A cross-linguistic acoustic study of voiceless fricatives

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Abstract

Results of an acoustic study of voiceless fricatives in seven languages are presented. Three measurements were taken: duration, center of gravity, and overall spectral shape. In addition, formant transitions from adjacent vowels were measured for a subset of the fricatives in certain languages. Fricatives were well differentiated in terms of overall spectral shape and their co-articulation effects on formant transitions for adjacent vowels. The center of gravity measurement also proved useful in differentiating certain fricatives. Duration generally was less useful in differentiating the fricatives. In general, results were consistent across speakers and languages, with lateral fricatives displaying the greatest interspeaker variation in their acoustic properties and /s/ providing the greatest source of interspeaker variation.

1. Introduction

As early as the pioneering studies of fricatives carried out by Hughes and Halle (1956), Strevens (1960), and Jassem (1962), it has been clear that fricatives are potentially differentiated along a number of acoustic parameters, e.g. spectral shape, duration, overall intensity. While a relatively large body of research has indicated that a number of properties may be fruitfully used to classify fricatives, the set of languages forming the basis for generalizations about the acoustic structure of fricatives remains very limited. Numerous studies have examined the fricatives of English, e.g. Hughes and Halle (1956), Harris (1958), Forrest et al. (1988), Behrens and Blumstein (1988a, b), Tomiak (1990), Jongman et al. (2000) and various fricatives produced by trained phoneticians, e.g. Strevens (1960), Jassem (1962), Shadle (1985), Shadle et al. (1991), while only a relatively few studies have targeted fricatives in languages other than English, e.g. Halle (1959) on Russian, Westerdale (1969) on French, Lindblad (1980) on Swedish, Kudela (1968), Jassem (1979) on Polish, Lacerda (1982) on Portuguese, Norlin (1983) on Cairene Arabic, Svantesson (1986) on Mandarin Chinese, Tronnier and Dantsuji (1993) on Japanese and German. There is a particularly acute dearth of studies employing the same set of measures to compare fricatives produced by several speakers of different languages. Probably the largest cross-linguistic study of fricatives is Nartey's (1982) unpublished UCLA dissertation which presents auditory spectra, expressed in critical bands, of fricatives in fourteen languages.

The present study seeks to increase our typological knowledge of the acoustic structures of fricatives by examining data on fricatives in a genetically diverse set of seven languages: Aleut, Apache, Chickasaw, Gaelic, Hupa, Montana Salish, and Toda. All of these languages possess relatively rich fricative inventories consisting of between four and nine fricatives, thereby allowing for cross-linguistic comparison of fricatives. Several of the examined languages also include fricatives which have not been the subject of previous quantitative study; the present study thus broadens our understanding of the acoustic characteristics of a wide range of fricatives. Finally, comparison of data from multiple speakers allows for examination of interspeaker variation in the acoustics of fricatives.

2. Methodology

2.1. Languages

The corpus for the present study consists of data from seven languages collected as part of an NSF grant to Peter Ladefoged and Ian Maddieson to study endangered languages. The seven languages included Aleut (Western dialect), Apache (Western dialect), Chickasaw, Scottish Gaelic, Hupa, Montana Salish, and Toda. The examined languages form a genetically diverse set with only two languages bearing a remote genetic affiliation to each other; these two languages, Hupa and Western Apache, belong to different branches within the Athabaskan family (Na Dene phylum), Hupa to the Pacific coast branch and Western Apache to the southern branch.

The fricatives investigated in the present study were voiceless fricatives contained in words elicited in isolation from native speakers by researchers conducting fieldwork designed to document and record the basic phonetic properties of the examined languages. The languages contained between four (Western Aleut, Chickasaw) and nine (Toda) voiceless fricatives, differing in the location of the primary constriction and the presence and degree of lip rounding. Table 1 lists the examined languages, the original study documenting their phonetic structures, their genetic affiliations (according to Grimes 2001), their geographic location, and their inventory of voiceless fricatives.

Table 1. Languages examined in present study

Language[Sources]	**Genetic affiliation**	**Geographic location**	**Voiceless Fricatives**
Aleut (Western) [Taff et al. 2001]	Eskimo-Aleut	North America (Aleutian islands)	s, ç, ɬ, x, χ
Apache (Western) [Gordon et al. 2001]	Na Dene	North America (Arizona)	s, ʃ, ɬ, x
Chickasaw [Gordon et al. 2000]	Muskogean	North America (Oklahoma)	f, s, ʃ, ɬ
Gaelic (Scottish) [Ladefoged et al. 1998]	Indo-European	Europe (Scotland)	f, f^j, s, ʃ, ç, x
Hupa [Gordon 1996]	Na Dene	North America (California)	s, ʃ, ɬ, x, x^w, x̹^{w}
Montana Salish [Flemming et al. 1994]	Salishan	North America (Montana)	s, ʃ, ɬ, x^w, χ, χ^w
Toda [Shalev et al. 1994]	Dravidian	Asia (India)	f, θ, s̪, s, ʃ, ʂ, ɬ, ɬ̣, x

2.2. Recordings

As part of the original data collection, speakers were recorded using a high quality noise canceling head-mounted microphone and data were captured on DAT for the majority of the languages, except for the Hupa, Montana Salish, and Toda recordings, which were made using a high quality analog audio cassette recorder. The environment in which the examined fricatives occurred was held constant within languages (with some substitutions where gaps in the original recorded data precluded a perfect match across fricatives). In all languages, the fricatives (wherever the data allowed) occurred adjacent to the vowel /a/ (and for languages in which fricatives were word-medial, after the vowel /i/). A list of the words containing the examined fricatives in each language appears in Appendix 1. Each word containing a targeted fricative was repeated twice by each speaker, though in isolated cases, only a single token of a certain fricative uttered for a given speaker was suitable for analysis. Each Toda word was uttered once by each speaker.

Data were digitized from the original recording at 22.05kHz using Scicon's PcQuirer software system in preparation for acoustic analysis, which was also completed using the same software. Sampling at this rate allowed for measurement of a broad frequency range, while also respecting the limits of the recording medium, a particularly important consideration in the case of data collected using analog audio cassettes.

2.3. Measurements

A number of acoustic measurements designed to differentiate the examined fricatives were taken. First, duration measures of each fricative were made from a waveform with the assistance of a spectrogram in cases where segmentation was difficult using only the waveform. The onset and cessation of noise were used as benchmarks for determining the beginning and end, respectively, of each fricative. Second, FFT power spectra were computed for each fricative using a 1024 point frame, which amounted to 46 milliseconds given the sampling rate of 22.05kHz. The window for each spectrum was centered around the middle of each fricative to reduce co-articulation effects. Spectra for the two repetitions of each fricative for each speaker were then averaged together, yielding a average spectrum for each fricative for an individual speaker. Third, the center of gravity (centroid or spectral mean) was also calculated for the frequency range 0-10kHz for each fricative (Forrest et al. 1988, Zsiga 1993, Jongman et al. 2000). The center of gravity for each fricative was calculated by multiplying each frequency value in the numerical spectrum by its corresponding intensity value and then dividing the sum of these products by the sum of all the frequency values of the spectrum. As a final measure, formant transitions for vowels adjacent to certain fricatives were computed using a 12 or 14 coefficient LPC display checked against a 512 point frame (23 milliseconds) FFT spectrum encompassing the portion of the vowel immediately adjacent to the fricative. The fricatives targeted for measurement of their vowel transitions were those which either previous research had indicated were profitably differentiated through their transitions or which were otherwise relatively poorly separated through the other measurements taken, i.e. /f/ and /θ/, retroflex fricatives, velar and uvular fricatives, and fricatives distinguished through rounding.

3. Results

Sections 3.1-3.7 present results for individual languages. The words containing the measured fricatives for each language appear in Appendix 1. Comparison of fricatives across the examined languages is deferred until section 4.

3.1. Chickasaw

Chickasaw possesses four fricatives: a labiodental /f/, an alveolar /s/, a postalveolar /ʃ/, and an alveolar lateral /ɬ/. Data from 12 Chickasaw speakers, 7 females and 5 males, were collected. The targeted fricatives all appeared in either disyllabic or trisyllabic words following an unstressed /i/ and a stressed /a/ (see Appendix 1).

3.1.1. Duration

Duration measures were not found to differentiate the four fricatives of Chickasaw reliably. A two factor ANOVA (fricative and gender) pooled over all speakers indicated no significant effect of the fricative on duration measurements: $F(3, 82) = 1.036$, $p=.3813$. Gender had a significant effect on duration with fricatives being longer for female speakers than for male speakers: $F(1, 82) = 7.115$, $p=.0092$. Averaged over all speakers, /s/ was slightly longer than other fricatives (see Table 2), but pairwise comparisons by Fisher's posthoc tests did not indicate any statistically reliable length difference between any pairs of fricatives.

Table 2. Average duration in milliseconds for 12 speakers of Chickasaw

	f	s	ʃ	ɬ
F1	104.0	140.6	109.7	52.2
F2	113.5	108.2	100.8	90.9
F3	145.1	161.6	129.4	171.9
F4	128.9	137.8	114.5	120.5
F5	131.9	140.5	127.7	148.4
F6	122.0	121.9	98.4	102.3
F7	105.2	125.5	138.9	126.6
M1	87.5	110.0	115.2	-----
M2	113.9	104.0	79.1	112.0
M3	114.3	126.0	122.3	112.9
M4	110.3	119.6	119.6	115.3
M5	95.4	95.3	90.4	123.1
Average	**115.5**	**123.6**	**112.8**	**116.0**

3.1.2. Gravity centers

A two factor ANOVA (fricative and gender) indicated a highly significant effect of fricative type on gravity center: $F(3, 82) = 11.660$, $p<.0001$. Gravity centers for the alveolar /s/ were highest. Pairwise Fisher's posthoc comparison revealed the difference between /s/ and all other fricatives to be significant at minimally the $p<.01$ level. Pairwise comparison between other fricatives did not reach statistical significance. Gender also exerted a significant effect on duration values with higher gravity centers observed for the female speakers: $F(1, 82) = 6.565$, $p=.0122$. Gravity centers for individual speakers appear in Table 3. There is considerable variation between speakers in the rank ordering of gravity centers for the three fricatives other than /s/.

Table 3. Average gravity centers in Hz for 12 speakers of Chickasaw

	f	s	ʃ	ɬ
F1	4193	5423	4675	4462
F2	5150	5674	4709	5119
F3	4235	5142	4827	4685
F4	4848	4943	4558	4469
F5	4925	5854	5158	5102
F6	4720	5653	4954	4658
F7	4228	4480	4333	4523
M1	4369	5407	4775	4938
M2	4600	4686	4268	4858
M3	4584	5003	4827	4866
M4	4352	4737	4252	4546
M5	4326	4519	4510	4358
Average	**4562**	**5163**	**4679**	**4715**

3.1.3. Spectra

Spectra averaged over the female Chickasaw speakers (calculated after inspection of individual speakers indicated little interspeaker variation in spectral characteristics) are plotted in Figure 1. Spectra for the male speakers appear in Figure 2. Due to interspeaker variation in the spectra for /s/

and /ɬ/ among the male speakers, spectra for these two fricatives are separated according to speaker.

The labiodental /f/ is characterized by the flattest spectrum for both male and female speakers gradually dropping in intensity as frequency increases. /f/ also displays the lowest overall intensity of the fricatives: at virtually all frequencies, intensity is lowest for /f/. The postalveolar /ʃ/ displays a relatively sharp spectral peak between 2.5kHz and 4kHz, approximately the same for both male and female speakers. For the female speakers, the spectrum for the lateral /ɬ/ is similar to that of /ʃ/. However, the spectral peak is not as sharp for /ɬ/ and there is a second peak for the lateral at approximately 7kHz. In addition, there is greater low frequency noise below 1kHz for the /ɬ/. For the female speakers, the greatest noise for the alveolar /s/ is centered at the highest frequencies of the four fricatives, between 5kHz and 8kHz, in keeping with the high gravity center for /s/.

The male speakers differ considerably among themselves in their spectra for /s/, presumably reflecting differences in the exact location and length of the constriction as well as tongue body shape. Large differences in acoustic spectra for /s/ (and other coronal obstruents) between speakers of the same language may be relatively common, as Dart's (1991, 1998) data from French and English suggest. Chickasaw speakers M1 and M4 have spectra similar to those of the female speakers for /s/ with greatest noise between approximately 5kHz and 8kHz. The high frequency noise band for speaker M4 is broader than for speaker M1, extending as low as 3kHz. Speaker M2 differs from the other speakers in producing an /s/ with a narrow peak centered at about 4kHz. Though similar in shape to the spectrum of /ʃ/ for speaker M2, the /s/ nevertheless differs in the frequency location of the spectral peak, which is higher for /s/ than for /ʃ/. The /s/ spectrum for speaker M3 has a two peaked distribution with one peak at about 3kHz and one at 6kHz. Finally, speaker M5 has a flat high intensity spectrum for /s/ with noise only tailing off at frequencies above 8kHz. Interspeaker variation among male speakers in their production of /ɬ/ is also considerable, though speakers M1, M3, and M4 have their most pronounced peaks centered around 2.5kHz. Speaker M3 displays a second sharp peak at around 4.5kHz. A less acute peak at about 4kHz characterizes the /ɬ/ spectrum for speaker M5. The spectrum for speaker M2 displays three relatively gentle peaks between 3kHz and 8kHz.

