2000).

- Vowel context: Vowel quality influences spectral moments (Nittrouer, 1995; Zharkova, 2021). We predict differences in spectral moments according to the front–back or high–low dimensions: Centroids will be higher and skewness values lower when preceding front versus back vowels and high versus low vowels.
- Word position: We make no firm predictions concerning the influence of word position on spectral moments given the lack of pertinent research.

Duration

A secondary aspect of the study is to investigate the influence of child- and word/sound-related factors on fricative duration. We predict the effects of the following:

- Age: Fricative duration should decrease with age (Kent & Forner, 1980; Smith, 1978).
- Voicing: Duration should be greater for voiceless compared to voiced fricatives (Jongman et al., 2000; Song et al., 2013).
- Vowel context: Fricative duration may vary according to the height of the vowel: Fricatives will be longer when followed by high than low vowels (Nissen & Fox, 2005).
- Word position: Duration should be greater for final compared with initial and medial segments as found by Oller (1973).

We do not predict differences according to PoA, and we have no firm predictions concerning the influence of gender and bilingualism on duration given the lack of pertinent research.

Method

Participants

Participants include 89 French-speaking monolingual and bilingual children, aged 2;6–6;10. The data come from two studies: Kehoe and Havy's (2019) and Kehoe and Girardier's (2020), in which over 140 French-speaking children were tested at the speech laboratory of the University of Geneva or onsite at kindergartens or public schools in Geneva. All parents signed an informed consent form as required by the ethics committee at the University of Geneva. Because of the time-consuming nature of the acoustic analysis and in order to have age-matched groups of monolingual and bilingual children, we selected a subsample from these studies. From the Kehoe and Havy (2019) study, we selected 20 children: 10 monolinguals and 10 bilinguals. All children were aged 2;6 (±2 weeks). In order to have a greater number of productions from 2-year-olds, we also added three children, two monolinguals aged 2;7 and one aged 2;8 who were tested as part of the Kehoe and Girardier (2020) project but who were not included in the published study, because they were younger than 3 years. From the Kehoe and Girardier (2020) study, we selected 65 children with the aim of having eight monolinguals and eight bilinguals at each age range: 3, 4, 5, and 6 years. At age 3 years, we added an additional monolingual so as to even up numbers of productions across monolingual and bilingual children. Table 1 shows the number of monolinguals and bilinguals in each age group and the number of productions retained in the final analyses. A series of two-way t tests indicated that there were no significant age differences between the monolinguals and bilinguals at each age group, Age 2: $t(22) = 0.14$, $p = .89$; Age 3: $t(14) = 0.66$, $p = .52$; Age 4: $t(14) = -1.68$, $p = .11$; Age 5: $t(14) = 0.92$, $p = .38$; Age 6: $t(14) = 0.43$, $p = .68$. The average age was 2;6 (range: 2;6–2;8) for the 2-year-olds; 3;4 (range: 2;11–3;10) for the 3-year-olds; 4;6 (range: 4;1–4;11) for the 4-year-olds; 5;5 (range: 5;0–5;11) for the 5-year-olds; and 6;4 (range: 5;11–6;10) for the 6-year-olds.[2]

In the 2-year-old group, percent exposure to French was determined by having the parents complete the Language Exposure Questionnaire (Bosch & Sebastián-Gallés, 1997). Monolinguals were designated as children who received 90%–100% exposure to French, whereas bilinguals were those who received 30%–80% exposure. In the older group, bilingual status was based on a questionnaire (loosely based on the PABIQ; Tuller, 2015), in which parents indicated whether their child spoke another language at least 30% of the time in addition to French. We did not measure percent exposure; however, parents were

Table 1. Number of participants and productions retained across age.

Age	No. of children		No. of productions	
	Mon	Bi	Mon	Bi
2	13	11	204	194
3	9	8	225	239
4	8	8	248	288
5	8	8	257	261
6	8	8	291	297

Note. Mon = monolinguals; Bi = bilinguals.

[2]The Kehoe and Girardier (2020) database contained fewer monolinguals than bilinguals and fewer children aged 3 years. In order to obtain even numbers of children across age and monolingual–bilingual groups, it was necessary to include slightly younger children at certain age ranges. Thus, in the 3-year-old group, there are two children aged 2;11, and in the 6-year-old group, there are two children aged 5;11.

required to judge the language usage of French and the other language on a scale from 1 to 5. We coded values "2" and "3" as "not dominant" in French and "4" as dominant in French. To equate language experience information across the younger and older groups, we applied the same procedure to the younger data; we coded 60% exposure or more in French as dominant and 50% exposure or less in French as not dominant in French. In the group of 43 bilinguals, 22 children were dominant and 20 were not dominant in French. There were missing data on one child. The children had all received exposure to French before the age of 3 years. Information on the monolingual and bilingual participants including age, gender, dominance in French, and languages spoken is presented in Tables A1 and A2 in Appendix A. The languages spoken by the bilinguals included English, German, Swedish, Catalan, Italian, and Spanish. In some cases, children were trilingual, speaking two different languages at home.

Table 2. Examples of word stimuli containing alveolar and alveopalatal fricatives.

Sound	Word-initial	Word-medial	Word-final
s	cinq	chaussure	brosse
	six	dessin	glace
	singe	piscine	vis
	cerise	princesse	six
	salade	garçon	ours
z	zebre	cuisine	chaise
		maison	cerise
		musique	chemise
		oiseau	église
		dinosaure	surprise
ʃ	chaise	cochon	vache
	chat	échelle	bouche
	chapeau	caché	cloche
	cheval	fourchette	flèche
	chemise	t-shirt	planche
ʒ	jupe	bougie	singe
	jaune	étagère	rouge
	jambe		nuage
	girafe		fromage
	jambon		garage

Stimuli

The stimuli for the children included words ranging from one to three syllables with target alveolar and alveopalatal fricatives situated in word-initial, -medial, or -final positions. The majority of words can be found in the l'Inventaire Français du Développement Communicatif (IFDC; Kern & Gayraud, 2010) and/or in the Developpement du langage de production en français (DLPF) Version 3 (31–36 mois; Bassano et al., 2005). Most of the words were targeted in the naming tasks; however, we also included words that were frequently produced spontaneously by children in the recording session (e.g., dessin and surprise). We did not target words that contained fricatives within a consonant sequence (e.g., chien /ʃjɛ̃/ "dog"; escargot /ɛskaʁgo/ "snail"); however, we made an exception for consonant sequences containing /r/ (e.g., ours /uʁs/ "bear" and fourchette /fuʁʃɛt/ "fork") since /r/ in these sequences is often deleted in early acquisition (Kehoe, 2021). We were not able to elicit many words containing /z/ in word-initial or /ʒ/ in word-medial position, because they are infrequent in French. Examples of the word stimuli are shown in Table 2.

Procedure

Children took part in an object or word naming task of approximately 20–30 min (see Kehoe & Havy, 2019, & Kehoe & Girardier, 2020, for further details). The 2-year-olds were tested in the speech laboratory at the University of Geneva, and the older children were tested in a quiet room in the children's kindergarten or school. They were required to name a picture or an object following the question "Qu'est-ce que c'est?" (What is that?) or "Comment ça s'appelle?" (What is that called?) In the majority of cases, children responded with a single word (e.g., six "six") or article plus a noun (e.g., une flèche "an arrow") but, occasionally, they produced phrases as well (e.g., c'est une flèche "It's an arrow"). We included the stimulus word regardless of whether it was produced in isolation, combined with an article, or within a short phrase. The testers were instructed to elicit spontaneous productions of stimulus words but, when this was not possible, to obtain productions through imitation. The average number of productions containing fricatives was 17 for the 2-year-olds (range: 7–37); 27 for the 3-year-olds (range: 9–38); 33 for the 4-year-olds (range: 24–46); 32 for the 5-year-olds (range: 19–55); and 37 for the 6-year-olds (range: 25–56).

Data Analyses

Children's productions were recorded with a portable digital tape recorder (Marantz Tascam DR-2d) and a unidirectional electret condenser microphone placed on a table in front of the child, approximately 30–40 cm from the child's mouth. Recordings were made with a 44.1-kHz sampling rate and 24-bit quantization. Every effort was made to reduce background noise by preventing children from playing with noisy toys and limiting any sound effects. When noise overlay was detected on a word during the recording session, the child was asked to repeat the word. During acoustic analysis, tokens characterized by noise overlay were excluded (see below).

Using Phon, a software program designed for the analysis of phonological data (Rose & MacWhinney, 2014), each child's WAV file was segmented, and stimulus words were identified and transcribed. Four French-speaking graduate students, who had experience in phonetic transcription, including training in the speech laboratory, performed the analyses. In total, 3,306 words containing alveolar and alveopalatal fricatives were extracted from the recording sessions of the 89 children. From this total, we excluded 85 tokens in which the target sibilant fricative was substituted by a nonsibilant fricative or by a stop. Finally, we excluded 717 tokens because they were characterized by noise overlay, low or high volume, or were tokens that were difficult to segment. The final number of items included in the database was 2,504. The items consisted of words in which the target sibilant was transcribed as a sibilant fricative or affricate.

Acoustic analyses were conducted in Praat (Boersma & Weenink, 2016). We used the time waveform, spectrogram, and amplitude contour to aid in the segmentation of fricatives. In word-initial position, the onset of the fricative was defined as the first appearance of aperiodic noise on the waveform and the offset was the first zero-crossing of the periodic waveform of the following vowel.[3] In word-medial position, we measured the period between the offset and then the onset of full formant structure of the preceding and following vowel (Machaĉ & Skarnitzl, 2009). In word-final position, the onset of the fricative was the offset of full formant structure and the offset was the end of aperiodic noise. Once the fricative segment was identified, we recorded its duration (ms) and then ran a Praat script, which extracted six spectra across the length of the fricative, averaged these spectra, and computed spectral moments based on this averaged spectrum (see Shadle, 2012).[4] The spectra were determined using a low-frequency cutoff of 300 Hz and a high-frequency cutoff of 22,050 Hz.