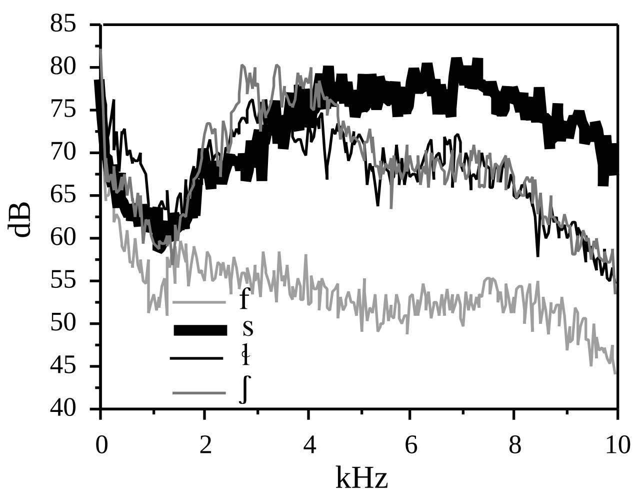


Figure 1. Averaged acoustic spectra (female speakers) for Chickasaw fricatives

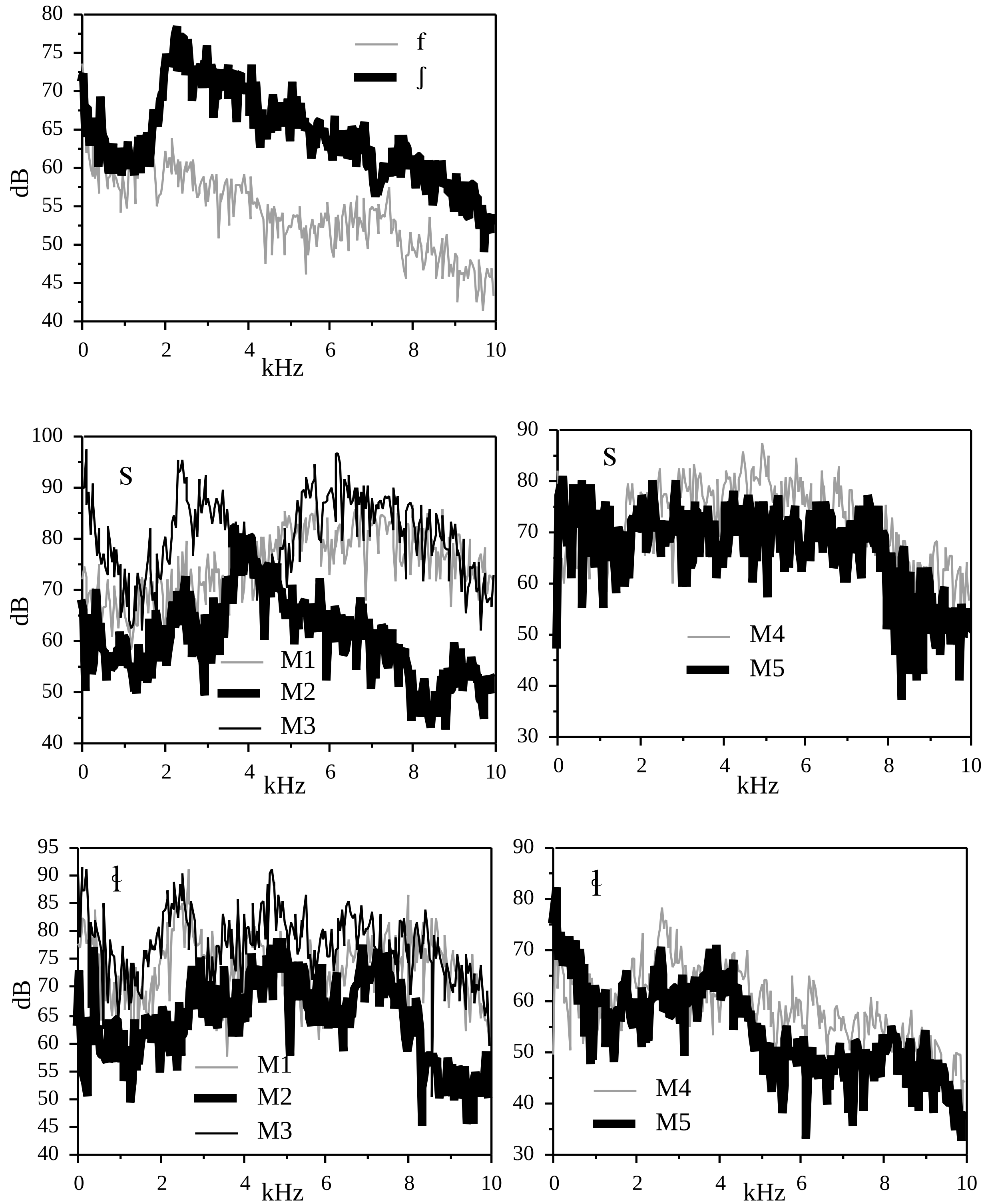


Figure 2. Averaged acoustic spectra (male speakers) for Chickasaw fricatives

3.2. Western Apache

Four fricatives were examined in Western Apache: an alveolar /s/, a postalveolar /ʃ/, an alveolar lateral /ɬ/, and a velar /x/. Data from 8 Western Apache speakers, 3 females and 5 males, were collected. The targeted fricatives all appeared following /i/ and before /a/ (see Appendix 1).

3.2.1. Duration

Durations for the four Western Apache fricatives averaged over all the speakers are shown in Table 4. Averaged over all speakers, duration did not reliably differentiate the fricatives, F (3, 51) = .281, p=.8390 according to a two factor ANOVA (fricative and gender). Nor did any of the pairwise comparisons of fricatives indicate significant duration differences. However, for the female speakers, /ɬ/ was significantly longer than the other three fricatives: /ɬ/ = 232ms compared to /s/ = 183ms, /ʃ/ = 188ms, /x/ = 168ms. This difference contributed to a significant effect of gender on durations, F (1, 51) = 11.246, p=.0015, as well as an interaction between fricative and gender: F (3, 51) = 3.988, p=.0126.

Table 4. Average duration in milliseconds for 8 speakers of Western Apache fricatives

	s	ʃ	ɬ	x
F1	173.1	185.9	-----	219.1
F2	182.0	186.1	229.3	134.8
F3	193.1	193.2	234.3	150.3
M1	121.9	141.0	81.7	76.2
M2	122.1	125.5	91.0	159.1
M3	204.7	178.3	-----	237.1
M4	182.7	200.9	127.3	195.2
M5	174.0	196.4	204.5	159.6
Average	**172.3**	**175.9**	**161.3**	**166.4**

3.2.2. Gravity centers

Fricatives were well differentiated by the gravity center measurement: in a two factor ANOVA (fricative and gender), F (3, 54) = 97.452, p<.0001. All pairwise comparisons of fricatives grouped over all speakers were also significant at the p<.01 level according to Fisher's posthoc tests. Gravity centers were highest for /s/ and were progressively lower for /ʃ/, /ɬ/ and /x/ in turn, as shown in the values shown in Table 5. All speakers displayed the same rank ordering of fricatives in gravity center values, except for speakers M2 and M5 for whom gravity centers were lower for /ʃ/ than for /ɬ/. Gender did not exert an effect on gravity center values: F (1, 54) = 2.732, p=.1042, though there was a significant interaction between fricative and gender: F (3, 54) = 9.110, p<.0001. This interaction is largely attributed to the fact that the center of gravity is consistently higher for /ʃ/ than for /ɬ/ for the female speakers but not for certain male speakers.

Table 5. Average gravity center frequencies in Hz for 8 speakers of Western Apache

	s	ʃ	ɬ	x
F1	5831	4804	4634	4286
F2	5810	5189	4538	4162
F3	5482	5128	4593	4068
M1	5176	5037	4662	4374
M2	5378	4411	4582	4294
M3	5512	4924	----	4456
M4	4851	4620	4539	4555
M5	5363	4637	4809	4582
Average	**5461**	**4859**	**4623**	**4347**

3.2.3. Spectra

Overall spectral shape also served to differentiate the four Western Apache fricatives clearly from each other, as evidenced in the spectra for the female speakers in figure 3 and the male speakers in figure 4. Spectra for /ɬ/, /ʃ/, and /x/ represent averages of all speakers of the same gender, while those for /s/ are separated by speaker due to interspeaker variation. Areas of greatest noise for /x/ occurred below 2kHz with a second less intense spectral peak occurring at approximately 4kHz, and a third weaker peak occurring at approximately 7kHz. For the lateral fricative, noise was concentrated at slightly lower frequencies: approximately 2-2.5kHz. The lateral also displayed relatively weak high frequency peaks, at 5kHz and 7kHz. Spectral peaks were slightly higher in frequency for /ʃ/, centered around 4kHz for females and 3.5kHz for males. The alveolar /s/ displays the greatest interspeaker variation in spectral characteristics, though for all speakers, the strongest concentrations of noise fall at higher frequencies for /s/ than for the other fricatives. Thus, the differences between fricatives in the location of spectral peaks in Figures 3 and 4 correspond to the differences in gravity centers discussed in section 3.2.2. Speakers F1, F2, M2, and M3 show similar spectra for /s/ with noise peaking at frequencies between 6kHz and 9kHz. For speaker M2, there is still considerable noise at low frequencies which creates a more gentle slope up to the principal concentrations of noise at higher frequencies. Speakers M1, M4, and M5 differ from the other speakers in having a relatively low frequency peak for /s/, falling at about 5kHz for speakers M1 and M4 and at about 6kHz for speaker M5. The peak for speaker M4 is particularly acute relative to the other speakers.

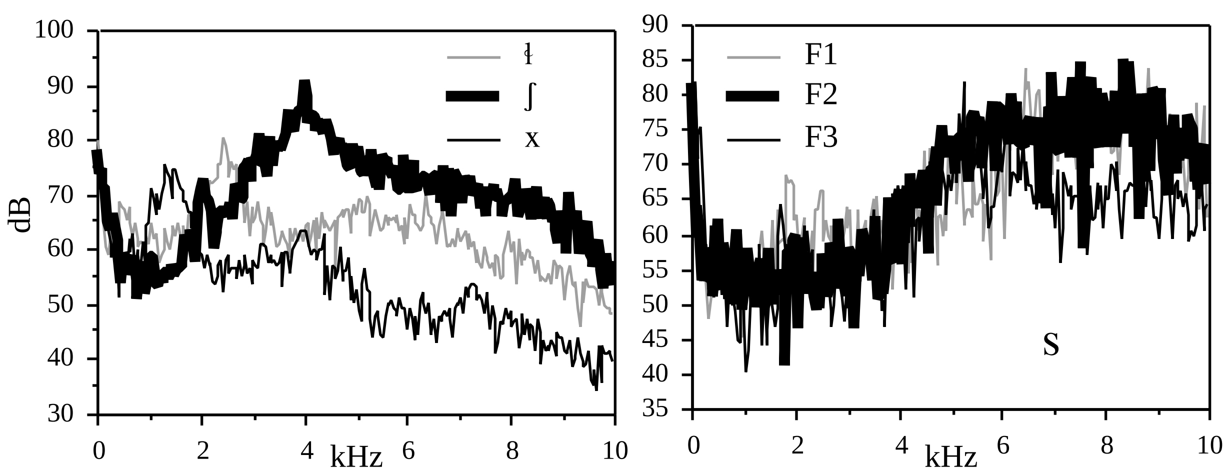


Figure 3. Averaged acoustic spectra (female speakers) for Western Apache fricatives

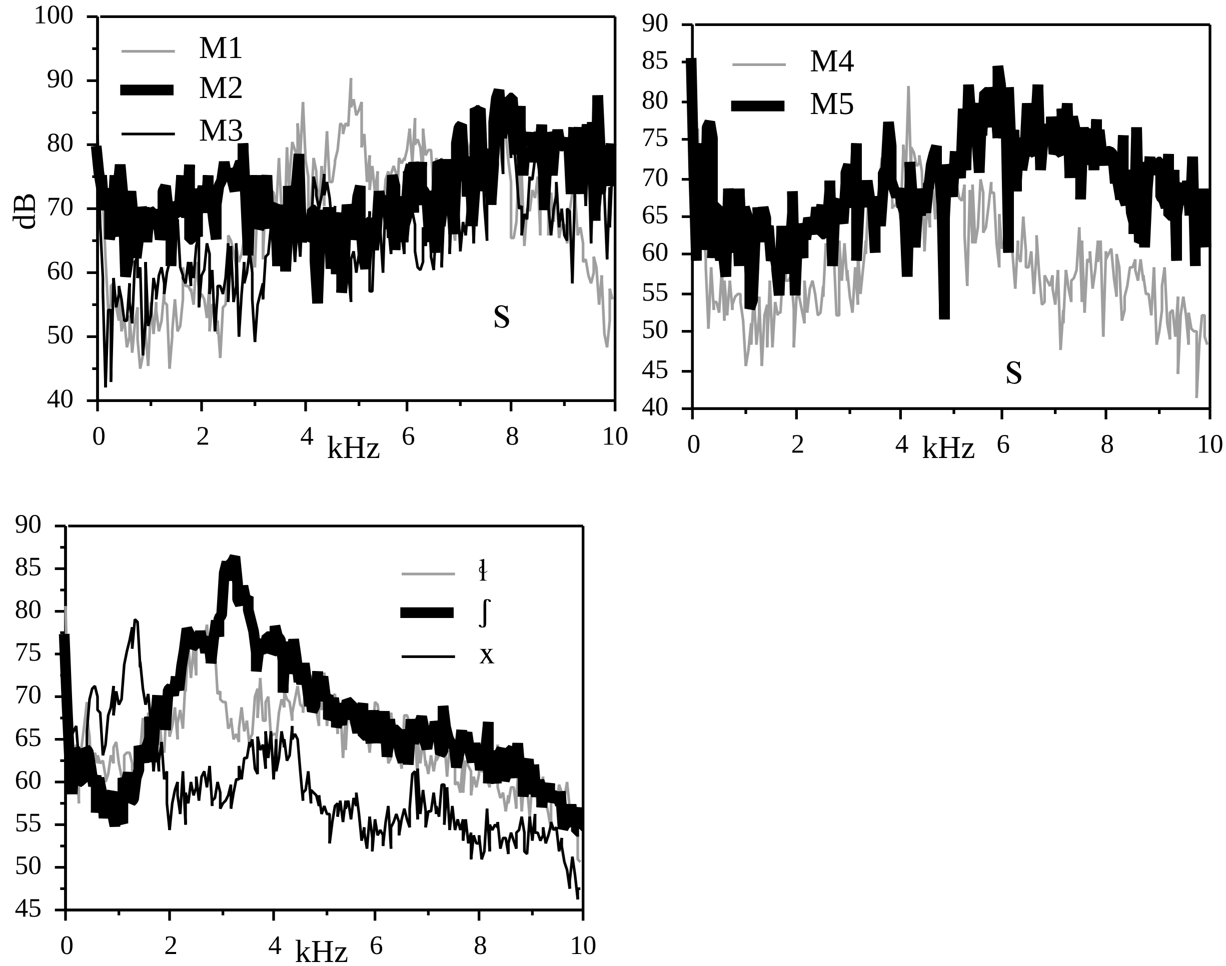


Figure 4. Averaged acoustic spectra (male speakers) for Western Apache fricatives

3.3. Gaelic

Six fricatives were examined in Gaelic: a labiodental /f/, a palatalized labiodental /f^j/, an alveolar /s/, a postalveolar /ʃ/, a palatal /ç/ and a velar /x/. Data from 9 Gaelic speakers, 3 females and 6 males, were collected. The targeted fricatives all appeared word-initially preceding /a/ (see Appendix 1).