Data-Coding and Statistical Analyses

In the statistical analyses, independent variables included child- and word/sound-related factors. Child-related variables were age (in months), gender (male and female), bilingual status (monolingual and bilingual), and L1/L2 alveopalatal inventory size (ranging from 2 to 10). To determine alveopalatal inventory size, we counted the number of alveopalatal/palatal fricatives and affricates in the L1 and L2 of the children. Table B1 in Appendix B contains information on the alveopalatal fricatives and affricates in the languages of the bilinguals (see also the last column in Table A2 in Appendix A). For example, monolinguals were coded as having an alveopalatal fricative inventory size of 2, and Spanish–French bilinguals were coded as having an alveopalatal fricative inventory size of 3 (2 alveopalatal fricatives in French +1 in Spanish) and English–French bilinguals were coded as having an alveopalatal fricative inventory size of 6 (2 in French +4 in English). We took into consideration both languages of the bilinguals so as to distinguish monolinguals from bilinguals who had the same number of alveopalatals in their inventories (e.g., a French–Portuguese bilingual who has two alveopalatal fricatives in French and two in Portuguese). We hypothesized that bilinguals who need to produce alveopalatal fricatives across both of their languages, even phonemically similar ones, may experience different perceptual and productive challenges than monolinguals who have only one set of alveopalatal fricatives. In the case of trilinguals, we coded the L1 with the greatest amount of exposure.[5]

Word/sound-related variables were PoA (alveolar and alveopalatal), voicing (voice, voiceless), and word position (initial, medial, and final) of the target fricative. Vowel quality was coded in terms of two dimensions: high–low (high, mid, and low) and front–back (front, central, and back). High vowels were /i, y, u/; mid vowels were /e, ɛ, ø, œ, ə, o, ɔ, ɛ̃, ɔ̃/, and low vowels were /a, ɑ̃/. Front vowels were /i, y, e, ɛ, ɛ̃/; central vowels were /ø, œ, ə, a/; and back vowels were /u, o, ɔ, ɔ̃, ɑ̃/. Because the main model included all syllable positions, we coded the vowel that followed the fricative in word-initial and -medial positions, and the vowel that preceded the fricative in word-final position. Later, we ran an additional model, one containing words in which fricatives were situated in word-initial and -medial positions to examine more closely the effect of the following vowel on spectral moments and duration.

In addition to the child- and word/sound-related variables, we included three control variables. We coded the number of syllables in the word, whether the production was imitated or spontaneous, and the context (i.e., whether the word was produced in isolation, in combination with an article, or within a longer phrase). Imitation may lead to more target-like productions (Goldstein et al., 2004) and since there were greater numbers of imitated productions in the younger children's repertoires, it was important to control for this effect. We coded for the number of syllables in the word and the context in which the word was produced as these factors may influence duration measures (Lehiste, 1972). In general, a sound situated in a shorter word is longer than a sound situated in a longer word. Similarly, a sound produced in a single word is longer than a sound produced in a phrase.

[3]In a small percentage of word-initial fricatives (approximately 5%), there was a short period of reduced frication (almost silence) before the onset of voicing of the following vowel. In these tokens, segmentation was made at the end of the (high energy) frication and before the first zero crossing of the following vowel.

[4]We thank V. Delvaux for the use of this script.

[5]In the case of trilinguals, we also coded the language with the highest number of alveopalatal fricatives. The results were the same regardless of whether we coded the language with the greatest language exposure or the more complex alveopalatal system.

The analyses were performed using R statistical software (R Development Core Team, 2020) and the lme4 package (Bates et al., 2015) for mixed models. Comparisons were made using likelihood ratio tests (LRTs), which yield a chi-squared statistic. Random factors included participant and word token. To determine differences between groups, we employed pairwise comparisons (emmeans function in R).

Reliability

In terms of phonetic transcription, 12 participants (approximately 12% of the data) were retranscribed by a second transcriber using the Blind Transcription function of the Phon program. Point-to-point phoneme agreement was moderate to good (87.5%).

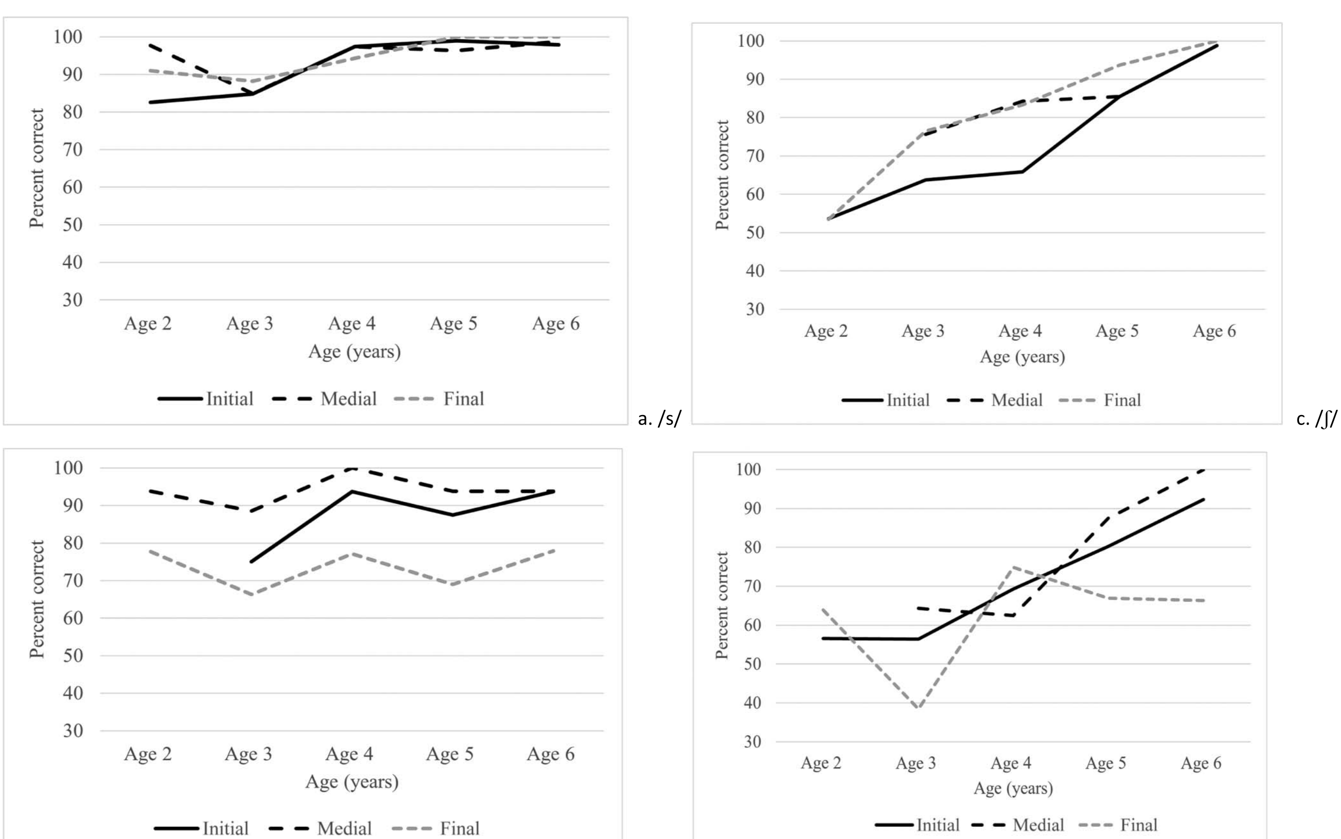
In terms of the acoustic analysis, the data of 12 children (approximately 10% of the data; 240/2,504 tokens) were reanalyzed acoustically. The average absolute difference between the original and reanalyzed data was 14.38 ms (SD = 16.82) for fricative duration and 368.86 Hz (SD = 332.01) for spectral means. The Pearson r correlation coefficient between the original and recoded measures was significant for both measures: duration: $r(238) = .94$, $p < .001$; spectral mean: $r(238) = .97$; $p < .001$. The absolute differences for duration are consistent with reliability results reported by Song et al. (2013) for fricative duration in young children. The duration and spectral differences associated with the reliability measures are smaller than the subsequent duration and spectral differences reported in the analyses.

Results

Percent Correct

First, we display the percent correct production of the four sibilant fricatives across the three word positions and five age ranges (see Figure 1 and Tables C1 and C2 in Appendix C). The percent correct results are based on the phonetic transcription of all productions of target sibilants including those substituted by sounds other than fricatives. Children aged 2 years did not produce sufficient numbers of words with initial /z/ and medial /ʃ/ and /ʒ/ for these words to be included in the analyses. In the case of /s/ (see Figure 1a), there are few age-related effects: Percent production is high across all word positions (i.e., greater

Figure 1. Percent correct production of the four sibilant fricatives (Panel a: /s/; Panel b: /z/; Panel c: /ʃ/; Panel d: /ʒ/) across word position (initial, medial, and final) and different age ranges of children.



than 80% at ages 2 and 3 years; greater than 90% at ages 4–6 years). Similarly, there are few age-related effects for /z/ (see Figure 1b); rather, there are clear positional effects: /z/ is produced with greater percent accuracy in word-initial and -medial than -final position. In the case of /ʃ, ʒ/, there are age-related effects with older children obtaining higher percent correct scores than younger children (see Figures 1c and 1d). As for positional effects, initial /ʃ/ poses more difficulties than medial and final /ʃ/ for children aged 3–5 years and final /ʒ/ poses more difficulty than initial and medial /ʒ/ at several age ranges. Six-year-old children are far from producing final /ʒ/ with 100% accuracy.

Centroid Values

We present the mean centroid values for the four sibilant fricatives across the three word positions and five age ranges (see Figure 2 and Tables D1–D2 in Appendix D). Graphs indicate that centroid values are greater for /s/ and /z/ in comparison with /ʃ/ and /ʒ/ (compare Figures 2a vs. 2c and Figures 2b vs. 2b), although the differences are less clear for the voiced fricatives. Across all sounds, values decline with increasing age. Centroid values do not differ greatly across syllable positions with the exception of /z/, whereby centroid values are higher for final /z/ in comparison with medial /z/. Initial /z/ falls in between the two extremes.

To determine which factors most influenced centroid and skewness values, we ran mixed-effects linear regression (LMER) models. We entered variables one at a time starting first with control variables, followed by child- and word/sound-related variables, and then followed by their interactions. We removed variables that were not significant (see Grandon & Vilain, 2020, for a similar approach to model building). There were 2,504 individual items included in the analysis. The significance of the fixed factors was determined by examining the *p* values provided by the lmer test function and confirmed by conducting LRTs, which determined whether the variable significantly changed the fit of the model. Information criteria such as the Akaike information criterion (AIC) and Bayesian information criterion (BIC) were employed to determine the best fitting model. Multiple comparisons were conducted employing the emmeans function, which adjusts for Type 1 error using the Tukey's honestly significant difference test.

Figure 2. Mean centroid values of the four sibilant fricatives (Panel a: /s/; Panel b: /z/; Panel c: /ʃ/; Panel d: /ʒ/) across word position (initial, medial, and final) and different age ranges of children.

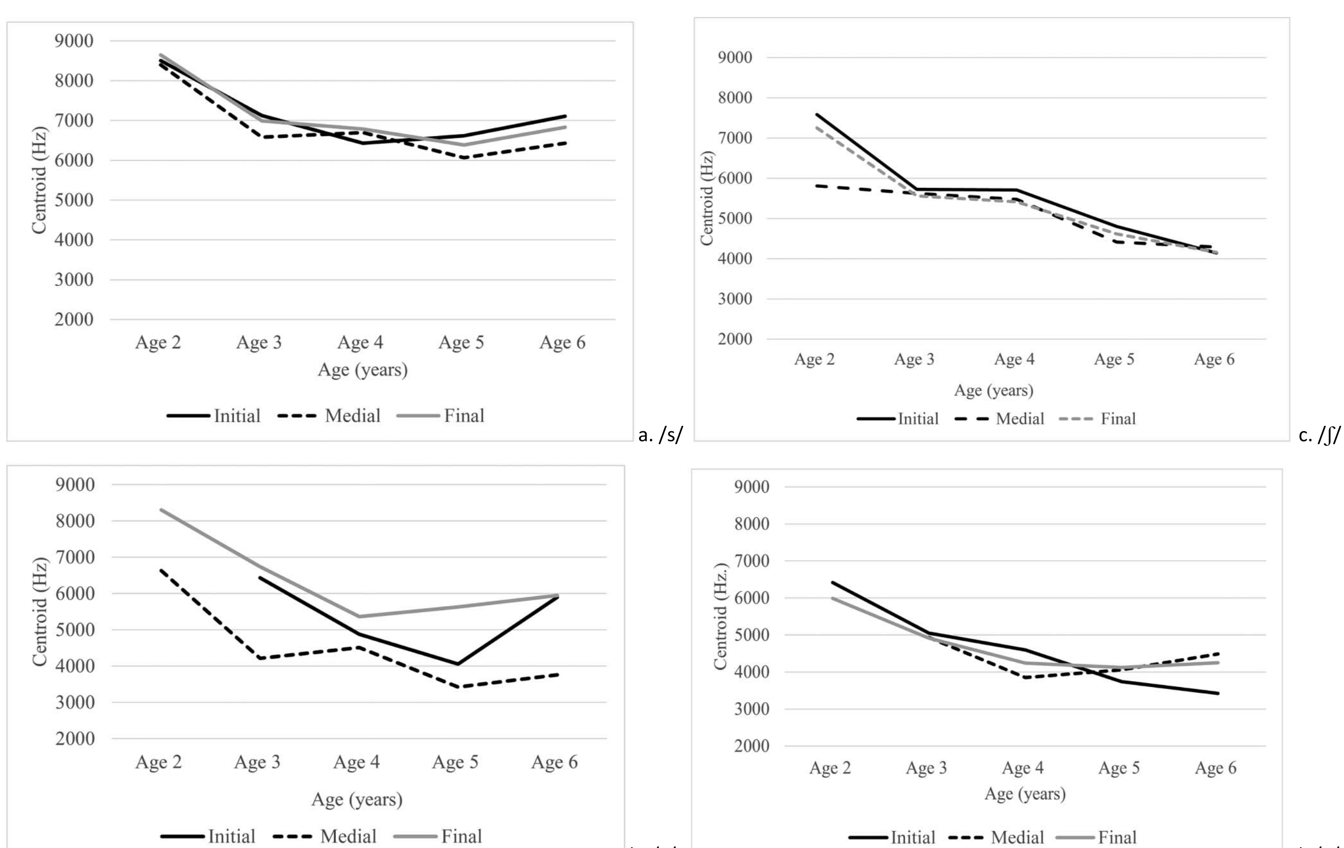


Table 3. Best fitting model to explain the factors that influence the first spectral moment or centroid.

Fixed effects	Estimate	*SE*	*t* value	Pr(>|*t*|)
(Intercept)	10094.085	423.221	23.851	< .001***
Imitation	−278.518	107.110	−2.600	.009**
Age (months)	−43.545	6.281	−6.933	< .001***
Gender	−706.580	200.472	−3.525	< .001***
Alveopalatal inventory	−161.299	59.646	−2.704	.008**
PoA	−830.528	267.032	−3.110	.002**
Voice	−773.955	144.831	−5.344	< .001***
Syllable position-i	203.913	131.987	1.545	.13
Syllable position-m	−164.404	149.582	−1.099	.28
Frontback-front	487.120	104.980	4.640	< .001***
Frontback-central	183.703	131.811	1.39	.17
Age × PoA	−13.673	4.001	−3.417	< .001***
pal.inventory × PoA	97.294	35.690	2.726	.006**
Syllable position-i × voice	−569.958	218.615	−2.607	.01*
Syllable position-m × voice	−975.675	246.118	−3.964	< .001***
Random effects				
Group name	Variance	*SD*		
Participant (intercept)	771685	878.5		
Word (intercept)	33015	181.7		

Note. *SE* = standard error; PoA = place-of-articulation.
**p* < .05. ***p* < .01. ****p* < .001.

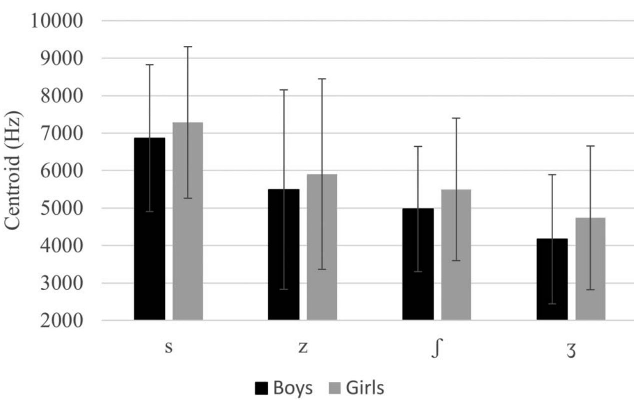
Table 3 presents the best fitting model for the factors that influenced centroid values. In terms of control variables, the presence of imitation was the only factor that was significant. Productions that were imitated had higher centroid values than productions that were spontaneously produced, $\chi^2(1) = 6.66$, $p = .01$. In terms of the child-related variables, age, gender, and alveopalatal inventory size all influenced centroid values. Centroid values decreased as age increased,[6] and centroid values were higher in girls than boys, $\chi^2(1) = 11.65$, $p < .001$. The effect of gender on the centroid values of the four sibilant fricatives is shown in Figure 3. There was no general effect of bilingualism on centroid values, but there was a specific effect: As alveopalatal fricative inventory size increased, centroid values decreased. In terms of the word/sound-related variables, PoA, voice, and front–back vowel quality all influenced centroid values. Centroid values were higher for alveolar in comparison with alveopalatal fricatives, higher for voiceless as compared with voiced consonants, and higher in the vicinity of front versus middle and back vowels, $\chi^2(1) = 16.79$, $p < .001$. We ran pairwise comparisons to determine which vowel groups were different. Results indicated that centroids were higher in the vicinity of front than back vowels ($t = 4.24$, $p < .001$). There were no differences between the other vowel groups. Finally, three interactions were found to be significant. The first interaction, Age × PoA, indicated that as age increased, the centroid difference between alveolar and alveopalatal PoA increased, $\chi^2(1) = 11.63$, $p < .001$, as shown in Figure 4. The second interaction, Alveopalatal Inventory Size × PoA, indicated that as alveopalatal inventory size increased, the centroid difference between alveolar and alveopalatal PoA decreased, $\chi^2(1) = 7.42$, $p = .006$.[7] A scatter plot illustrating the interaction between PoA and inventory size is shown in Figure 5. The third interaction, Word Position × Voice, indicated that the influence of word position on centroid values differed according to whether the target fricative was voiced or voiceless, $\chi^2(1) = 15.93$, $p < .001$. Pairwise comparisons indicated that there were no differences in centroid values across word position for voiceless fricatives but there were for voiced fricatives: Centroid values were significantly higher for final ($t = 5.5$, $p < .001$) and initial fricatives ($t = 3.27$, $p = .02$) in comparison to medial fricatives.

We reran the model on a database that included only initial and medial fricatives to verify the effect of vowel quality on the centroid values of the preceding fricative. To remind the reader, by including fricatives in

[6]When variables were also implicated in interaction effects as was the case with age, we provide only the likelihood ratio test result for the interaction effect.

[7]To confirm the influence of alveopalatal fricative inventory size, we also reran the model using a categorical variable, alveopalatal fricative complexity (see Table B.1 in Appendix B), rather than the continuous variable. In the categorical variable, languages with small numbers of alveopalatal fricatives were coded low complexity and languages with high numbers were coded high complexity. We found the same result as that of inventory size, namely, a significant main effect and a significant PoA and complexity interaction. In addition, given that there were few children who had large inventory sizes, we excluded these children and reran the model without these extremes. The findings still indicated that inventory size and its interaction with PoA influenced model fit to data.

Figure 3. Bar graph of centroid values for boys and girls for the four sibilant fricatives /s, z, ʃ, ʒ/. Standard deviations are indicated by error bars.



word-final position in the main database, we confounded the effect of vowel influence by having vowels that both preceded and followed the fricative. Results on the reduced database confirmed that the front–back dimension had a significant effect on spectral moments, $\chi^2(2) = 8.32$, $p = .02$. Centroid values were significantly higher before front than back vowels ($t = 2.99$; $p = .01$). There were no differences between the other vowel groups.

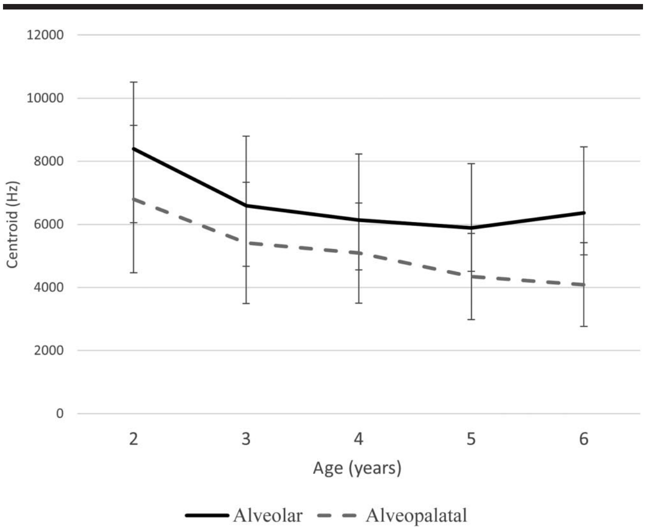
Skewness

Skewness values across position and age are given in Tables E1–E2 in Appendix E. Table 4 presents the best fitting model for the factors that influence skewness values. In general, the same factors that influenced centroid also influenced skewness values. The presence of imitation was once again a significant predictor. Imitated productions had lower skewness values than spontaneous productions, $\chi^2(1) = 5.65$, $p = .02$. In terms of the child-related variables, gender and alveopalatal inventory size influenced skewness. Girls had lower skewness values than boys, $\chi^2(1) = 9.02$, $p = .003$, and as alveopalatal inventory size increased, skewness values decreased. In terms of word/sound-related variables, voice and front–back vowel quality influenced skewness values. Voiceless fricatives had lower skewness values than voiced fricatives, and fricatives in the vicinity of front vowels had lower skewness values than in the vicinity of central and back vowels, $\chi^2(1) = 12.00$, $p = .002$. Pairwise comparisons indicated that skewness values for fricatives associated with front vowels were significantly different from those associated with back vowels ($t = 3.1$, $p = .008$). Neither age nor PoA were significant predictors on their own but were involved in interactions. There was a significant Age × PoA effect, $\chi^2(1) = 42.54$, $p < .001$. As shown in Figure 6, the difference between the skewness values of alveolar and alveopalatal fricatives increased with age. There was also a significant interaction between alveopalatal fricative inventory size and PoA, $\chi^2(1) = 16.05$, $p < .001$. As inventory size increased, the difference between the skewness values of alveolar and alveopalatal fricatives decreased (see Figure 7). Finally, there was a significant interaction between syllable position and voice, $\chi^2(2) = 8.71$, $p = .01$. Pairwise comparisons indicated that skewness values were lower for voiceless fricatives as compared to voiced fricatives in initial ($t = 4.56$, $p < .001$) and medial ($t = 5.61$, $p < .001$) but not in final position ($t = 2.65$, $p = .09$).