3.3.1. Duration

A two factor ANOVA (fricative and gender) pooling together results over all speakers indicated a significant effect of fricative place (but not gender) on duration: $F(5, 92) = 6.484$, $p<.0001$. Pairwise comparison of fricatives revealed that this overall effect was attributed to the greater duration of /s/ relative to other fricatives and the shorter duration of /f/ relative to other fricatives, although not all speakers display this pattern, as is apparent in Table 6. Pairwise posthoc comparisons of /s/ and /f/ with other fricatives indicated significant differences between these two fricatives and other fricatives, including each other.

Table 6. Average duration in milliseconds for 8 speakers of Gaelic

	f	f^j	s	ʃ	ç	x
F1	81.9	107.0	138.2	116.4	85.2	123.6
F2	52.2	-----	121.1	133.9	118.4	101.7
F3	45.7	130.9	130.2	91.7	130.4	106.0
M1	54.9	60.0	101.5	100.3	99.4	83.5
M2	107.0	137.0	126.0	104.1	95.2	93.8
M3	81.3	105.0	123.5	125.9	108.5	109.0
M4	114.3	120.2	146.4	128.2	105.2	162.0
M5	92.6	134.4	155.9	106.9	107.8	107.7
M6	56.7	66.5	132.2	88.7	115.4	84.4
Average	**74.0**	**107.6**	**130.4**	**110.7**	**108.6**	**107.9**

3.3.2. Gravity centers

Gravity center measures also differed significantly as a function of differences in place of articulation (but not gender): over all speakers, F (5, 94) = 5.591, p<.0001. Gravity centers for /s/ were significantly higher than those for the other fricatives: p<.01 according to Fisher's posthoc tests. Gravity centers for /x/ were reliably lower than those for all other fricatives except for /f/ at the p<.05 level. Values for individual speakers appear in Table 7. Gravity centers were highest for /s/ for all speakers except speaker F1 and F2. The tendency for gravity center values for /x/ to be lower than for other fricatives was apparent for all speakers except for M3, M4 and M5.

Table 7. Average gravity center frequencies in Hz for 8 speakers of Gaelic

	f	fj	s	ʃ	ç	x
F1	4926	4705	4850	4457	4792	4384
F2	4056	4368	4209	4054	4185	3976
F3	4946	4911	5567	4718	4531	4194
M1	4275	4228	4591	4280	4267	4160
M2	4540	4684	5020	4638	4552	4049
M3	4273	4123	4416	3903	4302	4008
M4	4392	4708	5553	4835	4372	4617
M5	4444	4445	4600	4152	4301	4145
M6	4076	4305	5151	4530	4444	4343
Average	**4415**	**4497**	**4884**	**4396**	**4416**	**4209**

3.3.3. Spectra

Averaged spectra for the female Gaelic speakers appear in Figure 5, while those for the male speakers are shown in Figure 6. Due to individual differences, spectra for /f/ are separated for the female speakers, while spectra for /s/ are separated for both the female and male speakers.

Spectra for /f/ show a generally flat profile with a gradual fall off in noise as frequencies increase. Speaker F2 is somewhat anomalous in displaying an increase in noise going from 2 to 3 Hz before noise levels off at approximately 9kHz at which point there is a steep decline in noise. The palatalized labiodental is differentiated from its non-palatalized counterpart through its steep rise in intensity culminating in a peak at about 2.5kHz, slightly higher in frequency for the female speakers. The palato-alveolar /ʃ/ is similar in spectral shape and location of the spectral peak to the palatalized labiodental. However, its peak noise band between 2-4kHz is slightly broader and more intense than that of /f^j/. The palatal /ç/ and the velar /x/ likewise are characterized by noise peaks in the lower half of the spectrum followed by a gradual decline in noise at higher frequencies. Peaks for /ç/ hover around 3-4kHz, higher than for either /f^j/ or /ʃ/. The densest noise concentrations for /x/ fall below 2kHz, lower than for any of the other non-diffuse spectra, i.e. fricatives other than /f/. The alveolar /s/ displays substantial interspeaker variation in its spectral characteristics, though, in general, the bulk of its noise occurs in the upper half of the spectrum, unlike the other fricatives. Thus, speakers F1, F3, M4, M5, and M6 have the greatest noise in /s/ above 5kHz. The other four speakers, F2, M1, M2, and M3, display a peak at lower frequencies, between 3kHz and 5kHz depending on the speaker. It may also be noted that the spectrum for /s/ for speakers M2 and F2 also have a fairly diffuse pattern relative to the /s/ produced by other speakers, perhaps suggesting a more laminal articulation, under the assumption that /s/ is alveolar (and not dental) for these speakers (see Dart 1991, 1998, who finds that apical alveolars and laminal dentals have sharper peaks than laminal alveolars and apical dentals in French and English). For those speakers whose /s/ is characterized by relatively low frequency peaks, the spectral shape of /s/ rather closely resembles that of /ç/. Nevertheless, the two fricatives are differentiated through the overall greater noise of /s/, particularly at higher frequencies where noise for /s/ tends to plateau rather than show the steady decline characteristic of /ç/.

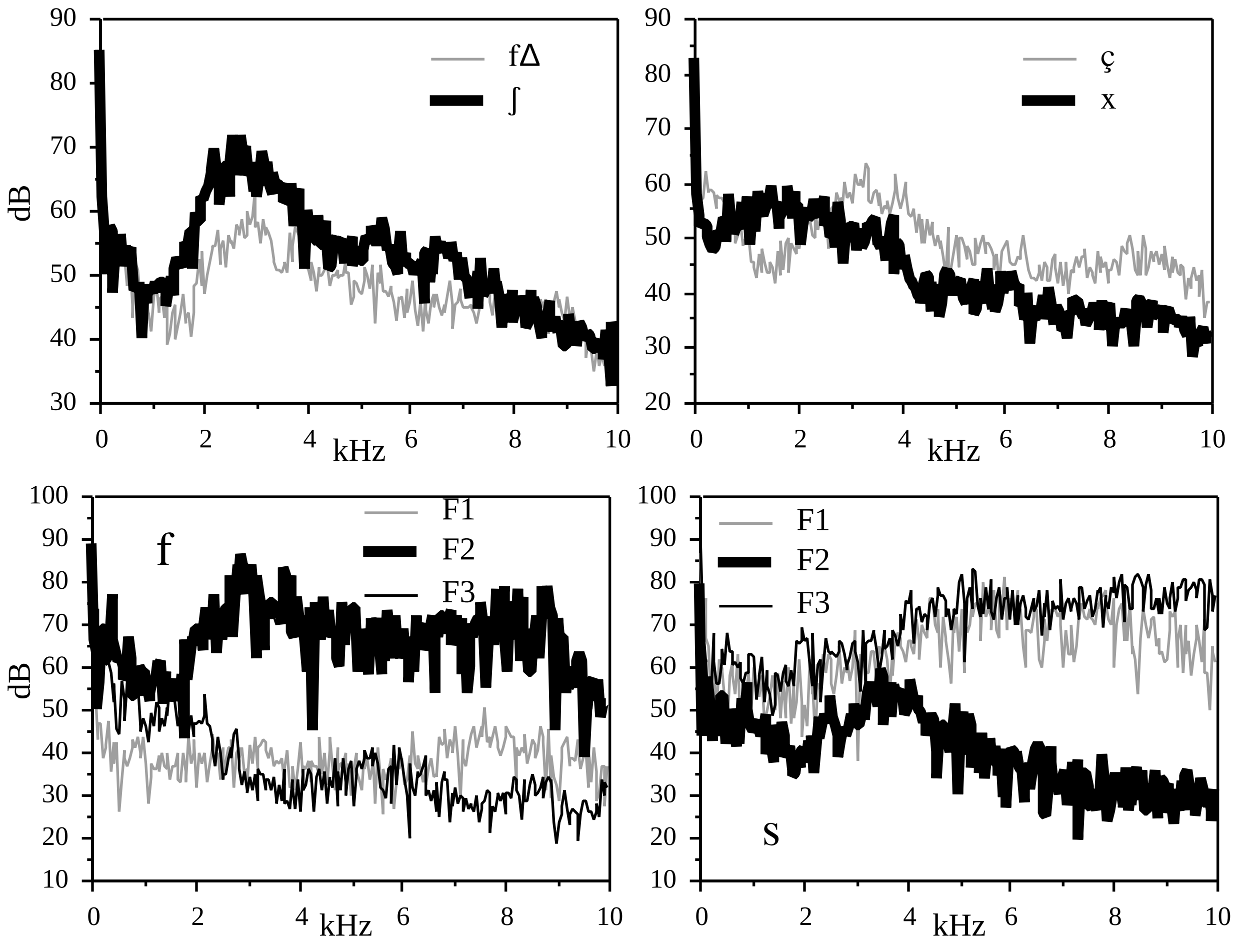


Figure 5. Averaged acoustic spectra (female speakers) for Gaelic fricatives

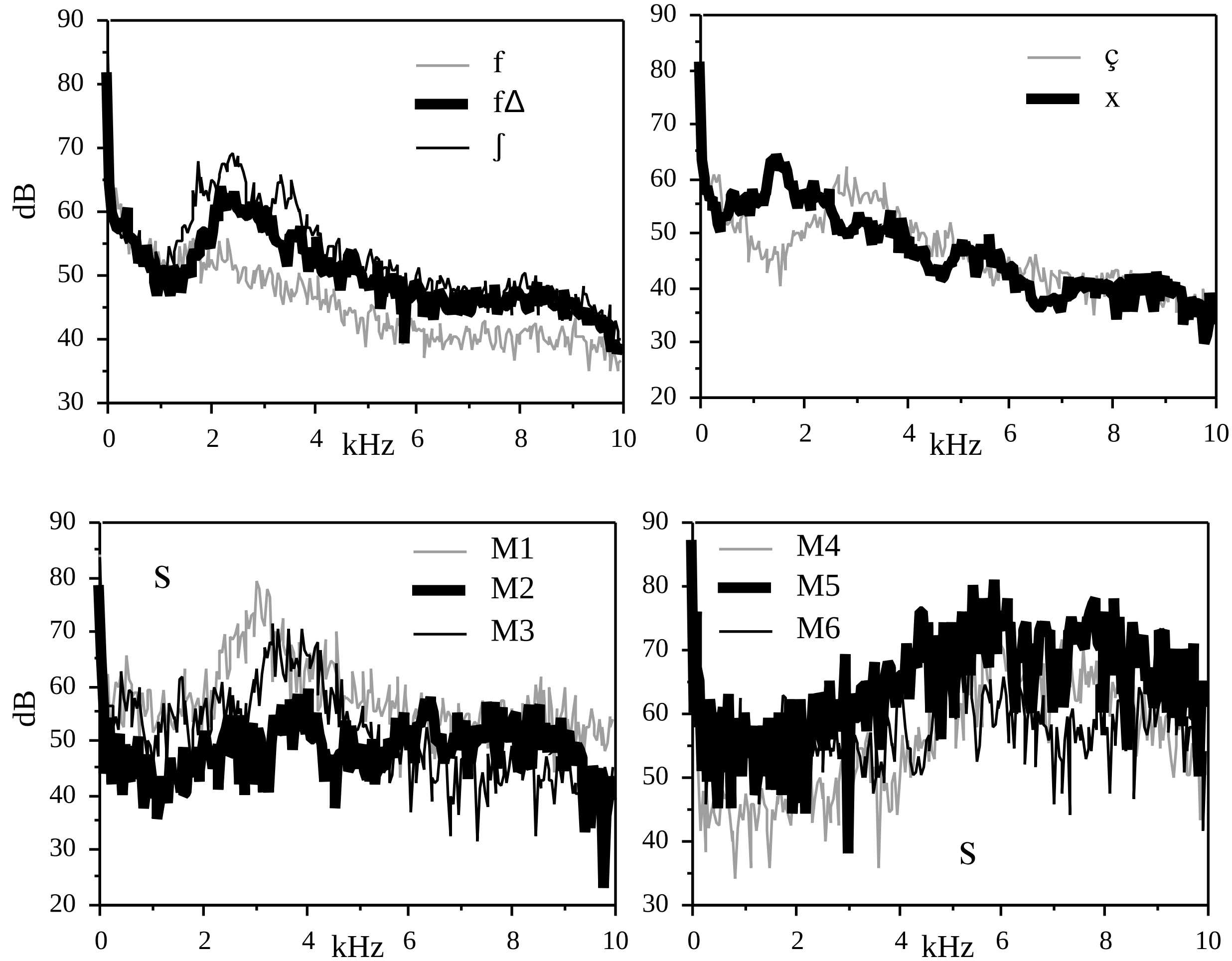


Figure 6. Averaged acoustic spectra (male speakers) for Gaelic fricatives

3.4. Western Aleut

Five fricatives were examined in Western Aleut: an alveolar /s/, an alveolar lateral /ɬ/, a palatal /ç/, and a velar /x/, and a uvular /χ/. Data from 6 Western Aleut speakers, 4 females and 2 males, were collected. All fricatives appeared adjacent to the vowel /a/. Distributional restrictions necessitated recording certain of the fricatives in word-initial position, the palatal and lateral, and certain ones in final position, the alveolar, the velar, and uvular (see Appendix 1).

3.4.1. Duration

Duration differed significantly as a function of fricative (but not gender) according to a two factor ANOVA (fricative and gender) $F(4, 46) = 3.807$, $p=.0094$. As is apparent in Table 8, /s/ was the longest fricative (though not for speaker M1), followed by /x/, and then the other three fricatives, /ç/, /ɬ/, and /χ/, all of which had roughly equivalent durations averaged over all speakers. Fisher's posthoc tests indicated that /s/ was significantly longer at the $p<.01$ level than all fricatives except for /x/. /x/ in turn was longer than /ç/ and /ɬ/ at the $p<.05$ level, though it should be noted that the relatively short duration of /ç/ and /ɬ/ is plausibly attributed to their being in word-initial rather than word-final position. Comparison of word-initial and word-final /s/ in the word /sas/ 'birds' indicates a significant lengthening effect in final position: word-initial /s/ averaged 181ms and word-final /s/ averaged 362ms, a significant difference according to an unpaired t-test, t (1,18) = 6.435, p<.0001). Separate ANOVAs for initial and final position indicate no significant effect of fricative place on duration, although final /s/ was significantly longer than final /χ/ (its only position in the data) according to a posthoc test, p=.0135.