As before, we reran the model on a database that included only initial and medial fricatives to verify the effect of vowel quality on the skewness values of the preceding fricative. Results confirmed that the front–back dimension had a significant effect on skewness, $\chi^2(2) = 10.00$, $p = .007$. Skewness values were significantly lower before front than back vowels ($t = 2.72$; $p = .02$). There were no differences between the other vowel groups.

In summary, the main difference between the findings of the statistical models for centroid and skewness values was that young children still differentiated alveolar and alveopalatal PoA by centroid but they did not do so by skewness values. For both measures, differences between PoA increased with age.

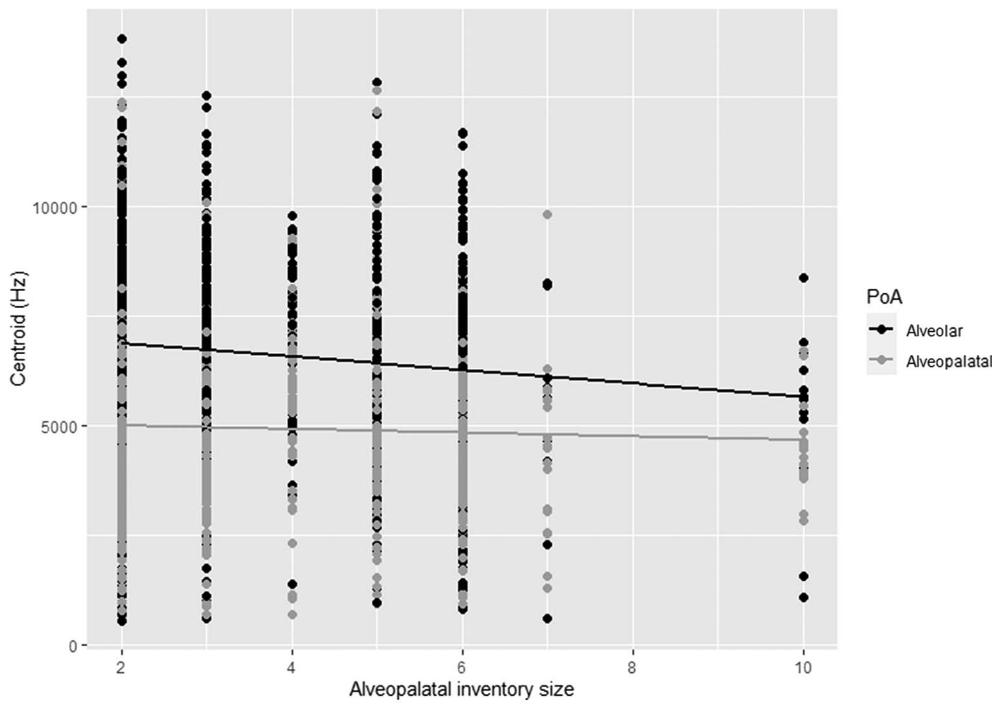
Figure 4. Mean centroid values for alveolar and alveopalatal fricatives across age. Standard deviations are indicated by error bars.



Duration

Findings on the mean duration of alveopalatal fricatives for the four sibilant fricatives across the three word positions and five age ranges are presented in Figure 8 (see Tables F1–F4 in Appendix F). The graph shows that voiceless fricatives are longer than voiced fricatives (compare Figures 8a vs. 8b and 8c vs. 8d). Across all sounds,

Figure 5. Scatter plot of centroid values across alveopalatal inventory size showing the interaction of inventory size and place-of-articulation (PoA). The centroid differences between alveolar and alveopalatal fricatives decreased with increasing inventory size.



duration is longer in final compared to medial and initial positions. Medial voiceless fricatives tend to be longer than initial voiceless, and medial voiced fricatives tend to be shorter than initial voiced. There are few age-related effects.

The best-fitting model for the factors that influence fricative duration is provided in Table 5. Among the control variables, two were found to be significant: syllable number and context. That is, fricative duration was longer in shorter versus longer words, $\chi^2(1) = 10.64$, $p = .001$,

Table 4. Best fitting model to explain the factors that influence the third spectral moment or skewness values.

Fixed effects	Estimate	*SE*	*t* value	Pr(>|t|)
(Intercept)	−7.192e-01	3.057e-01	−2.352	.02*
Imitation	2.392e-01	9.996e-02	2.393	.02*
Age	7.455e-03	4.435e-03	1.681	.09
Gender	4.133e-01	1.339e-01	3.087	.003**
Alveopalatal Inventory	8.934e-02	4.158e-02	2.148	.03*
PoA	−7.895e-02	2.501e-01	−0.316	.75
Voice	3.672e-01	1.279e-01	2.872	.005**
Syllable position-i	−1.465e-01	1.167e-01	−1.255	.21
Syllable position-m	−1.461e-01	1.297e-01	−1.127	.27
Frontback-front	−3.106e-01	9.053e-02	−3.431	.001**
Frontback-central	−5.548e-02	1.155e-01	−0.480	.63
Age × PoA	2.474e-02	3.777e-03	6.550	< .001***
pal.inventory × PoA	−1.360e-01	3.390e-02	−4.013	< .001***
Syllable position-i × voice	3.272e-01	1.903e-01	1.720	.09
Syllable position-m × voice	6.696e-01	2.156e-01	3.106	.003**
Random effects				
Group name	Variance	*SD*		
Participant (intercept)	0.2985	0.5463		
Word (intercept)	0.0158	0.1257		

Note. *SE* = standard error; PoA = place-of-articulation.
**p* < .05. ***p* < .01. ****p* < .001.

Figure 6. Scatter plot of skewness values across age showing the interaction of age and place-of-articulation (PoA). The difference between the skewness values of alveolar and alveopalatal fricatives increased with age.

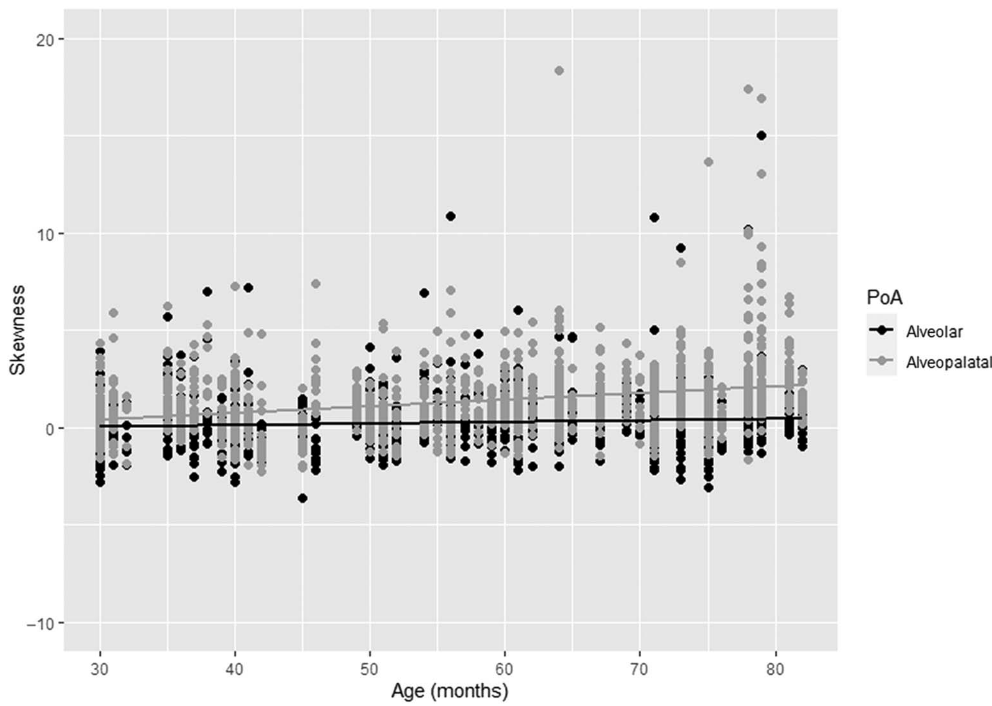


Figure 7. Scatter plot of skewness values across palatal inventory size showing the interaction of alveopalatal inventory size and place-of-articulation (PoA). The difference between the skewness values of alveolar and alveopalatal fricatives decreased with inventory size.

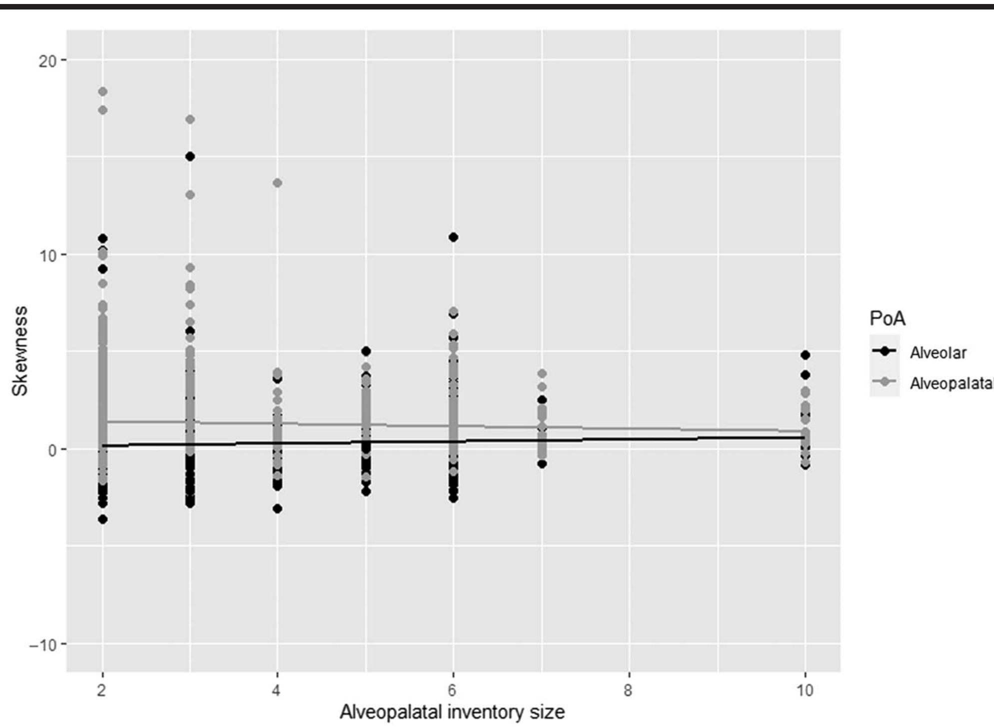


Figure 8. Mean duration of the four sibilant fricatives (Panel a: /s/; Panel b: /z/; Panel c: /ʃ/; Panel d: /ʒ/) across word position (initial, medial, and final) and different age ranges of children.