Table 8. Average duration in milliseconds (all speakers) for Western Aleut fricatives

	s	ç	ɬ	x	χ
F1	-----	200.7	279.3	300.2	271.4
F2	499.0	181.5	194.8	332.6	235.7
F3	322.1	239.5	166.5	------	223.1
F4	307.4	222.1	290.1	233.9	219.7
M1	354.1	192.2	169.4	490.6	355.5
M2	326.6	307.2	256.0	196.8	153.6
Average	**361.8**	**223.8**	**226.0**	**310.8**	**243.1**

3.4.2. Gravity centers

There was an overall effect of fricative type (but not gender) on gravity center frequencies according to a two factor ANOVA (fricative and gender) pooling results over all speakers: F(4, 45) = 42.728, p<.0001. Gravity center values for /s/ were higher than those for all other fricatives, as shown for individual speakers in Table 9. Pairwise posthoc comparison of /s/ with other fricatives indicated significant differences at the p<.0001 level in all cases. The palatal fricative /ç/ has significantly higher (at the p<.05 level according to posthoc tests) gravity center values than the three fricatives other than /s/.

Table 9. Average gravity center frequencies in Hz for 6 speakers of Western Aleut

	s	ç	ɬ	x	χ
F1	5077	4804	4223	4374	4144
F2	5361	4537	4259	4355	4289
F3	5127	4393	-----	4183	4316
F4	5165	4757	4642	4418	4380
M1	5244	4830	4342	4317	4541
M2	5340	4789	4568	4444	4476
Average	**5219**	**4648**	**4430**	**4364**	**4358**

3.4.3. Spectra

The strongest noise peaks for both the velar and the uvular fricatives occur at frequencies below 2kHz, slightly lower for the uvular than for the velar. Additional peaks for both fricatives occur at higher frequencies. Peaks for the uvular occur at approximately 4kHz, 6kHz, and 8kHz for the female speakers (see Figure 7). These spectral peaks fall at slightly lower frequencies for the male speakers (Figure 8). Peaks for the velar are more apparent for the male speakers, for whom there are pronounced peaks at approximately 4kHz and 7.5kHz. The female speakers tend to have flatter spectra on average with the most pronounced peak above 2kHz falling at 4kHz. The lateral displays a relatively flat spectrum with an overall declination in noise associated with increases in frequency. The most pronounced peaks for the lateral fall between 2-2.5kHz and 4-4.5kHz. The palatal /ç/ has a relatively acute peak at about 4kHz for the female speakers and the male speaker M1. The second male speaker also has an acute peak for /ç/, falling at a slightly lower frequency, approximately 3kHz, still higher in frequency than the strongest peak for either of the posterior fricatives or the lateral. As in Chickasaw, Western Apache, and Gaelic, /s/ shows marked differences between speakers in its spectral characteristics, though the general trend is for the bulk of the noise in /s/ to fall in the upper half of the spectrum. The female speakers tend to have peaks for /s/ at approximately 5-6kHz, slightly lower for speaker F3. Both male speakers produce /s/ characterized by a relatively diffuse spectrum above 3kHz. Both speakers display a broad noise band above 6kHz in addition to a more acute peak at around 4kHz, which is more sharply defined in the case of speaker M2.

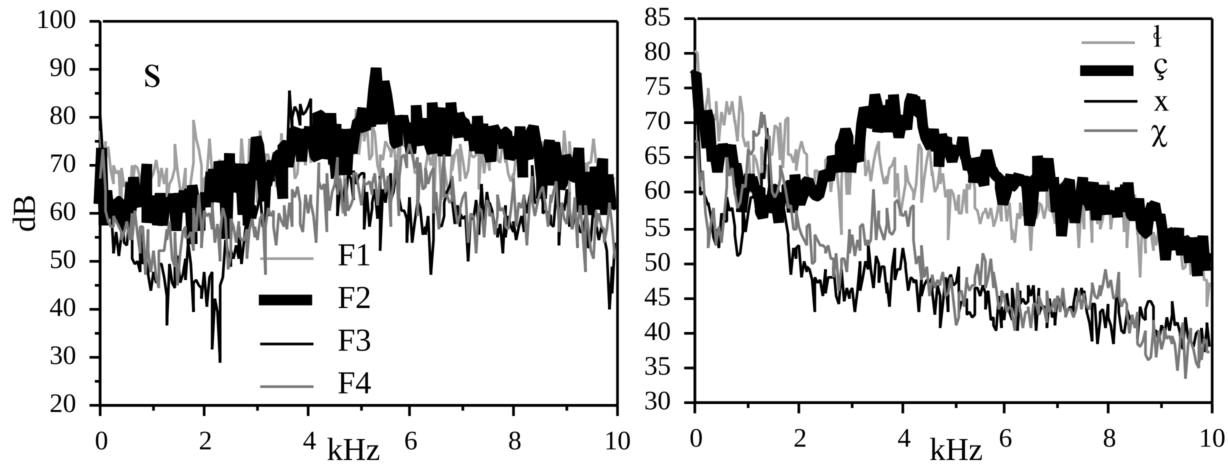
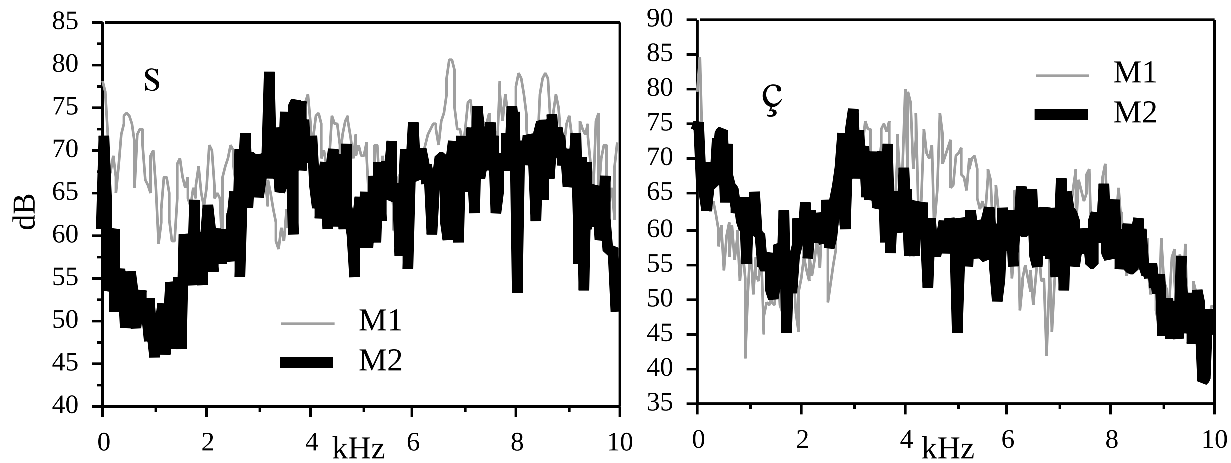


Figure 7. Averaged acoustic spectra (female speakers) for Western Aleut fricatives



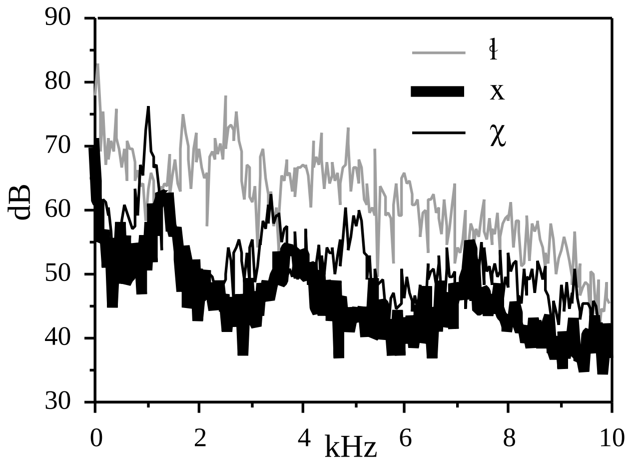


Figure 8. Averaged acoustic spectra (male speakers) for Western Aleut fricatives

3.4.4. Formant transitions

Formant values for the first and second formant were calculated over the final 23 milliseconds (512 points) of the vowel /a/ immediately preceding the velar and uvular fricatives in order to determine whether vowel to fricative transitions served to facilitate the distinction between velar and uvular fricatives in Western Aleut. Formant values were also calculated over an equivalently long window centered around the middle of the vowel, to determine whether effects of the fricative on vowel quality persisted beyond the portion of the vowel immediately adjacent to the fricative. The consonant preceding the measured vowel had similar places of articulation, /z/ preceding the vowel before the velar fricative and /ð/ before the pre-uvular vowel, meaning that potential differences in the vowel formants are likely attributed to the difference between the velar and uvular fricatives following the vowel.

The results averaged over the six speakers in Figure 9 indicate that the uvular raises the first formant and lowers the second formant relative to the velar, suggesting a lowering and backing effect on the vowel adjacent to the uvular. This effect is most pronounced during the vowel to consonant transition (filled symbols in Figure 9) but persists to a lesser extent, more prominently in the case of F2 than F1, through the middle of the vowel (open symbols). T-tests indicated that neither the F1 nor F2 difference at the mid point of the vowel was statistically significant. The F1 difference also did not reach significance during the portion of the vowel adjacent to the fricative. However, the F2 difference during the transition was significant at the $p<.05$ level according to a t-test: $t(1, 21) = 2.167$, $p=.0419$.

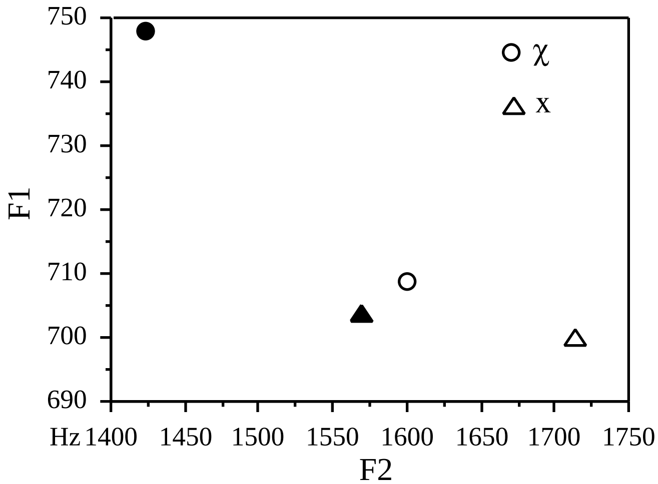


Figure 9. Averaged F1 and F2 transitions (in Hz) in vowels adjacent to velar and uvular fricatives (all speakers) in Western Aleut: filled symbols are transitions, unfilled symbols are from the middle of the vowel.

3.5. Montana Salish

Six fricatives were examined in Montana Salish: an alveolar /s/, an alveolar lateral /ɬ/, a postalveolar /ʃ/, a uvular /χ/, a labialised velar /xʷ/, and a labialised uvular /χʷ/. Data from 5 Montana Salish speakers, 3 females and 2 males, were collected. All fricatives appeared in word-initial position adjacent to the vowel /a/ (see Appendix 1).

3.5.1. Duration

Overall the effect of fricative on duration values did not reach significance: F (5, 17) = 2.252, p=.0960, according to a two factor ANOVA (fricative and gender) pooled over all speakers. Gender also did not affect duration: F (1, 17) = 1.229, p=.2830. Pairwise comparison of fricatives in posthoc tests indicated that the labialised uvular was significantly shorter than the fricatives other than the labialised velar /xʷ/ and the lateral /ɬ/.

Table 10. Average duration in milliseconds for 5 speakers of Montana Salish fricatives

	s	ʃ	ɬ	xʷ	χ	χʷ
F1	209.6	178.0	173.5	-----	144.5	70.1
F2	149.0	195.5	166.2	175.7	202.2	144.7
F3	160.6	158.3	163.8	73.9	164.3	115.3
M1	160.6	187.8	185.7	185.9	209.5	162.9
M2	179.3	174.7	114.9	122.3	193.2	133.4
Average	**171.8**	**178.9**	**160.8**	**139.5**	**182.7**	**125.3**

3.5.2. Gravity centers

Gravity center frequencies differed significantly as a function of the fricative (but not gender) according to a two factor ANOVA pooled over all speakers: F (5, 33) = 6.013, p=.0005. Fisher's posthoc tests revealed three sources for this overall result. First, the alveolar /s/ had significantly higher (at minimally the p<.05 level) average gravity center values than any of the other fricatives except for the lateral /ɬ/, though speaker M2 is exceptional in having lower center of gravity values for /s/ than for /ʃ/, /ɬ/ and /χ/. Second, the lateral fricative had higher gravity centers (at minimally p<.01) on average than all fricatives other than /s/, with speaker M1 breaking this tendency, as the center of gravity was higher for his /xʷ/ than for his /ɬ/. Finally, the labialised velar had significantly lower gravity centers than /ʃ/ at the p<.05 level, though M1 does not follow this pattern. Average gravity center values for individual speakers appear in Table 11.

Table 11. Average gravity center frequencies in Hz for 5 speakers of Montana Salish

	s	ʃ	ɬ	xʷ	χ	χʷ
F1	4744	4106	4405	3975	4100	4158
F2	4668	4047	4388	3677	3899	3970
F3	4548	4170	4194	3920	3915	3886
M1	4676	4017	4123	4360	4109	4089
M2	4366	4413	4576	3889	4407	4136
Average	**4601**	**4134**	**4334**	**3924**	**4043**	**4032**

3.5.3. Spectra

As in the other examined languages, the alveolar /s/ tends to have the bulk of its noise at high frequencies relative to other fricatives. There was considerably less interspeaker variation in spectra for /s/ than in other languages as indicated by the pooling of results across speakers in Figure 10, females on the left and males on the right. Palato-alveolar /ʃ/ and lateral /ɬ/ have lower frequency spectral peaks, at about 3kHz, than /s/. /ʃ/ and /ɬ/ are differentiated primarily through two features. First, /ɬ/ has greater overall noise throughout the entire spectrum, particularly at higher frequencies, a difference which contributes to the higher gravity center values for /ɬ/ relative to /ʃ/. Second, the most prominent spectral peak is broader for /ɬ/ than for /ʃ/ even though they both are centered at similar frequencies.