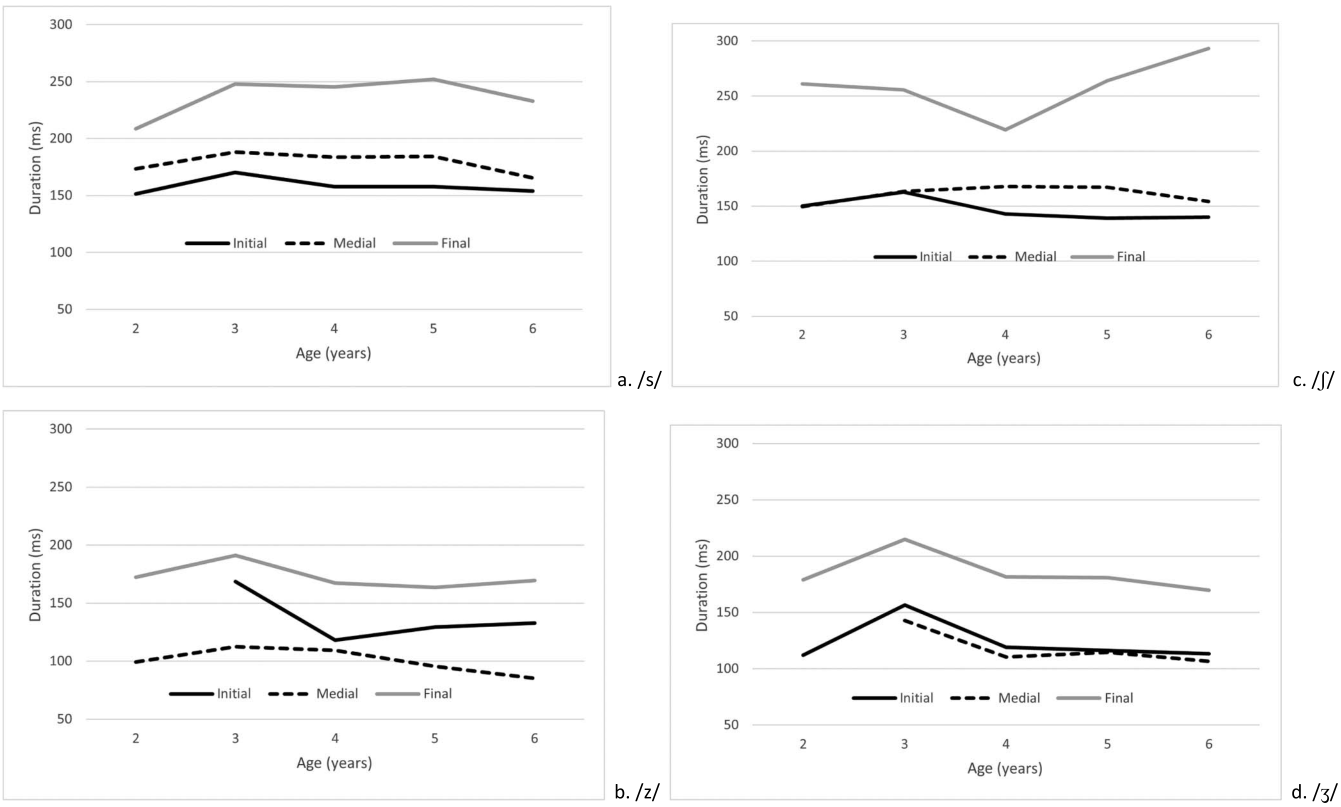


Table 5. Best fitting model to explain the factors that influence the duration of fricatives.

Fixed effects	**Estimate**	***SE***	***t* value**	**Pr(>|t|)**
(Intercept)	262.3479	15.0810	17.396	< .001***
Phrase-phrase	−17.2618	5.4479	−3.168	.001**
Phrase-word	0.1752	2.9109	0.060	.95
Sylno	−12.9049	3.8675	−3.337	.002**
Age	0.1191	0.2266	0.525	.60
Gender	−11.8650	6.0295	−1.968	.052
Voice	−35.3295	10.3610	−3.410	< .001***
Syllable position-i	−44.6649	11.0925	−4.027	< .001***
Syllable position-m	−26.9181	12.5255	−2.149	.03*
Height-low	−19.2398	6.3456	−3.032	.004**
Height-mid	−12.6638	4.6773	−2.707	.009**
Age X voice	−0.5712	0.1579	−3.616	< .001***
Age X syl pos-i	−0.3824	0.1725	−2.217	.03*
Age X syl pos-m	−0.4483	0.1970	−2.276	.02*
Syl pos-f X PoA	22.2401	6.3194	3.519	< .001***
Syl pos-i X PoA	−11.0325	5.5558	−1.986	.051
Syl pos-mX PoA	−2.3734	7.7914	−0.305	.76
Syl pos-i X voice	29.4256	9.9022	2.972	.005**
Syl pos-m X voice	8.8252	10.2046	0.865	.39
Random effects				
Group name	Variance	*SD*		
Participant (intercept)	666.8	25.82		
Word (intercept)	103.1	10.15		

*$p < .05$. **$p < .01$. ***$p < .001$.

and when the word was said in isolation versus in a phrase, $\chi^2(1) = 10.37$, $p = .006$. Concerning the latter variable, pairwise comparisons indicated that fricatives were shorter when situated in single words than in phrases ($t = 3.25$, $p = .007$) and were shorter in words combined with an article than in a longer phrase ($t = 3.15$, $p = .005$). There was no difference between the length of fricatives in single words and in single words plus articles ($t = .06$, $p = .99$). Among the child-related variables, gender was marginally significant, $\chi^2(2) = 3.77$, $p = .05$: Girls displayed a tendency to produce fricatives longer than boys. Age as a main effect did not influence fricative duration, but it interacted with several other variables (see below). There was also no significant effect of bilingualism on fricative duration.

Among the word/sound-related factors, voice, syllable position, and vowel height influenced fricative duration. Voiceless fricatives were longer than voiced fricatives. Final fricatives were longer than initial and medial fricatives, and fricatives were longer in the vicinity of high than low vowels, $\chi^2(2) = 10.76$, $p = .005$. Regarding the influence of vowel height on fricative duration, pairwise comparisons indicated that fricatives were longer in the vicinity of high than mid ($t = 2.33$, $p = .04$) or low vowels ($t = 2.68$, $p = .02$). In addition, there were two interactions that involved age: Age × Voice, $\chi^2(2) = 13.04$, $p < .001$, and Age × Word Position, $\chi^2(4) = 6.50$, $p = .04$. The Age × Voice interaction indicated that there were few age-related effects on the duration of voiceless fricatives but there were on the duration of voiced fricatives. As age increased, the duration of voiced fricatives decreased. The Age × Word Position interaction indicated that, as age increased, the duration of initial and medial fricatives decreased but the duration of final fricatives remained the same. Thus, the difference between the duration of initial and final ($t = 13.80$, $p < .001$) and medial and final fricatives ($t = 8.21$, $p < .001$) increased; the difference between initial and medial fricatives was similar ($t = 1.16$, $p = .48$). There were also two interactions that involved word position. Word Position × PoA, $\chi^2(3) = 15.23$, $p = .02$, and Word Position × Voice, $\chi^2(2) = 7.98$, $p = .02$. The Word Position × PoA interaction indicated that alveolar fricatives were of similar duration to alveopalatal fricatives in all word positions except final position whereby alveopalatal fricatives were significantly longer than alveolar fricatives ($t = 3.15$, $p = .02$). The Word Position × Voice interaction indicated that final fricatives were longer than initial and medial fricatives, regardless of whether they were voiced or voiceless; however, medial voiceless fricatives were longer than initial voiceless fricatives ($t = 3.09$, $p = .03$), whereas there were no differences in duration between medial and initial voiced fricatives. The interaction between voice and word position should be interpreted with caution given that /z/ in word-initial and /ʒ/ in word-medial position were less well sampled than in other positions.

We reran the model on a database that included only initial and medial fricatives to verify the effect of vowel quality on the duration of the preceding fricative. Results indicated a marginal effect of vowel height on fricative duration, $\chi^2(2) = 5.78$, $p = .056$. We simplified the model since two of the interaction effects involving word position were no longer significant once final fricatives were removed from the database. In a simplified model, vowel height significantly influenced fricative duration, $\chi^2(2) = 7.79$, $p = .02$. Fricatives were longer before high than low vowels ($t = 2.47$; $p = .04$). There was no difference between the other vowel groups.

Discussion

This study investigated the development of alveolar and alveopalatal fricatives in French-speaking monolingual and bilingual children, aged 2;6–6;10. Our aim was twofold: to present data on the percent accuracy of fricatives across age and word position, and to conduct a spectral moments' analysis, focusing on the first and third spectral moments. Concerning the latter, we examined whether French-speaking children distinguish alveolar and alveopalatal fricatives from an early age and which factors, both child- and word/sound-related, affect spectral moments. We were also interested in the influence of these factors on fricative duration. Our findings indicated that multiple factors influence the spectral and temporal qualities of alveolar and alveopalatal fricatives. We summarize these findings in the following paragraphs and consider how they contribute to our understanding of the acquisition of alveopalatal fricatives in young children.

Percent Accuracy

An important aspect of our analyses was to present the percent accuracy of alveolar and alveopalatal fricatives across different age ranges and word positions, providing data that may be useful for researchers and clinicians interested in fricative production. We observed few age effects on the accuracy of alveolar fricatives but strong word position effects for /z/. In contrast, age effects were present for alveopalatal fricatives: Younger children obtained lower percent accuracy than older children. Word-position effects were also present, particularly for /ʒ/. A salient finding was that final voiced fricatives were characterized by lower percent accuracy than fricatives in other positions.

MacLeod et al. (2011), in a normative study of consonant acquisition in Canadian French–speaking children, reported that /s, ʃ, ʒ/ were late sounds, not being mastered (i.e., produced accurately by 90% of the children) during the analysis period (by age 4;5). They found that /z/ was an early acquired sound being mastered by age 3;0. Our findings are consistent with theirs for /ʃ, ʒ/ since percent accuracy was certainly lower than 90% at age 4–5 years. Our findings differ for /s/ and /z/. We documented high percent accuracy for /s/ with children achieving 90% accuracy in all word positions by 4 years. As for /z/, only medial /z/ was produced with roughly 90% accuracy at 3 years. McLeod (2009) points out that /s/ may display variable ages of acquisition across studies (from 3 to 7 years) due to the influence of dentition on /s/ production (whether the children have lost their central incisors). Uncontrolled effects of dentition may explain some of the differences between our results and those of MacLeod et al. (2011). We have no clear explanation for the differences in /z/ accuracy between the two studies, but note that Aicart-de Falco and Vion (1987) in a study of consonant acquisition in European French-speaking children obtained results similar to ours for /z/.