The back fricatives are distinguished from the more anterior fricatives through their low frequency spectral peaks below 2kHz. Among the back fricatives, rounding is associated with especially low spectral peaks, as both the rounded velar and uvular fricatives situate their lowest frequency peak below that of the unrounded uvular. As in Western Aleut, all of the back fricatives display multiple spectral peaks, with the lowest frequency peak being strongest. The secondary peaks are least pronounced for the labialised velar and most pronounced for the labialised uvular. The relatively flat shape of the mid frequency spectrum for the labialised velar relative to the labialised uvular is perhaps the most evident feature differentiating /xʷ/ and /χʷ/ for the female speakers. It is also noteworthy that the labialised fricatives have less overall noise throughout the spectrum than the non-labialized uvular.

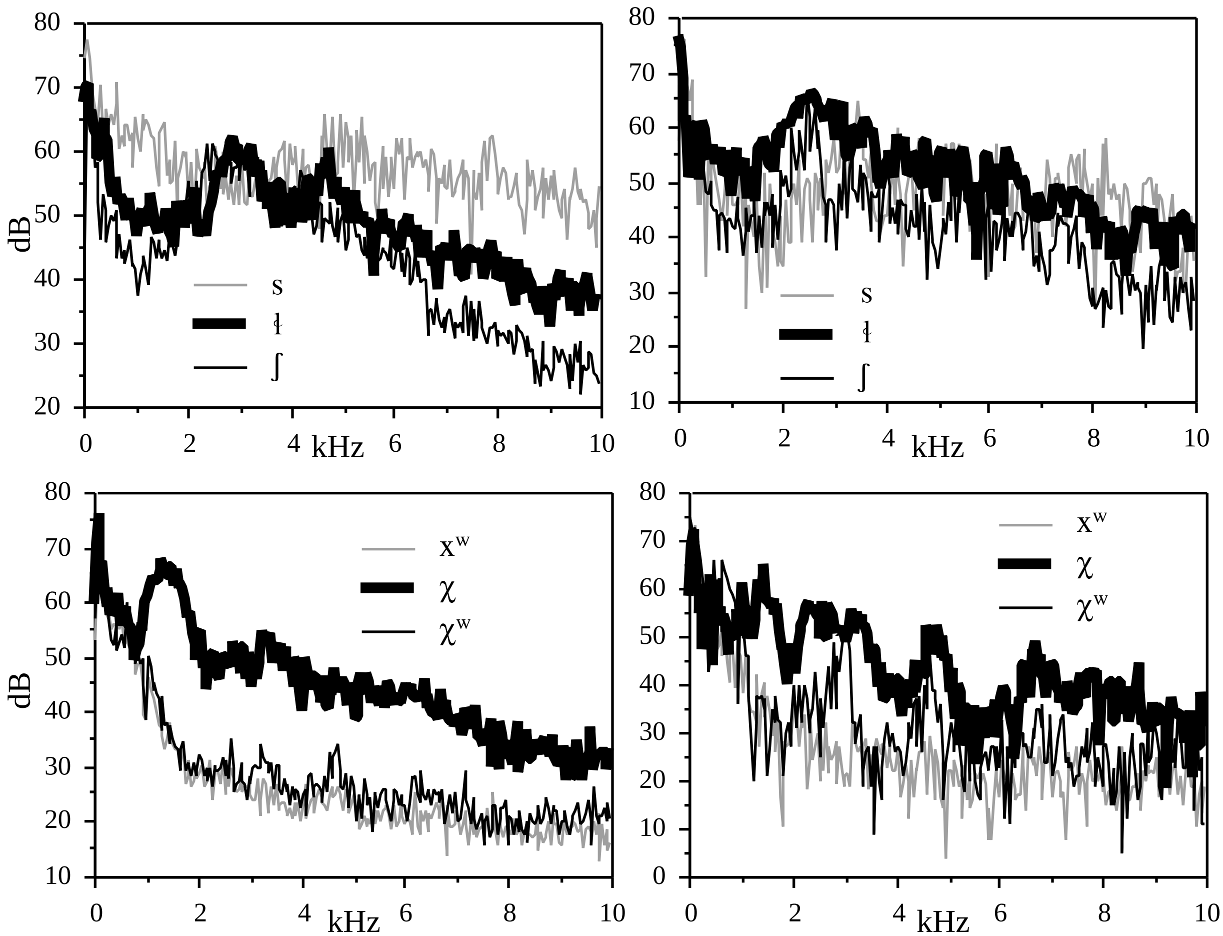


Figure 10. Averaged acoustic spectra (females on left, males on right) for Montana Salish fricatives

3.5.4. Formant transitions

Formant values for the first and second formant were calculated over the first 23 milliseconds (512 points) of the vowel /a/ immediately following the posterior fricatives /xʷ/, /χ/, and /χʷ/. Formant values were also calculated over an equivalently long window centered around the middle of the vowel. This second measurement was more important in Montana Salish than in Western Aleut, since the consonant following the measured vowel was not the same in all words. The vowel after the labialised velar was followed by /l/, the vowel after the labialised uvular was followed by /χʷ/ and the vowel following the non-labialized uvular was followed by a uvular ejective /q'/.

The results averaged over the five speakers in Figure 11 indicate that rounding triggers substantial lowering of second formant, and to a lesser extent the first formant, during the consonant-to-vowel transition. Average F1 values for both the rounded posterior fricatives hover around 550Hz, while the average for the unrounded uvular is approximately 700Hz. An ANOVA including fricative and gender as independent variables indicated a less than but almost significant effect of fricative on F1 transitions, $F(2, 9) = 3.563$, $p=.0689$, and a significant effect of gender on F1, $F(1, 9) = 8.630$, $p=.0165$. Formant values were higher for female speakers than for male speakers. Posthoc tests pinned to the ANOVA indicated a significant difference in F1 transition values between vowels preceding both of the rounded fricatives and vowels preceding the unrounded uvular: $p=.0274$ for /xʷ/ vs. /χ/ and $p=.0329$ for /χʷ/ vs. /χ/. Vowels preceding the two rounded fricatives did not differ significantly from each other in F1 values according to a posthoc test: $p=.9128$.

By the middle of the vowel, the average F1 value for the unrounded uvular is nearly equivalent to that of the rounded uvular. The low F1 value for the rounded velar persists into the middle of the value, though this could be attributed to a difference in place of articulation of the following consonant: alveolar after the vowel following /xʷ/, and uvular after the vowel following /χ/ and /χʷ/. An ANOVA did not reveal any significant difference between fricatives in their F1 values during the middle of the vowel, $F(2, 9) = .408$, $p=.6765$, although gender once again exerted a significant effect on formant values with those of the females being higher than those of the males, $F(1, 9) = 8.683$, $p=.0163$.

F2 values taken during the transitions were significantly lower for the rounded fricatives relative to the unrounded ones (see Ladefoged and Maddieson 1996 for similar effects in Pohnpeian). A two factor ANOVA (fricative and gender) indicated a significant effect of fricative on F2 transitions, $F(2, 9) = 10.245$, $p=.0048$, as well as an effect of gender (higher values for female speakers), $F(1,9) = 5.334$, $p=.0463$. Posthoc tests indicated a significant difference in F2 values between the unrounded uvular and both the rounded velar ($p=.0129$) and the rounded uvular ($p=.0014$) fricatives. Of the two rounded fricatives, F2 values are substantially lower for the rounded uvular, 937Hz vs. 1066Hz, though this difference does not reach significance in a posthoc test, $p=.1738$. This F2 difference increases in the middle of vowel ($F[2, 9] = 6.932$, $p=.0151$ in an ANOVA) with predictably higher values for female than for male speakers ($F[1, 9] = 6.410$, $p=.0321$). It is unclear to what extent the greater difference in the middle of the vowel is a function of the difference in the preceding or the following consonant. The vowel after the rounded uvular is followed by another rounded uvular which potentially is responsible for at least a portion of the F2 lowering during the middle of the vowel.

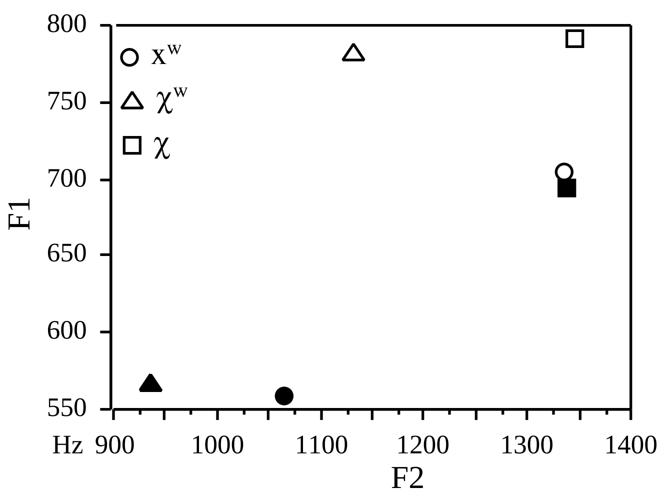


Figure 11. Averaged F1 and F2 transitions (in Hz) in vowels adjacent to velar and uvular fricatives (all speakers) in Montana Salish: filled symbols are transitions, unfilled symbols are from the middle of the vowel.

3.6. Hupa

Hupa posseses six fricatives: an alveolar /s/, a postalveolar /ʃ/, an alveolar lateral /ɬ/, a velar /x/, a slightly rounded velar /xʷ/, and a more rounded velar /x̹ʷ/. The three way contrast in degree of rounding among the velar fricatives is quite unusual. The unrounded and the more rounded velar are inherited sounds from proto-Athabaskan whereas the slightly rounded velar is the product of a sound change affecting proto-Athabaskan *ʃ (Hoijer 1960). Data from two (of the remaining eight or fewer speakers [Grimes 2001] of Hupa), one female and one male, were analyzed. The fricatives were recorded in word-final position following the vowel /a/ in the case of all fricatives for the male speaker and /ʃ/, /ɬ/, and /x/ for the female speaker and following /ɹ/ in the case of /s/, /xʷ/ and /x̹ʷ/ for the female speaker.

3.6.1. Duration

Duration values for the two Hupa speakers appear in Table 12. There are considerable differences between the two speakers in the relative length of fricatives. /s/ is the longest fricative for the female speaker but is similar in length to /ʃ/ for the male speaker.

Table 12. Average duration in milliseconds (all speakers) for 2 speakers of Hupa

	s	ʃ	ɬ	x	xʷ	x̹ʷ
F1	326.0	211.5	256.7	153.1	307.4	222.1
M1	226.7	230.3	181.8	186.4	188.9	161.6
Average	**276.4**	**217.7**	**219.2**	**169.8**	**248.1**	**201.9**

3.6.2. Gravity centers

As in the other languages, gravity centers for /s/ are highest on average, though this tendency is only evident for the male speaker (see Table 13). The three posterior fricatives have relatively low gravity center values compared to the fronter fricatives. The rounded fricatives have slightly lower gravity centers than their unrounded counterpart for the female speaker, but for the male speaker rounding only triggers lowering in the more rounded velar.

Table 13. Average gravity center frequencies in Hz for 2 speakers of Hupa

	s	ʃ	ɬ	x	xʷ	x̹ʷ
F1	4493	4384	4413	4153	3682	4084
M1	5227	4552	4523	4379	4389	4133
Average	**4797**	**4440**	**4468**	**4228**	**4035**	**4100**

3.6.3. Spectra

The spectrum for /s/ is associated with the highest frequency noise concentrations of the fricatives, as shown in Figure 12. This feature is particularly evident for the female speaker, whose /s/ is characterized by a relatively sharp peak at approximately 5kHz. The male speaker has a less acute peak for /s/, although noise is still greatest at 5kHz with a slight drop-off in noise at higher frequencies. For the male speaker, /ʃ/ has a very similar spectrum to /s/. /ʃ/ however is characterized by a greater decrease in noise at frequencies above 6kHz and the presence of an additional lower frequency peak at approximately 3kHz. This peak at 3kHz also characterizes the spectrum of /ʃ/ for the female speaker. The lateral /ɬ/ has a noise peak at about 3kHz and a second one at approximately 5kHz. The lateral /ɬ/ also has less overall noise throughout the spectrum than /ʃ/ for the male speaker.

The posterior fricatives are in general poorly differentiated from each other. They all share a low frequency spectral peak below 2kHz and additional lower intensity spectral peaks at higher frequencies, most notably between 5kHz and 6kHz. The two rounded fricatives are associated with a slightly lower frequency first spectral peak than the unrounded /x/ for the male speaker but not for the female speaker. Spectral differences between the two rounded velar fricatives are subtle at best for both the male and female speaker, though it may be noted that higher frequency peaks tend to be more acute for the more rounded velar. This difference in acuity of peaks is evident in the peak at 6kHz for the female speaker and in peaks at 5kHz and 7kHz for the male speaker.