Spectral Moments

PoA and Age

Previous findings on English-speaking children present conflicting findings on whether young children can distinguish alveolar and alveopalatal PoA based on spectral moments. Nittrouer (1995), for example, found a significant PoA effect on centroid values in children as young as 3 years, whereas Nissen and Fox (2005) found one only at 5 years old. In our study, we documented a significant main effect of PoA on centroid values suggesting that French-speaking children as young as age 2;6 were able to distinguish alveolar and alveopalatal fricatives (see Figure 4). However, we did not document a significant main effect for skewness, indicating that this particular spectral moment was not sensitive to PoA differences in the younger children (see Figure 7). In both statistical models, the interaction between age and PoA was significant, indicating that the differences between alveolar and alveopalatal fricatives became greater with age. Holliday et al. (2015) reported that the centroid for /ʃ/ was high at the youngest age, approximating the one for /s/, and then it declined with age. Our results show a reduction in centroids for both alveolar and alveopalatal fricatives with age, although greater changes were observed in the alveopalatal fricatives. In the case of skewness, alveopalatal fricatives evidenced the main age-related change; the skewness values for alveopalatals and alveolars were close at 2 years but the values for alveopalatals became more positive with increasing age. Why a contrast was observed earlier in centroids and not skewness is not clear but may relate to the fact that the centroid is a more robust measure of PoA discrimination than skewness (Nirgianaki, 2014).

Gender

We observed a clear gender effect in our spectral moments' analyses: Girls obtained higher centroid and lower skewness values than boys. This effect did not interact with age suggesting that gender effects were present across the age range. This finding agrees with several reports of gender differences in the spectral moments' analyses of sibilants in children (Bang et al., 2017; Ford et al., 2018; Fox & Nissen, 2005; Li et al., 2016; Nissen & Fox, 2005). Nevertheless, the reported gender-related findings have not been completely homogeneous. Nissen and Fox (2005), for example, found higher spectral means for /s/ in boy speakers, which is opposite to what has been reported in the adult literature. The current findings, however, revealed gender-related differences, which parallel the adult data and which are suggestive of learned speech behavior. Munson et al. (2006) reported that the spectra of /s/ may be associated with perceived sexual identity differences; the /s/ in gay/bisexual men was more negatively skewed than in heterosexual men, a pattern more typical of heterosexual women. Li et al. (2016) found that gender identity accounted for the acoustic dimensions of /s/ more strongly than body height or age. These and the findings of gender differences in sibilants in very young children suggest that the spectra of sibilants are a sensitive measure of sociolinguistic and socio-indexical factors. We assume that gender differences in spectral moments are salient in the input to children and that children are able to reproduce these differences from an early age.

Bilingualism

An important finding of the study was that there were L1 effects on the realization of spectral moments. Bilingual status on its own did not influence spectral moments; rather, the size of the alveopalatal fricative inventory across the children's two languages influenced both spectral means and skewness. Children who spoke more alveopalatal fricatives in their home language had greater difficulty realizing a PoA distinction than monolinguals and bilinguals who spoke fewer alveopalatal fricatives in their home language. Philippart de Foy et al. (2020) observed that Arabic–French children realized a PoA contrast in their spectral moments in French earlier than Italian–French children, which she ascribed to the more complex consonant inventory of Arabic compared to Italian. This finding, which suggests that phonological complexity in the L1 aids the acquisition of similar phonological features in the L2, has been reported in several studies of bilingual phonological acquisition (Keffala et al., 2018; Kehoe & Havy, 2019).[8] Instead, we observed

[8]Philippart de Foy et al. (2020) judged Arabic phonology as being more complex than Italian on the basis of the entire consonant inventory, whereas we coded only alveopalatal fricatives (and affricates).

an opposite effect. Speaking several alveopalatal fricatives in the home language did not aid the acquisition of a PoA distinction but appeared to make it more difficult. Why would this be so?

One possibility is that different acoustic cues, apart from spectral moments, may be associated with the PoA contrast of alveopalatal fricatives in the child's L1. For example, Li et al. (2009) report that spectral means were not the best acoustic cue to distinguish alveolar and alveopalatal PoA in Japanese; rather, F2 onset had to be combined with the first spectral moment to separate Japanese alveolar and alveopalatal fricatives. Differences in cue weighting between the child's L1 and L2 may lead to difficulties assigning appropriate cues to the right target language (e.g., spectral means in French vs. spectral means + F2 onsets in Japanese), and consequently to the poorer results we observed in some of the bilingual children. A second possibility is that speaking many alveopalatal fricatives across two languages, some of which overlap on spectral characteristics, may be a perceptual and productive challenge that leads to some "compromise" or compensatory strategies. The child's alveopalatal fricatives may be realized with spectral values in between those of their L1 and L2, analogous to the intermediate VOT values reported in bilingual VOT research (Flege & Port, 1981; Kehoe et al., 2004). Thus, our findings would be consistent with Flege's (1995) speech learning model (SLM) and its revised equivalent (Flege & Bohn, 2021). According to the SLM, when two similar sounds are acquired, a process of perceptual assimilation occurs in which the categories of the L1 and L2 merge. Such a possibility would need to be confirmed by conducting a spectral moments' analysis of sibilant fricatives in the two languages of the bilingual and in monolingual controls to determine whether the alveopalatal fricatives of the bilinguals differ from the monolinguals and in ways that lead to reduced PoA differences between them and the alveolar fricatives.

We should nevertheless point out that our metric of using inventory size is limited in that it does not incorporate information on fricative frequency. A language could have few palatal fricatives in the inventory but ones that are frequent; another language could have a greater number of fricatives in the inventory but ones that are less frequent. Other factors apart from frequency (e.g., saliency and functional load) could lead to alveopalatal fricatives being acquired earlier in one language than another. These factors (frequency and age of acquisition) could potentially influence the findings, suggesting the need for future studies to incorporate such factors into a more complete measure of fricative complexity.

Word/Sound-Related Effects

Our spectral moments' analyses of the child French data confirmed many of the phonetic effects reported in the child and adult English data. The spectral mean was lower, and spectral skewness was higher in voiced as compared with voiceless fricatives. These findings are consistent with Jongman et al.'s (2000) findings on English-speaking adults, which indicate significant effects of voice on spectral moments. Similarly, our analyses confirmed an effect of vowel quality on spectral moments. Spectral means were higher, and skewness values were lower when the fricative was followed by a front versus back vowel, a finding that reflects coarticulation effects: the anticipation of the vowel gesture during the production of the fricative (Grandon & Vilain, 2020). Studies with children have tended to use controlled stimuli with a limited number of vowel environments (e.g., /i, a, u/), whereas this study used less controlled stimuli with a wider range of vowels. Previous studies implicate both the front–back (/i/ vs. /u/) and height (/i/ vs. /a/) dimensions as influencing spectral values (Bang et al., 2017; Nittrouer, 1995; Zharkova, 2021); however, only the front–back dimension emerged as a significant factor in our statistical models. We cannot exclude that the use of a wider range of vowels may have obscured some effects of the vowel environment, leading only to the front–back dimension influencing spectral moments.

The influence of word position has been less frequently studied in spectral moments' analyses. One of the few studies that have examined its influence reports few effects of word position on spectral moments (Shadle & Mair, 1996). Our findings are generally in agreement with this. If we examine the results displayed in Figure 2, we observe similar spectral means across all word positions for /s, ʃ, ʒ/, the exception being /z/, in which there were some apparent differences according to word position: Centroid values were higher for final as compared with initial and medial fricatives. Our statistical models also indicated no main effect of word position on spectral moments, but there was an interaction between word position and voicing. In the case of centroid values, there were no effects of word position on voiceless but there was an effect on voiced fricatives: Final and initial fricatives were characterized by higher centroids than medial fricatives. In the case of skewness, the same type of effect was observed but the difference was only significant between medial and final fricatives; skewness values were lower for voiced final compared to medial fricatives. In addition, there was no significant effect of voicing on the skewness values of final fricatives. To explain these findings, we draw, the readers' attention to the percent accuracy results presented in Figure 1, which show clear positional effects on the accuracy of target /z/ and, to a lesser extent, /ʒ/. Final voiced fricatives were characterized by lower accuracy scores than initial and medial voiced fricatives. Although the scope of our study does not allow for a thorough investigation of the errors produced by the children, previous analyses of some of the data indicate that devoicing of final voiced fricatives was a common error pattern (chaise /ʃɛz/ → [ʃɛs] "chair"; rouge /ʁuʒ/ → [ʁuʃ] "red": Kehoe et al., 2021). If children were realizing final voiced fricatives as voiceless, the higher centroid values for final as compared with initial and medial voiced fricatives and the lack of a voicing distinction for skewness in final position may result from this tendency of devoicing.

Influence of Imitation

Our study included several control variables alongside the child and word/sound-related factors. One variable, the presence of imitation, influenced spectral moments. Productions that were imitated had higher centroid and lower skewness values than productions that were not imitated. Given that imitated productions were more present in the younger children, it might be tempting to assume that the imitation effect reflected age-related changes in spectral moments; however, our model also controlled for age, suggesting that factors apart from age contributed to this effect. It is likely that having an adult acoustic model prior to pronouncing a word may lead to a more precise production than when the word is produced spontaneously. Higher spectral means and lower skewness values for /s/ in adults have been associated with judgments of higher speech clarity (Munson et al., 2006), a finding that may explain the effect of imitation in the current context. Imitation may lead to the use of a clear speech mode. Although imitation has not always been found to influence measures such as percent accuracy (Goldstein et al., 2004; Kehoe & Havy, 2019), it may influence more fine-grained acoustic measures such as these.

Duration

In contrast to the statistical findings with spectral moments, child-related factors influenced duration only to a minor degree. There was no simple effect of age on fricative duration, and there was only a tendency for girls to produce fricatives longer than boys. In addition, there was no general or specific effect of bilingualism on fricative duration. Word/sound-related factors, however, influenced fricative duration to a major degree. Voicing, syllable position, and vowel quality all influenced the duration of fricatives. Our results are consistent with those previously reported in the child and adult literature: Voiceless fricatives are longer than voiced fricatives (Jongman et al., 2000; Nirgianaki, 2014; Song et al., 2013); segments in final position are longer than in initial or medial position (Oller, 1973; Smith, 1978); and fricatives are longer when they precede high than low vowels (Jongman et al., 2000; Nirgianaki et al., 2009). There were significant main effects for all these variables indicating that children as young as age 2;6 were sensitive to these phonetic effects in their productions. Our findings supported previous studies in showing no main effect of PoA on duration (Jongman et al., 2000; Nissen & Fox, 2005), although we did document a Word Position × POA interaction with alveopalatal fricatives being longer than alveolar fricatives in word-final position. We also documented a Word Position × Voicing interaction. Oller (1973) reported that initial segments (in his study, stop consonant /b/) were longer than medial ones; however, in this study, we observed that medial voiceless fricatives were longer than initial, and there were no differences in duration between voiced initial and medial fricatives.