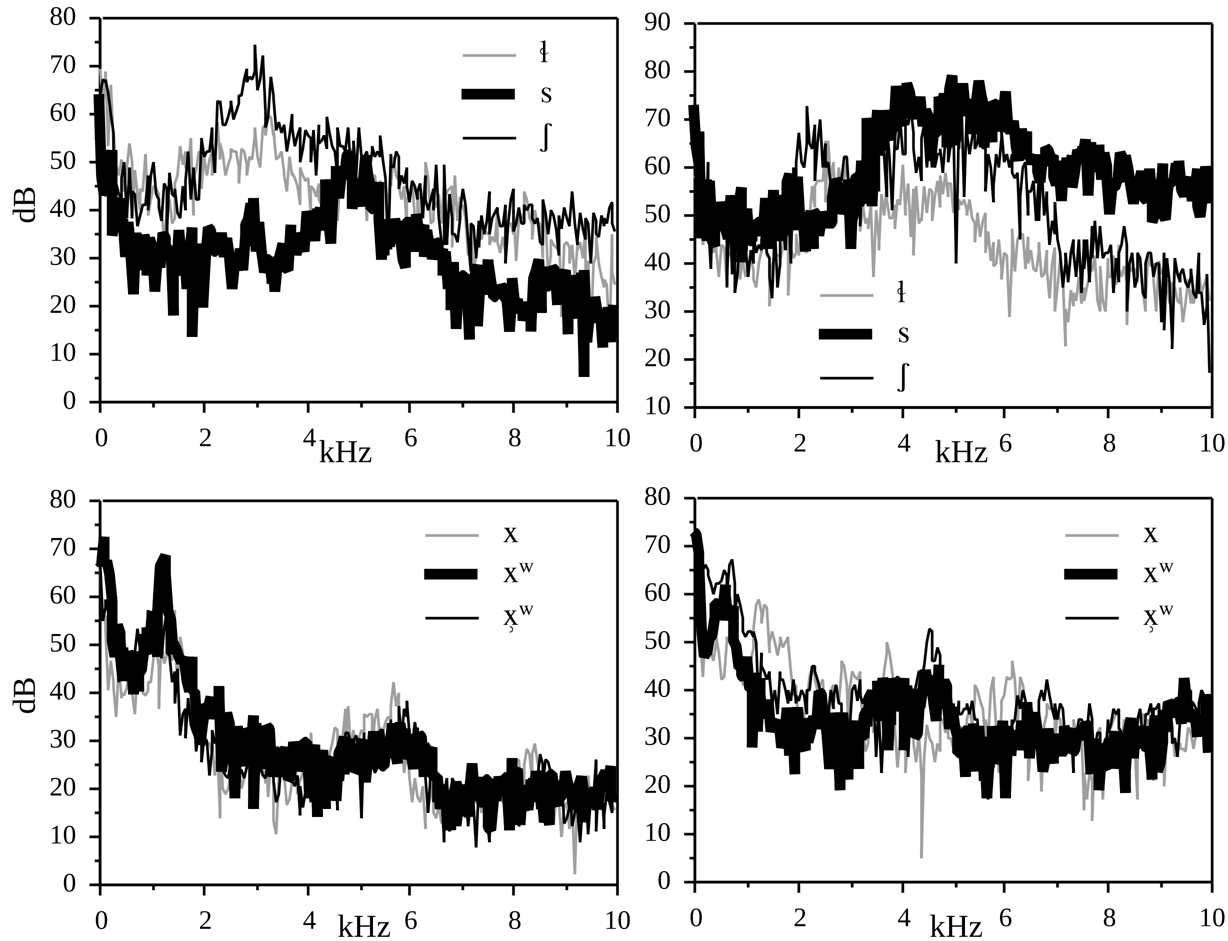


Figure 12. Averaged acoustic spectra (female on left, male on right) for Hupa fricatives

3.6.4. Formant transitions

Values for the first and second formant were calculated over the last 23 milliseconds (512 points) of the vowel immediately preceding the posterior fricatives. The vowel preceding the targeted fricatives was /a/ in the case of the male speaker, and [u] (phonemically /ɪ/) for the female speaker. Data from vowels preceding all three posterior fricatives, /x/, /xʷ/, and /x̹ʷ/ were collected from the male speaker, whereas data preceding the two rounded fricatives were examined for the female speaker. Formant values were also calculated over an equivalently long window centered around the middle of the vowel. Results appear in Figure 13, female speaker on the left and male speaker on the right.

Both the female and the male speaker display the same lowering of F2 in the portion of the vowel immediately preceding the more rounded velar /x̹ʷ/ relative to the vowel adjacent to the less rounded /xʷ/. This lowering effect vanishes by the middle of the vowel. In addition to the lowering of F2, there is a slight lowering of F1 associated with the additional rounding of /x̹ʷ/ for the male speaker, a difference which is localized to the vowel to consonant transition. For the male speaker, F1 and F2 values for the unrounded velar /x/ are higher than values for both of the rounded velars. The lowering effect of rounding on F1 for the male speaker but not the female speaker is likely attributed to a difference in the quality of the measured vowel rather than a gender difference. The vowel was a low vowel for the male speaker and a high vowel for the female speaker. Although rounding is associated with lowering of the second formant in all vowels (more so for non-low vowels), rounding asymmetrically triggers lowering of F1 in low, but not in high or mid, vowels due to the relatively large front cavity in low vowels which influences both F1 and

F2 (see Stevens 1998 for discussion). The lowering effect of rounding on F1 and F2 transitions in vowels preceding rounded fricatives was also observed in Montana Salish in which the measured vowels were also low (section 3.5.4).

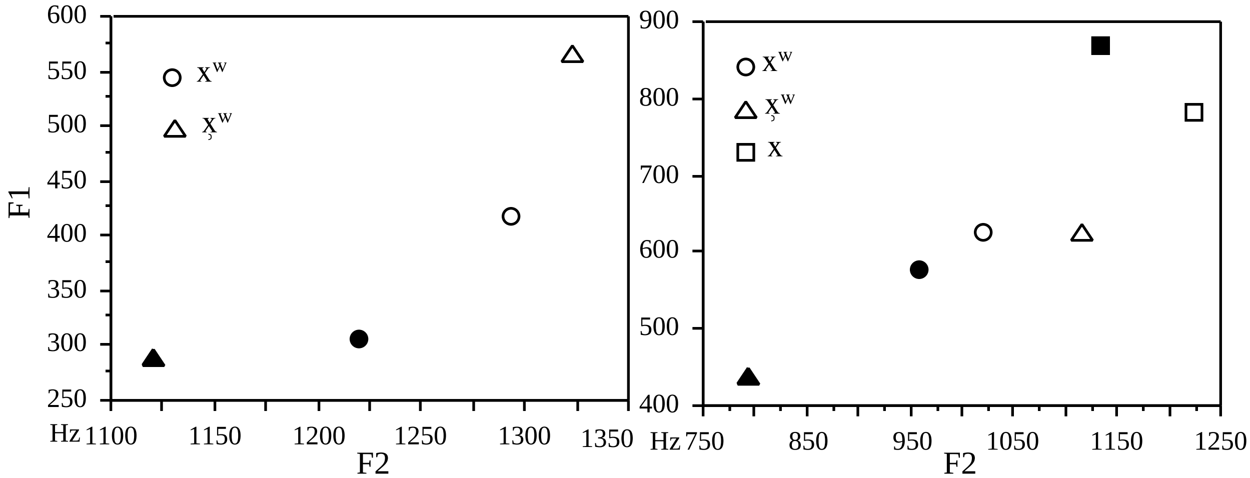


Figure 13. Averaged F1 and F2 transitions (in Hz) in vowels adjacent to velar fricatives (female speaker on left, male on right) in Hupa: filled symbols are transitions, unfilled symbols are from the middle of the vowel.

3.7. Toda

Toda has nine voiceless fricatives: a labiodental /f/, a dental non-sibilant /θ/, a laminal denti-alveolar sibilant /s̪/, an apical alveolar /s/, a laminal postalveolar /ʃ/, a sub-apical retroflex /ʂ/, an alveolar lateral /ɬ/, a retroflex lateral /ɬ̣/, and a velar /x/ (see Shalev et al. 1994, Ladefoged and Maddieson 1996 for articulatory data). The fricatives were recorded in word-final position after the vowel /ɔ/, except for the two lateral fricatives which were recorded word-finally after the vowel /ɑ/. Data were measured for a total of six speakers, three males and three females.

3.7.1. Duration

Duration values averaged over all speakers appear in Table 14. A two factor ANOVA (fricative and gender) indicated that duration values differed significantly between fricatives: $F(8, 36) = 4.209$, $p=.0012$. Gender did not affect duration values: $F(1, 36) = .213$, $p=.6471$. The primary source for the overall difference between fricatives was the short duration of /f/ relative to other fricative. The difference between /f/ and other fricatives except for /x/ was significant in pairwise Fisher's posthoc tests at the $p<.01$ level. /x/ was also significantly shorter than /ʃ/ and /ʂ/ at the $p<.05$ level according to a posthoc test. The postalveolar /ʃ/ was longer in general than all other fricatives; this difference did not reach significance in pairwise comparisons except those with /f/ and /x/.

There is an interesting point of divergence between male and female speakers. For the male speakers /f/ and /θ/ are of equivalent durations on average, but shorter than most other fricatives, whereas for the female speakers, /f/ is shorter than all other fricatives.

Table 14. Average duration in milliseconds for 6 speakers of Toda

	f	θ	s̪	s	ʃ	ʂ	ɬ	ɬ̣	x
F1	73.2	233.3	233.6	233.9	290.3	275.7	153.5	195.9	125.4
F2	71.4	148.5	168.5	179.6	158.3	190.3	183.4	201.8	102.6
F3	50.5	309.9	168.9	222.8	310.3	169.0	197.8	211.5	143.3
M1	186.9	179.5	243.1	205.4	278.1	277.6	231.7	205.9	240.0
M2	136.2	118.3	192.4	143.9	166.5	161.2	184.2	162.2	113.0
M3	149.1	167.2	204.1	204.1	234.2	210.6	186.4	195.1	176.8
Average	**111.2**	**192.8**	**201.8**	**198.3**	**239.6**	**214.1**	**189.5**	**195.4**	**150.2**

3.7.2. Gravity centers

Gravity center frequencies differed significantly as a function of fricative type (but not gender) according to an ANOVA: $F(8, 36) = 10.798$, $p<.0001$. The dental /s̪/ had the highest average gravity center values, as shown in Table 15. Pairwise posthoc comparisons indicated a significant difference at minimally $p<.05$ between /s̪/ and all other fricatives. Gravity centers were lowest for /θ/, /f/, /ɬ/ /ɬ̣/, and /x/ on average, none of which differed significantly from one another according to posthoc tests. Pairwise posthoc comparisons involving these fricatives and other fricatives all revealed significant differences at minimally $p<.05$ with two exceptions: /ɬ̣/ and /s/ did not reliably differ in gravity center values and /f/ did not differ from /s/ in gravity center values.

Table 15. Average gravity center frequencies in Hz for 6 speakers of Toda

	f	θ	s̪	s	ʃ	ʂ	ɬ	ɬ̣	x
F1	3906	4186	5042	4512	4747	4810	4002	3973	4364
F2	4215	4620	5093	4868	4676	4650	4221	3930	4481
F3	4156	3725	4877	4577	4491	4406	4214	4570	4277
M1	4445	4019	4580	4370	4877	4378	4348	4189	4109
M2	4372	3797	5289	4399	4855	4626	3960	4393	4370
M3	4513	4317	5284	4447	4579	4340	4240	4275	3784
Average	**4268**	**4111**	**5027**	**4529**	**4704**	**4535**	**4164**	**4222**	**4231**

3.7.3. Spectra

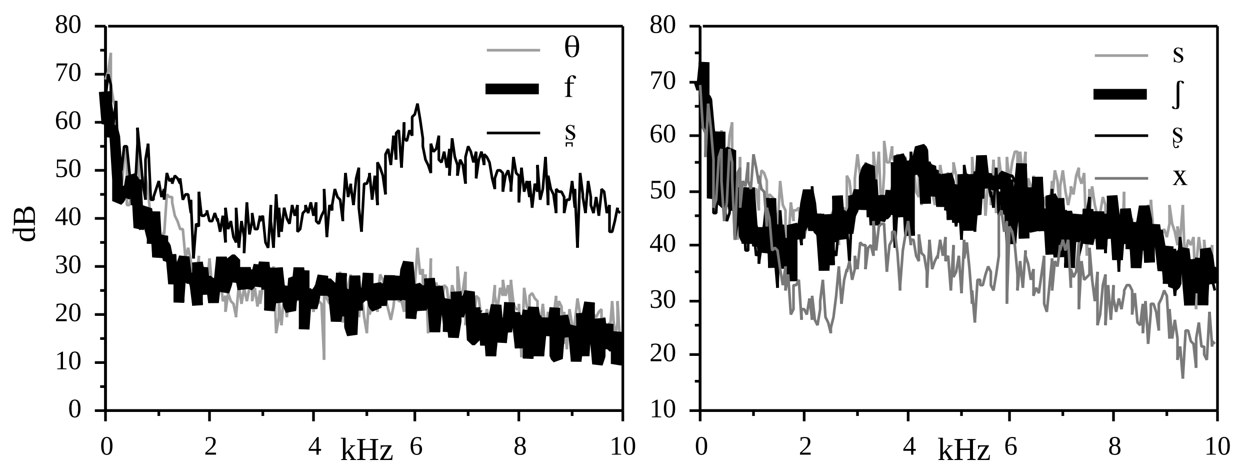
Averaged spectra for the Toda fricatives appear in Figures 14 (female speakers) and 15 (male speakers). Due to individual variation, spectra for /ɬ/ and /ɬ̣/ are separated by speaker for the females and spectra for /s̪/ and /s/ are separated by speaker for the males.

Starting from the anterior fricatives and working backwards, /f/ and /θ/ are characterized by flat spectra except for a relatively sharp low frequency peak at approximately 1kHz. The distinction between the dental /s̪/ and the alveolar /s/, not present in any of the other languages examined here, is reflected in a difference in the frequency of the highest noise concentrations. The bulk of the noise in /s̪/ is realized at higher frequencies, above 5kHz for the females and two of the three male speakers (all except M1), relative to the strongest noise band in /s/ which extends down to about 3kHz for the females and 2.5kHz for the males. One of the male speakers, M1, diverges from the other male speakers in having a single broad noise peak for the alveolar between 2.5kHz and 6kHz. The other two male speakers split this single peak into two, a relatively strong peak at 3kHz and a weaker peak at approximately 6.5kHz. The overall shape of the /ʃ/ spectrum is similar to the spectrum for /s/. For the female speakers, the spectral peak is broad and sloping and centered between 3kHz and 6kHz. It is distinguished from /s/ for the female speakers through its lesser noise in the upper half of the spectrum, though this difference is rather small. The distinction between /s/ and /ʃ/ is clearer for the male speakers. /ʃ/ has a broader spectral peak extending from 2.5kHz to 7kHz. /s/ on the other hand displays two peaks for two of the male speakers with the lower frequency edge for the first peak falling at a slightly higher frequency than the lower bound of the peak for /ʃ/. For speaker M3, who has a single peaked pattern for both /s/ and /ʃ/, the peak for /ʃ/ is broader in frequency and has a higher low frequency bound (approximately 3kHz vs. 2.5kHz) than /s/.

The lower edge of the peak noise band for /ʂ/ falls at a lower frequency than that of /s/ or /ʃ/, at about 2kHz for the males and 3kHz for the females. This difference is clearer for the male speakers but also distinguishes /ʂ/ from /s/ for the female speakers. For the female speakers, /ʂ/ differs from /s/ in the location of its peak noise. Whereas the peak for /ʃ/ is not reached until approximately 4kHz, noise reaches its peak by 3kHz for /ʂ/ before leveling off (see Shalev et al. 1994 for further discussion of the spectral properties of the coronal fricatives of Toda).

As in the other examined languages, the velar fricative has a low frequency spectral peak, below 2kHz, with additional higher frequency peaks at approximately 3.5 kHz and 6-7 kHz. For the male speakers, the lateral fricatives generally show the sharpest spectral peaks of all the fricatives other than the velar. The retroflex lateral /ɬ̣/ has a pronounced noise peak between 2kHz and 4kHz with other less prominent peaks at approximately 6kHz and 8kHz. The most prominent peak for the alveolar lateral /ɬ/ is slightly higher in frequency and somewhat narrower than that of /ɬ̣/, falling between approximately 3kHz and 4.5kHz. The difference in location of the spectral peak between /ɬ/ and /ɬ̣/ thus parallels the difference between /s/ and /ʂ/ for the male speakers.

For the female speakers, there is great variation in the realization of the lateral fricatives. For speakers F1 and F2, the retroflex lateral has an overall noise decline in the lower half of the spectrum and a relatively flat shape in the upper half with a sloping peak between 7 and 8kHz. For speaker F1, there is a peak in the spectrum for the alveolar lateral at about 3kHz followed by a declination in noise throughout the rest of the higher frequency range. Speaker F2 situates this peak at about 5kHz. The spectrum for the alveolar lateral for the speaker F3 is similar to that of F2, with a slightly broader peak extending higher in frequency. This third speaker has a sharp peak at 3kHz for the retroflex lateral and slightly less prominent peaks at 6kHz and 8kHz.



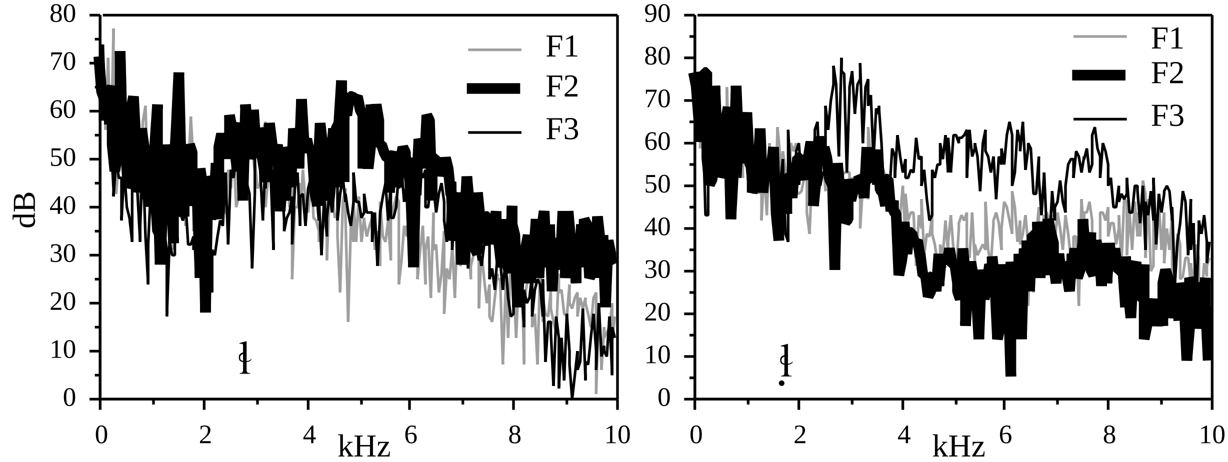


Figure 14. Averaged acoustic spectra (female speakers) for Toda fricatives

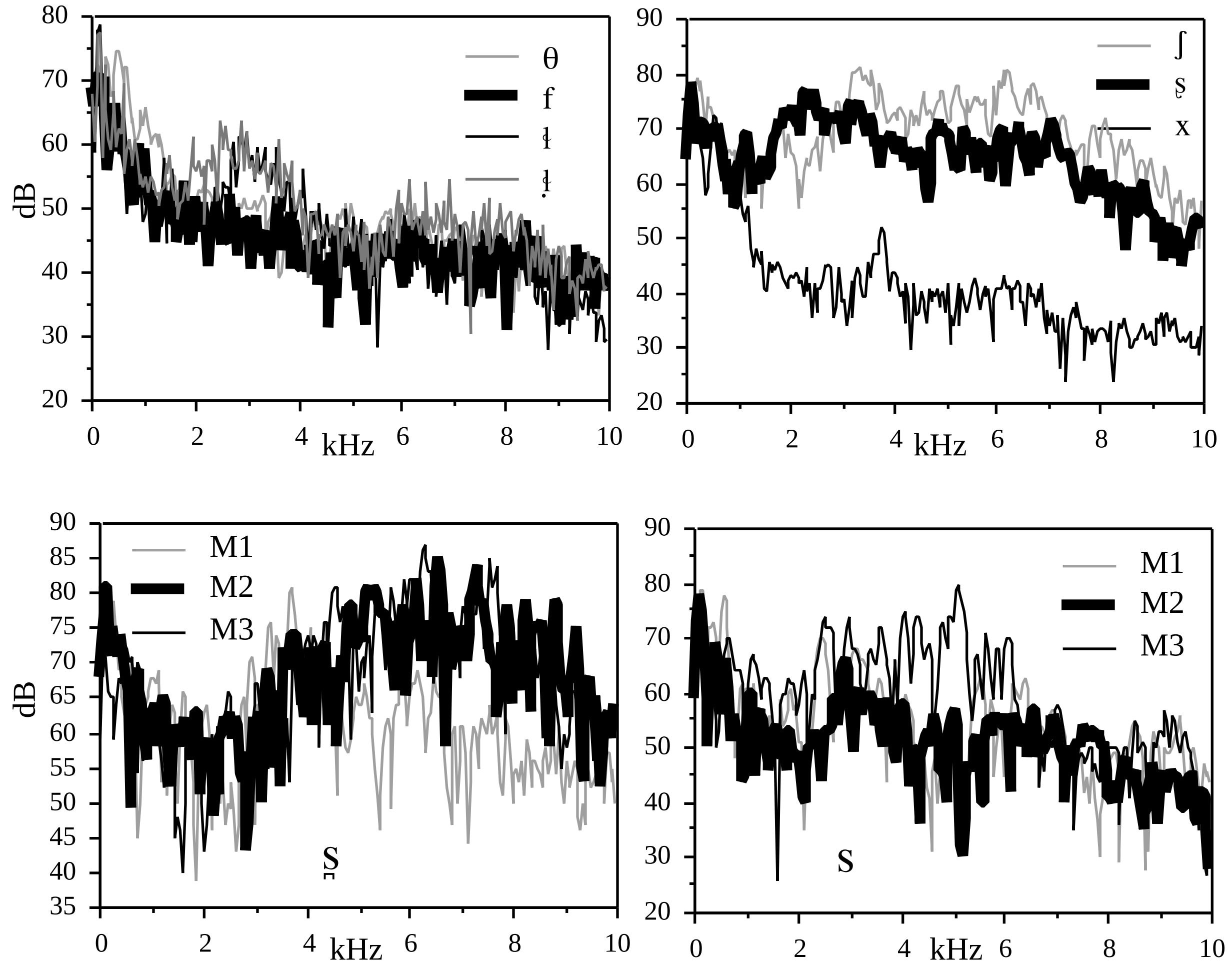


Figure 15. Averaged acoustic spectra (male speakers) for Toda fricatives

3.7.4. Formant transitions

Due to the subtle nature of the spectral differences between several of the Toda fricatives, vowel to consonant formant transitions were measured for the vowel preceding all the fricatives except for /x/. Results are separated into two groups according to the fricatives. First, in section 3.7.4.1, formant transitions for vowels adjacent to /f/ and /θ/ will be considered. Then, results for vowels adjacent to the coronal sibilants and the laterals will be examined in section 3.7.4.2.

3.7.4.1. Formant transitions for /f/ and /θ/

Frequency values for the first and second formant were calculated over the last 23 milliseconds (512 points) of the vowel /ɔ/ immediately preceding /f/ and /θ/, two fricatives which were relatively poorly differentiated in terms of gravity center frequencies and spectral characteristics. /f/ was found to be much shorter than /θ/ on average; however, this difference was only reliable for the female speakers. It has been suggested by Harris (1958) that /f/ and /θ/ are differentiated through the formant transitions of adjacent vowels. Results of testing this hypothesis for the Toda data appear in Figure 16, female speakers on the left and male speakers on the right. Formant values taken over an equivalently long window from the middle of the vowel are also included, as the preceding consonant context differs between the two fricatives. The word with final /f/ begins with /p/, whereas the word with final /θ/ begins with /t/.

F1 values do not differ between the vowel-to-consonant transition before /f/ and the transition before /θ/ for either the female or male speakers. F1 values do differ at the mid point of the vowel, with F1 values being higher for the vowel before /θ/ than the vowel before /f/. This difference is likely attributed to the difference in the preceding consonant.

More informative for differentiating the fricatives are the F2 transitions which are higher for /θ/ than for /f/. This difference does not reach statistical significance in an ANOVA for the female speakers ($F [1, 4)] = 1.226$, $p=.3302$), but does for the male speakers ($F [1, 4] = 26.236$, $p=.0069$). Much of the observed difference in Figure 15 for the female speakers is attributed to a substantial difference in F2 transition values for one of the female speakers. The other two female speakers show virtually no difference in F2 transition values between the two fricatives. By the middle of the vowel, there is no statistically significant difference in F2 values for either the female or the male speakers, though F2 values remain slightly higher in the vowel before /θ/ than the vowel before /f/, a difference which is plausibly attributed to the difference in the preceding context. It may also be noted that F2 values for the vowel adjacent to /f/ for the male speakers remain virtually identical from the transition through the middle of the vowel, suggesting a two-sided effect exerted by the labial consonants on either side of the vowel.

The salient F2 difference for the male speakers and one of the female speakers in the vowel-to-consonant transitions before the two fricatives complements the duration difference observed in the female speakers. It thus appears that male and female speakers differ in their strategies for differentiating /f/ and /θ/. Whereas the female speakers differentiate the two fricatives in duration, the difference is realized in the transitions of the second formant for the male speakers and one of the female speakers.

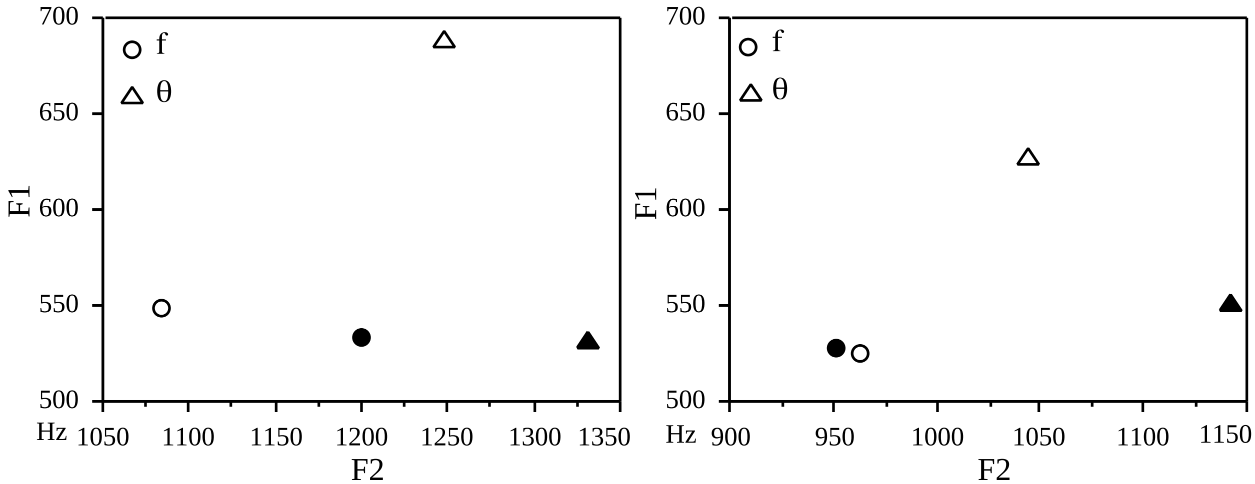


Figure 16. Averaged F1 and F2 transitions (in Hz) in adjacent vowel (female speakers on left, male speakers on right) for Toda /f/ and /θ/: filled symbols are transitions, unfilled symbols are from the middle of the vowel.

3.7.4.2. Formant transitions for coronal sibilants and lateral fricatives

Frequency values for the first three formants were calculated over the last 23 milliseconds (512 points) of the vowel immediately preceding the coronal sibilants /s̪/, /s/, /ʃ/ and /ʂ/ and the lateral fricatives /ɬ/ and /ɬ̢/. The third formant was measured in addition to the first two formants, as retroflexion has been shown to lower F3 in adjacent, particularly preceding, vowels in other languages due to the sublingual cavity created by retroflexion (Stevens and Blumstein 1975, Jongman et al. 1985, Dart 1991). The vowel preceding the coronal sibilants was /ɔ/ while the laterals were preceded by /ɑ/. An ANOVA indicated first formant transitions did not differ significantly depending on the following fricative. However, the second and third formant transitions were useful in distinguishing the fricatives. The following fricative had a highly significant effect on both the second formant ($F [5, 30] = 8.954$, $p<.0001$) and third formant ($F [5, 30] = 11.713$, $p<.0001$) transitions. Values for the second and third formant transitions averaged over the six speakers (similar results obtained for both male and female speakers) are plotted in Figure 17, sibilants on the left and laterals on the right. Formant values taken at the mid point of the vowel appear in open circles.

Looking first at the sibilants, values for both formants are quite similar at the mid point of the vowel. However, during the vowel-to-consonant transition (represented by the shaded points), /ʃ/ has much higher F2 values than the other three sibilants (reaching statistical significance at the $p<.01$ level in a Fisher's posthoc test), suggesting a higher tongue body position and more laminal articulation for /ʃ/ relative to other sibilants in Toda (cf. Shalev et al. 1994, who even suggest that /ʃ/ might be treated as a "palatalized consonant"). Furthermore, /ʂ/ has substantially lower F3 values (also statistically reliable) than the other fricatives, due to the sublingual cavity created through retroflexion. The dental and alveolar fricatives do not reliably differ in their effect on F2 and F3 values in the preceding vowel transition.

Turning to the laterals, retroflexion is also associated with lowered F3 values in the preceding vowel: $p=.001$ according to a posthoc test. Retroflexion in the lateral series also triggers raising of the second formant, though this effect was not statistically robust. The F2 difference between the two laterals is virtually gone by the middle of the vowel, while the F3 difference persists to some extent through the middle of the vowel, though it should be noted that the word containing the alveolar lateral begins a velar stop whereas the vowel before the retroflex lateral has no preceding consonant.