We may wonder why there was no main effect of age on fricative duration. In general, younger children have longer segment durations than older children and adults (Kent & Forner, 1980; Smith, 1978), a finding that may be attributed to their reduced speech motor capabilities. Nevertheless, several studies indicate that young children do not necessarily display longer durations than older children (Smith et al., 1996). In our study, however, age interacted with both voicing and syllable position. Younger children's voiced fricatives were longer than older children's voiced fricatives, but there were no differences in age for voiceless fricatives. Younger children's initial and medial fricatives were longer than older children's initial and medial fricatives, but there were no differences in age for final fricatives. The age effect for voiced fricatives is consistent with the fact that voiced fricatives are more complex than voiceless fricatives from a speech motor perspective and age-related effects may be observed because of their added articulatory complexity. The lack of age effects for final fricatives may reflect prosodic influences that are not necessarily operative in the other word positions. Final fricatives were situated in phrase-final position, and prosodic influences (e.g., phrase-final lengthening, final accent, and word boundary effects) may have led to lengthened segment durations during the age range studied.

As with the spectral moments' analysis, control variables also emerged as significant in our statistical models. Fricatives were longer when situated in a shorter versus longer word and when situated in a single word versus a phrase. The influence of word length and context on segment duration has been documented (for vowels and consonants) in both child and adult data (Kehoe, 2019; Lehiste, 1972; Port, 1981; Smith, 1978).

Acquisition of Alveopalatal Fricatives in Children

One of the motivations of this study was to understand what factors influence the acquisition of alveopalatal fricatives in young monolingual and bilingual children. Previous studies by Kehoe and colleagues indicated that the accuracy of alveopalatal fricatives was not influenced by the same set of variables that influenced the overall accuracy of consonants and vowels and syllable structure

(Kehoe & Havy, 2019; Kehoe & Girardier, 2020). Whereas a combination of L1 complexity, lexical, and language-external factors (e.g., percent language exposure, and dominance) influenced consonant and vowel measures and syllable structure, few variables influenced the accuracy of alveopalatal fricatives. This study aimed to determine whether a spectral moments' analysis would be a more sensitive gauge of children's developmental patterns with alveopalatal fricatives.

Our study showed that children's acoustic patterns were remarkably sensitive to a range of phonetic contextual factors that are known to influence adult speech. As noted above, children's spectral moments' and duration measures were influenced by PoA, voicing, vowel quality, and word position to varying degrees but all in ways consistent with adult systems. We observed that children's spectral moments were even sensitive to sociolinguistic factors such as gender differences and speech mode (imitated vs. spontaneous speech). They were also sensitive to subtle L1 effects related to the number of alveopalatal fricatives in the child's phonetic inventory. Thus, in the end, we were able to show that children, even as young as age 2;6, have acquired a great deal of acoustic knowledge on alveopalatal fricatives and on the distinction between alveolar and alveopalatal fricatives. Nevertheless, it will still take several years before 90% of them will be transcribed as having target-like alveopalatals and even more years if we consider specifically the plight of final voiced alveopalatal fricatives. Glaspey et al. (2022) recently reported that final /ʒ/ was not acquired in connected speech through the age of 10 years in English-speaking children.

Nittrouer (1995) posited that children's difficulty with alveopalatal fricatives may relate to the small size of their vocal tracts and the lack of a sublingual space for /ʃ/ and /ʒ/. Adults having a larger vocal tract are able to achieve a sublingual airspace between the underside of the tongue blade and the mandibular arch, which is one of the defining differences between /ʃ/ and /s/ production (Perkell et al., 1979). Zharkova (2021) also interprets her articulatory and acoustic findings as being consistent with Nittrouer's conclusion of reduced sublingual space. The reduced space comes about not only from the small size of children's vocal tracts but also from their poorer tongue–jaw coordination and reduced lingual differentiation in comparison with adults. In the case of the final voiced fricative /ʒ/, several authors have commented on the articulatory difficulty of final voiced obstruents in general and final voiced /ʒ/ in particular (Glaspey et al., 2022; Smith, 1979). Producing voiced obstruents in word-final position poses an aerodynamic challenge because children need to obtain the right balance of intraoral and subglottal pressure to maintain voicing (Glaspey et al., 2022; Smith, 1979). This requires subtle vocal-tract adjustments (e.g., lowering the larynx, expanding the oral cavity), which children are less skilled at than adults. Thus, articulatory limitations in combination with vocal tract growth appear to be important factors in explaining the protracted development of alveopalatal fricatives.

Clinical Implications

This study has implications for understanding fricative development in French-speaking children. We have included data on the percent correct production of /s, z, ʃ, ʒ/ across age range and word position (see Figure 1 and Appendix C, Tables C1 and C2), which may serve as developmental milestones for clinicians when deciding whether a child with speech sound errors conforms to the norm. Previous studies on spectral moments have focused on voiceless fricatives and word-initial position, whereas this study includes voiced fricatives and other word positions, providing additional information on fricative development. We can observe that percent correct production and centroid values for voiced /z/ and /ʒ/ are more variable and more often subject to word position effects than for voiceless fricatives, observations that may prove useful in planning speech sound intervention (e.g., in selecting word targets).

Limitations

Concerning the limitations of the study, one of the main ones was that we focused only on group results and did not take into account individual differences in the acoustic realization of fricatives. For example, we do not know if all children distinguished PoA on the basis of centroid values or just some of them. Another limitation is that we collected data on familiar words, and, as a result, we were not able to ensure equal numbers of productions across all sounds and word positions. In particular, word-initial /z/ and medial /ʒ/ were poorly represented in our database. In terms of our bilingual population, we also did not have even numbers of children with different alveopalatal fricative inventory sizes. It would be important to replicate this study with bilingual children speaking different languages selected to vary in their alveopalatal fricative inventory sizes. Future studies should also include older children and adults to determine at what age children exhibit the same POA contrast as adults.

Conclusions

This study measured the first and third spectral moments as well as the duration of alveolar and alveopalatal fricatives in the productions of monolingual and bilingual French-speaking children, aged 2;6–6;10. We documented both child- and word/sound-related effects on spectral moments and predominantly word/sound-related effects on duration. These acoustic results indicate that children know a great deal about alveolar and alveopalatal fricatives even though their accuracy results suggest more protracted development. An important finding was that the complexity of alveopalatals in the child's home language influenced spectral moments' realization. This finding joins many other studies in revealing that the phonological properties of the L1 may impact L2 production.

Data Availability Statement

The data are not publicly available due to ethical considerations but are available from the first author upon request.

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Participant Information

Table A1. Information on the monolingual participants including gender and age.

Age group	Child ID	Gender	Age (years;months)
2	Child 30	f	2;6
	Child 35	m	2;6
	Child 51	m	2;6
	Child 22	m	2;6
	Child 26	m	2;6
	Child 27	f	2;6
	Child 31	m	2;6
	Child 32	f	2;6
	Child 34	m	2;6
	Child 38	f	2;6
	Child 42	f	2;6
	EL	m	2;7
	GA	f	2;7
3	RL	f	2;11
	MF	m	3;0
	PN	m	3;0
	MR	m	3;3
	GH	m	3;4
	IA	m	3;5
	VM	m	3;9
	AM	f	3;9
	GI	f	3;10
4	CN	m	4;1
	MS	m	4;1
	BN	f	4;2
	KJ	m	4;2
	SL	m	4;3
	FL	f	4;8
	MS	f	4;8
	DWL	f	4;9
5	DE	f	5;0
	BM	f	5;1
	BZ	f	5;2
	LA	m	5;4
	MI	f	5;4
	AM	m	5;5
	DB	m	5;7
	GN	f	5;10
6	NA	f	5;11
	RY	m	5;11
	BS	m	6;1
	GM	f	6;3
	PB	m	6;6
	VE	m	6;6
	BL	m	6;9
	KC	f	6;10

Note. f = female; m = male.

Appendix A (p. 2 of 2)

Participant Information

Table A2. Information on the bilingual participants including gender, age, dominance in French, and alveopalatal inventory size in the L1.

Age group	Child ID	Gender	Age (years;months)	Dom in Fr.	L1	L1+	Alpal inv.
2	Child 43	m	2;6	Not dom	Spanish		1
	Child 44	f	2;6	Not dom	Spanish		1
	Child 48	f	2;6	Not dom	Spanish		1
	Child 50	m	2;6	Not dom	Spanish		1
	Child 36	f	2;6	Not dom	Italian		3
	Child 29	f	2;6	Not dom	English		4
	Child 14	m	2;6	Dom	Spanish		1
	Child 33	f	2;6	Dom	Italian	Spanish	3
	Child 17	m	2;6	Dom	Spanish		1
	Child 49	m	2;6	Dom	Swiss German		4
	AI	m	2;8	Not dom	Portuguese		2
3	CI	m	2;11	Dom	English		4
	CE	m	3;0	Not dom	Italian		3
	AL	m	3;1	Dom	English		4
	WJ	m	3;2	Not dom	German		4
	DL	m	3;4	Not dom	Italian	Dutch	3
	BC	f	3;4	Dom	Norwegian		2
	AL	m	3;5	Dom	Spanish		1
	MA	f	3;6	Dom	Spanish		1
4	OL	f	4;3	Dom	English		4
	CFM	f	4;4	Dom	Portuguese		2
	VC	f	4;6		English		4
	CN	m	4;6	Dom	Japanese		5
	BS	f	4;7	Not dom	Italian		3
	DL	f	4;8	Dom	Catalan		4
	NW	m	4;10	Not dom	Polish	Italian	8
	DGY	f	4;11	Dom	German		4
5	LC	m	5;1	Not dom	German	Swedish	4
	PK	m	5;1	Dom	Spanish		1
	OPA	f	5;4	Not dom	English		4
	RN	f	5;4	Dom	Spanish		1
	VM	f	5;7	Not dom	Italian		3
	JL	f	5;9	Dom	English	Bosnian	4
	LA	f	5;0	Dom	Spanish		1
	AA	f	5;11	Dom	Italian		3
6	FA	m	6;1	Dom	Italian		3
	RA	f	6;1	Not dom	Spanish		1
	BFJ	f	6;1	Not dom	Swedish	Farsi	1
	BM	F	6;3	Dom	German		4
	RD	m	6;3	Not dom	Portuguese		2
	FG	m	6;4	Dom	German	Spanish	4
	HD	m	6;7	Not dom	Spanish		1
	IS	f	6;7	Not dom	Swiss German		4

Note. Dom = dominance; Fr. = French; Alpal = alveopalatal; inv. = inventory; f = female; m = male.

Appendix B

Information on Alveopalatal/Palatal Fricatives

Table B1. Information on alveopalatal/palatal fricatives and affricates in the L1s of the bilingual children as well as in French.

Language	Alveopalatal and palatal affricates in inventory[a]	No. of consonants	Alveopalatal/palatal complexity
French	ʃ, ʒ	2	Low
Swedish	ɕ	1	Low
Spanish	ʧ, (ʃ, ʝ)[b]	1	Low
Norwegian	ʂ, ç[c]	2	Low
Portuguese	ʃ, ʒ	2	Low
Italian	ʃ, ʧ, ʤ	3	High
Catalan	ʃ, ʒ, ʧ, ʤ	4	High
English	ʃ, ʒ, ʧ, ʤ	4	High
(Swiss) German	ʃ, ʒ, ʧ, ç	4	High
Japanese	[ɕ, ç, ʑ, ʨ, ʥ][d]	5	High
Polish	ɕ, ʑ, ʨ, ʥ ʂ, ʐ, tʂ, dʐ[e]	8	High

[a]The inventory of alveopalatal/palatal fricatives and affricates was compiled by consulting multiple sources on the consonant inventories of these languages. [b]Sources vary according to the number of alveopalatals in Spanish. [ʃ] appears in loan words; [ʝ] may be realized as an approximant or affricate. [c]Some sources indicate [ʃ] rather than retroflex [ʂ]. [d]Japanese does not have underlying (alveo)-palatal fricatives but they surface due to palatalization process. /s, z, h/ are palatalized before /i/ and /j/ (Ito & Mester, 1995). [e]Velar consonants are palatalized preceding front vowels (van der Hulst & van de Weijer, 1991).

Appendix C

Descriptive Results on Percent Accuracy of Alveolar and Alveopalatal Fricatives

Table C1. Means and standard deviation of percent accuracy across age and syllable position for /s/ and /z/.

Age (years)	Variable	/s/ Initial	/s/ Medial	/s/ Final	/z/ Initial	/z/ Medial	/z/ Final
2	*M*	82.62	97.74	90.97		93.75	77.71
	SD	23.21	8.55	16.83		25.00	29.10
3	*M*	84.81	84.90	88.24	75.00	88.54	66.27
	SD	25.72	26.57	28.73	40.31	27.70	35.42
4	*M*	97.40	97.40	94.27	93.75	100.00	77.17
	SD	7.28	7.28	12.44	25.00	0.00	21.77
5	*M*	98.96	96.35	100.00	87.50	93.75	68.94
	SD	4.17	10.08	0.00	34.16	25.00	34.04
6	*M*	97.92	98.75	100.00	93.75	93.75	77.92
	SD	5.69	5.00	0.00	25.00	25.00	24.09

Table C2. Means and standard deviation of percent accuracy across age and syllable position for /ʃ/ and /ʒ/.

Age (years)	Variable	/ʃ/ Initial	/ʃ/ Medial	/ʃ/ Final	/ʒ/ Initial	/ʒ/ Medial	/ʒ/ Final
2	*M*	53.62		53.47	56.60		63.89
	SD	36.90		41.70	46.82		40.20
3	*M*	63.72	75.63	76.47	56.37	64.29	38.43
	SD	40.77	32.71	39.99	38.81	49.72	30.30
4	*M*	65.85	84.27	83.33	69.27	62.50	74.88
	SD	37.54	28.21	31.62	30.99	50.00	34.96
5	*M*	85.47	85.47	93.75	80.21	87.50	66.94
	SD	28.73	26.99	25.00	33.87	34.16	37.08
6	*M*	98.75	98.75	100.00	92.29	100.00	66.34
	SD	5.00	5.00	0.00	14.49	0.00	36.10

Appendix D

Descriptive Results on Centroid Values

Table D1. Means and standard deviations of centroid values across age and syllable position for /s/ and /z/.

Age (years)	Variable	/s/						/z/					
		n[a]	Initial	*n*	Medial	*n*	Final	*n*	Initial	*n*	Medial	*n*	Final
2	*M*	98	8501.46	39	8400.82	49	8642.85			12	6629.02	45	8301.71
	SD		2083.90		2213.74		2033.80				2723.03		1887.17
3	*M*	77	7125.70	52	6579.59	22	6990.99	13	6435.80	22	4216.38	36	6743.71
	SD		2073.64		1909.83		1683.02		2691.73		2807.86		1784.82
4	*M*	92	6429.98	54	6695.62	32	6789.28	14	4877.45	16	4512.47	45	5366.41
	SD		1667.55		1849.35		1745.62		3011.04		2628.43		2293.11
5	*M*	86	6614.02	45	6064.47	35	6387.07	13	4060.19	22	3427.25	43	5630.09
	SD		1594.28		1977.01		1600.18		2862.53		2241.78		1491.13
6	*M*	89	7110.09	57	6426.62	31	6832.27	12	5896.51	23	3757.38	49	5952.55
	SD		1610.40		1889.29		1630.84		2041.91		2150.57		2361.84

[a]*n* = number of tokens analyzed.

Table D2. Means and standard deviations of centroid values across age and syllable position for /ʃ/ and /ʒ/.

Age (years)	Variable	/ʃ/						/ʒ/					
		n[a]	Initial	*n*	Medial	*n*	Final	*n*	Initial	*n*	Medial	*n*	Final
2	*M*	52	7585.62	14	5805.81	29	7248.33	28	6419.45			28	5985.07
	SD		2076.42		2675.66		2051.57		2621.12				2001.81
3	*M*	68	5720.77	62	5622.93	25	5560.24	31	5048.54	9	4929.45	47	4911.64
	SD		1838.93		1887.30		1540.58		1988.74		1917.30		2037.11
4	*M*	74	5704.10	68	5477.65	35	5415.25	34	4593.31	13	3851.61	59	4237.79
	SD		1478.51		1296.59		1410.71		1805.19		1400.77		1457.09
5	*M*	70	4801.67	66	4408.06	26	4612.13	42	3743.83	11	4061.87	59	4121.86
	SD		1261.49		1407.63		1312.96		1595.24		1346.01		1101.43
6	*M*	89	4138.77	78	4287.80	33	4154.94	54	3418.45	13	4485.23	60	4248.71
	SD		1135.46		1297.43		1093.22		1612.53		1552.84		1263.78

[a]*n* = number of tokens analyzed.

Appendix E

Descriptive Results on Skewness Values

Table E1. Means and standard deviations of skewness values across age and syllable position for /s/ and /z/.

Age (years)	Variable	/s/						/z/					
		n[a]	Initial	*n*	Medial	*n*	Final	*n*	Initial	*n*	Medial	*n*	Final
2	*M*	98	−0.008	39	−0.31	49	−0.29			12	0.37	45	0.3
	SD		0.85		1.11		0.67				1.03		0.75
3	*M*	77	−0.09	52	0.14	22	−0.03	13	0.54	22	1.76	36	−0.07
	SD		1.23		1.29		0.96		1.72		2.5		0.99
4	*M*	92	0.17	54	0.03	32	0.11	14	1.16	16	1.49	45	1.45
	SD		0.9		1.02		1.01		1.77		2.11		4.39
5	*M*	86	0.05	45	0.36	35	0.13	13	2.03	22	1.63	43	0.54
	SD		0.83		1		0.75		2.07		1.6		0.99
6	*M*	89	−0.16	57	−0.05	31	0.036	12	0.14	23	1.85	49	0.68
	SD		1.06		1.07		0.87		0.97		2.85		2.76

[a]*n* = number of tokens analyzed.

Table E2. Means and standard deviations of skewness values across age and syllable position for /ʃ/ and /ʒ/.

Age (years)	Variable	/ʃ/						/ʒ/					
		n[a]	Initial	*n*	Medial	*n*	Final	*n*	Initial	*n*	Medial	*n*	Final
2	*M*	52	0.13	14	1.13	29	0.48	28	0.51			28	0.88
	SD		0.8		2.14		1.19		1.09				1
3	*M*	68	0.8	62	0.53	25	0.9	31	1.05	9	1.19	47	1.12
	SD		1.7		1.5		1.38		1.71		1.99		1.51
4	*M*	74	0.56	68	0.56	35	0.78	34	0.95	13	1.89	59	1.57
	SD		1.09		0.89		1.03		1.24		2.22		1.3
5	*M*	70	1.35	66	1.49	26	1.66	42	1.87	11	1.21	59	1.67
	SD		1.27		1.58		1.41		2.91		1.01		1.39
6	*M*	89	2.52	78	1.38	33	2.49	54	2.72	13	1.42	60	1.88
	SD		2.9		1.41		2.39		3.05		1.46		1.46

[a]*n* = number of tokens analyzed.

Appendix F

Descriptive Results on Fricative Duration

Table F1. Means and standard deviations of fricative duration across age and syllable position for /s/ and /z/.

Age (years)	Variable	/s/						/z/					
		n[a]	Initial	*n*	Medial	*n*	Final	*n*	Initial	*n*	Medial	*n*	Final
2	*M*	98	151.43	39	173.36	49	208.49			12	99.10	45	172.28
	SD		56.73		35.21		73.82				47.60		76.54
3	*M*	77	170.21	52	188.03	22	247.73	13	168.49	22	112.41	36	191.25
	SD		52.46		61.38		112.65		113.80		43.44		106.19
4	*M*	92	157.69	54	183.70	32	245.31	14	118.05	16	109.23	45	167.45
	SD		54.72		54.16		79.56		32.32		36.21		45.85
5	*M*	86	157.71	45	184.24	35	252.09	13	129.37	22	95.37	43	163.43
	SD		47.53		39.01		86.49		60.24		25.06		49.67
6	*M*	89	153.90	57	165.33	31	232.69	12	132.68	23	85.19	49	169.39
	SD		58.89		47.68		76.85		69.08		27.87		56.38

[a]*n* = number of tokens analyzed.

Table F2. Means and standard deviations of fricative duration across age and syllable position for /ʃ/ and /ʒ/.

Age (years)	Variable	/ʃ/						/ʒ/					
		n[a]	Initial	*n*	Medial	*n*	Final	*n*	Initial	*n*	Medial	*n*	Final
2	*M*	52	150.12	14	149.52	29	260.91	28	111.96			28	178.90
	SD		69.05		59.28		78.88		53.44				68.51
3	*M*	68	162.61	62	163.48	25	255.71	31	156.58	9	142.72	47	214.68
	SD		61.65		65.64		72.54		58.58		72.74		117.61
4	*M*	74	143.00	68	167.91	35	219.32	34	118.85	13	110.45	59	181.38
	SD		47.05		50.04		73.78		49.33		26.10		68.18
5	*M*	70	139.14	66	167.08	26	263.77	42	116.18	11	114.38	59	180.71
	SD		46.40		56.44		76.29		39.99		41.19		53.97
6	*M*	89	139.96	78	154.12	33	293.14	54	113.30	13	106.61	60	169.53
	SD		45.45		45.90		103.39		39.82		36.93		56.21

[a]*n* = number of tokens analyzed.