In summary, retroflexion triggers a lowering of the third formant in the preceding vowel and the palato-alveolar /ʃ/ is associated with raising of the second formant in the preceding vowel. The lowering of F3 by retroflexes may be regarded as an important cue in differentiating the two laterals, which share similar spectral properties. In addition, F3 lowering before /ʂ/ is presumably important in contrasting the retroflex sibilant and other sibilants, particularly for the female speakers, for whom /ʂ/ is poorly differentiated from /s/ and /ʃ/ spectrally. The raising effect of /ʃ/ on the second formant may also be decisive in distinguishing /ʃ/ from other coronal sibilants, particularly the alveolar /s/ with which it shares striking resemblance spectrally.

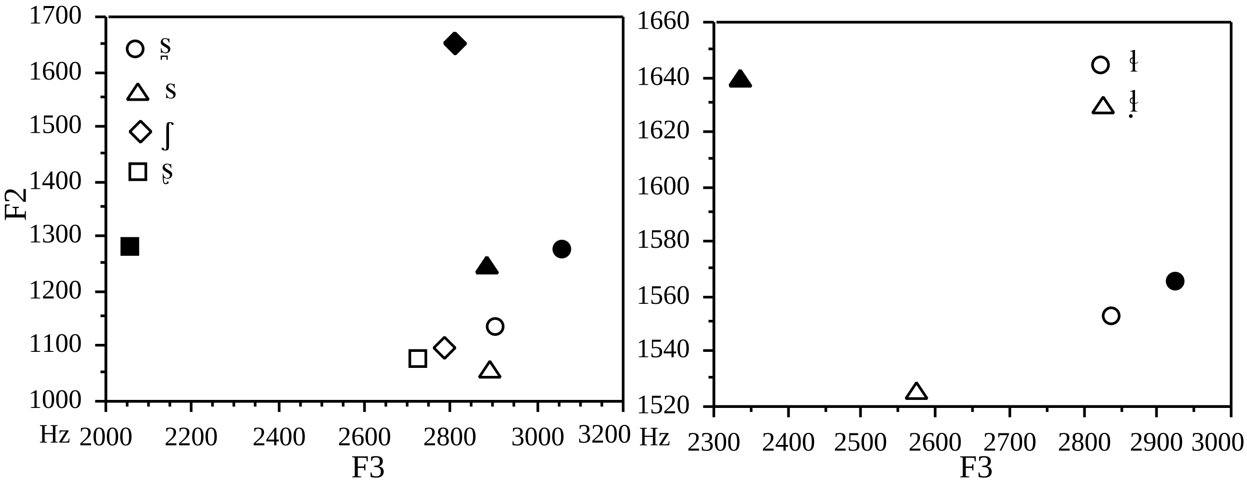


Figure 17. Averaged F1 and F2 transitions (in Hz) in adjacent vowel for Toda sibilant and lateral fricatives (sibilants on left, laterals on right): filled symbols are transitions, unfilled symbols are from the middle of the vowel.

4. Discussion

4.1. Duration

Duration in general acted as a poor differentiator of fricatives in the seven languages with some exceptions. The labiodental /f/ was shorter than other fricatives in Gaelic and for the female speakers of Toda. The relatively short duration of /f/ in Gaelic is consistent with findings from English indicating that non-sibilant fricatives are shorter than sibilants (e.g. Behrens and Blumstein 1988a, Jongman et al. 2000). However, /f/ was not reliably shorter than other fricatives in either Chickasaw or for the male speakers of Toda. In Western Aleut and Gaelic, /s/ was the longest of the fricatives, with a similar tendency found in Chickasaw and Hupa. However, /s/ was not the longest fricative in Western Apache, Toda, or Montana Salish. The velar /x/ varied considerably between languages in duration. It was the longest of the Western Aleut fricatives, but the shortest of the Hupa fricatives, and, together with /f/, the shortest of the Toda fricatives. /x/ did not stand out from other fricatives in its duration profile in Western Apache or Gaelic. The lateral fricative was generally not well differentiated from other fricatives in duration in the six languages with /ɬ/, although /ɬ/ was the longest of the fricatives for the female speakers of Western Apache. Finally, the labialised consonants /x^{w}/ and /χ^{w}/ in Montana Salish were shorter than other fricatives. Labialization was not associated with decreased duration, however, in Hupa, the other surveyed language with labialised fricatives.

4.2. Gravity centers

Gravity center frequencies robustly differentiated many of the fricatives in the examined languages. Of the fricatives, /s/ had the highest gravity center values in virtually all of the examined languages. The relatively high frequency center of gravity of the /s/ spectrum is shared with other languages examined in earlier research, e.g. Mandarin Chinese (Svantesson 1986), English (Jongman et al. 2000), Cairene Arabic (Norlin 1983). In Montana Salish, however, although there was a tendency for /s/ to have higher gravity centers than other fricatives, the difference between /s/ and the lateral /ɬ/ did not reach statistical significance. In Toda, which contrasts alveolar and dental sibilants, the dental sibilant has the highest gravity center values. In general, there was a tendency for fronter tongue articulations to have higher gravity center values. This correlation between frontness of the constriction and center of gravity is attributed to the smaller cavity in front of the constriction of relatively front fricatives. This shorter channel is associated with increased intensity of the front cavity resonances, the most prominent source of noise in a fricative (see Fant 1960, Stevens 1998 for discussion of the relationship between constriction location and spectral properties of fricatives).

In keeping with the correlation between constriction frontness and center of gravity, gravity centers for /ʃ/ were higher than gravity centers for /x/ in Western Apache, Gaelic, Hupa, and Toda. Norlin reports a similar difference between /ʃ/ and /x/ in Cairene Arabic. /ʃ/ also had significantly higher gravity centers than /ç/ in Western Aleut. A similar tendency was observed in Gaelic, though the difference was not consistent across speakers. The palatal /ç/ had higher gravity centers than more posterior fricatives in both Gaelic and Western Aleut. Furthermore, the velar fricative in Toda had lower gravity centers than the coronal sibilants.

There were some notable exceptions, however, to the correlation between frontness and gravity center values. In Toda, gravity centers for the alveolar /s/ were not reliably higher than those for the coronal sibilants /ʃ/, /s̢/ (and also /s̪/). Furthermore, /ʃ/ did not have higher gravity centers than /χ/ in Montana Salish. Gravity centers also did not reliably differentiate velars and uvulars in Montana Salish and Western Aleut. Furthermore, the non-sibilant dental /θ/ did not have higher gravity centers than other fricatives in Toda. Finally, the correlation between frontness and gravity center values does not hold of articulations not involving the tongue, in particular /f/, which did not have higher gravity centers than other backer fricatives in Chickasaw, Gaelic, and Toda. Retroflexion was not reliably associated with lowering of gravity centers in Toda: /ɬ/ and /ɬ̣/ had similar gravity centers as did /s̢/ in relation to the non-dental sibilants /s/ and /ʃ/. Rounding in the posterior fricatives was associated with lowering of gravity center values in Montana Salish, but not in Hupa.

The only pair of fricatives which displayed interlanguage variation in their relative gravity center values was /ʃ/ and /ɬ/. In Western Apache and Western Aleut, gravity centers for /ʃ/ were higher than those for /ɬ/. In Toda, both of the laterals /ɬ/ and /ɬ̣/ had lower gravity centers than the coronal sibilants, though the difference between /ɬ̣/ and /s/ did not reach statistical significance. In Montana Salish, on the other hand, /ʃ/ had lower gravity centers than /ɬ/. In Chickasaw and Hupa, there was no reliable difference between /ʃ/ and /ɬ/ in their gravity center values. This interlanguage variation is perhaps not surprising given that laterals can vary considerably between speakers and languages in their pronunciation cf. Ladefoged and Maddieson (1996). For example, laterals can be produced with differing degrees of tongue body raising, different constriction locations, and may be characterized by an opening on either one or both sides of the tongue.

4.3. Spectra

In general, there was considerable uniformity across speakers and languages in the spectral characteristics of comparable fricatives. Typically, the most pronounced noise peak in the spectrum is correlated with the backness of the fricative, such that backer fricatives have greater noise at lower frequencies in keeping with the longer anterior cavity associated with relatively posterior fricatives (see discussion in section 4.2). Thus, dorsal fricatives, including velars and uvulars, display an acute noise peak low in the frequency domain, below 2kHz, and one or more additional lower intensity peaks at higher frequencies (cf. Halle 1959 and Norlin 1983 for similar results in Russian and Cairene Arabic, respectively). Differences in rounding and backness condition further spectral differences among the dorsal fricatives, though these differences are not always reliable across speakers and languages. For the Western Aleut male speakers, the most prominent spectral peak for the uvular is lower in frequency than that of the velar (see Strevens 1960 for a similar difference between velar and uvular fricatives produced by trained phoneticians). A similar lowering of the first spectral peak is characteristic of rounded dorsal fricatives relative to their unrounded counterparts, a pattern which is evident in Montana Salish and Hupa. Like backing, rounding also has the effect of lengthening the cavity in front of the fricative constriction thereby enhancing the lower frequency components in the spectrum.

There are limits, however, to the lowering effect of rounding and backing on the primary spectral peak. For the Western Aleut females, the location of the first spectral peak does not differentiate the velars and uvulars. Furthermore, in Hupa, the rounded and the more rounded velar fricatives do not noticeably differ in their spectral properties. Nor does the unrounded velar have a lower main spectral peak than the two rounded velars for the female speaker of Hupa. Rounding has a greater lowering effect than backing on the primary spectral peak in the realization of the contrast between /xʷ/, /χ/ and /χʷ/ in Montana Salish. The two rounded fricatives have a lower frequency primary spectral peak than the unrounded uvular, but do not differ from each other in the location of their spectral peaks.

The locus of spectral noise typically increase in frequency as constrictions move farther forward in the mouth and the front cavity decreases in size (see above). Thus, /ʃ/ is characterized by a prominent noise peak between 2000 and 3000Hz and noise for /s/ is realized predominantly at even higher frequencies. This difference between /s/ and /ʃ/ parallels results from other studies, e.g. Hughes and Halle (1956), Behrens and Blumstein (1988a), Tomiak (1990), Jongman et al. (2000) on English, Halle (1959) on Russian, Jassem (1962), Lindblad (1980) on Swedish, Lacerda (1982) on Portuguese, Norlin (1983) on Cairene Arabic, Bladon et al. (1987) on Shona, Strevens (1960), Jassem (1968), Shadle et al. (1991) on fricatives uttered by phoneticians. In Toda, which distinguishes dental /s̪/ from alveolar /s/, noise for the dental is concentrated at higher frequencies than for the alveolar. Dart (1991, 1998) reports a similar difference between dental and alveolar realizations of /s/ in English and French (cf. also Jassem 1968). There is, however, considerable interspeaker variation in the spectral properties of /s/ in several of the examined languages despite the uniformly high gravity center values relative to other fricatives. The interspeaker variability in fricative production accords with acoustic data on other languages (cf. Hughes and Halle 1956 on English, Dart 1991, 1998 on English and French) and is linked to variation in constriction location and length and tongue shape and position. Unfortunately, a lack of articulatory data accompanying the acoustic data on individual speakers in the present study precludes a closer examination of the link between interspeaker differences in articulatory settings and their effect on spectral properties.

Retroflexion is also associated with lowering of spectral peaks (cf. Dart 1991 on O'odham and Jassem 1968 for similar findings in his self-production study, but also Lindblad 1980 on Swedish, in which spectral shape rather than location of the primary spectral peak distinguishes /ʂ/ from /ʃ/); thus, Toda /ʂ/ has the lowest frequency noise concentrations of the sibilants, a difference which is more apparent for the male speakers than for the female speakers. Toda /ɬ̣/ is similarly differentiated from its non-retroflex counterpart, though there is variation in this pattern among the female speakers. The palatal /ç/ is an exception to the correlation between constriction anteriority and the frequency of noise concentrations: in Gaelic, the greatest noise for /ç/ occurs at higher frequencies than for /ʃ/. The relatively high frequency peak associated with /ç/ in Gaelic replicates results from other studies, e.g. Jassem (1962) and Lindblad (1980) on Swedish, and Strevens (1960), Jassem (1968) and Shadle et al. (1991) for fricatives produced by phoneticians. Shadle et al. (1991) suggest that the unexpectedly high frequency noise concentrations of /ç/ relative to /ʃ/ are attributed to differences in the shape of the sublingual cavity for the two fricatives.

The non-sibilant fricatives /f/ (Chickasaw, Gaelic, and Toda) and /θ/ (Toda) are characterized by relatively flat spectra lacking the pronounced peaks of other fricatives (cf. Jassem 1962 on

Swedish, Lacerda 1982 on Portuguese, Norlin 1983 on Cairene Arabic, Svantesson 1986 on Mandarin, Behrens and Blumstein 1988a on English, Strevens 1960 and Jassem 1968 on fricatives produced by phoneticians). The flat spectrum of labiodentals is attributed to their virtual lack of any front cavity resonances. The lack of any prominent noise peaks in the 0-10kHz frequency range in the non-sibilant dental /θ/ is also presumably ascribed to its extremely small front cavity. The palatalized /fʲ/ (Gaelic) is differentiated from its non-palatalized counterpart through its abrupt increase in noise at about 2kHz, owing to its secondary constriction, followed by a relatively flat spectrum at higher frequencies.

As was the case for the gravity center measurements, /ʃ/ and /ɬ/ show interlanguage variation in the frequency location of their primary spectral peaks. In Chickasaw, the noise for /ɬ/ is centered at slightly higher frequencies than for /ʃ/, though this difference is small for the female speakers and there is considerable interspeaker variation in the spectral shape of /ɬ/ among the males. A similar difference between /ʃ/ and /ɬ/ in location of the spectral peak is also observed in Hupa. In Western Apache, on the other hand, the most prominent noise peak for /ɬ/ occurs at a slightly lower frequency than for /ʃ/: 2-2.5kHz for /ɬ/ and 3.5-4kHz for /ʃ/. A similar trend is seen for the laterals of Toda relative to /ʃ/. Nartey's (1982) critical band spectra suggests a parallel difference between /ɬ/ and /ʃ/ in Zuni and Navajo, the latter of which is closely related to Western Apache. In Montana Salish, the contrast between /ʃ/ and /ɬ/ is realized differently between the male and female speakers. For the female speakers, the most prominent spectral peak falls slightly higher in frequency for the lateral. For the male speakers, the difference is primary one of acuteness of the primary spectral peak: it is broader for the lateral. In summary, /ɬ/ is probably the largest source of variation between languages, though not necessarily speakers (see discussion of /s/ above), in spectral characteristics, varying on a language-specific basis both in terms of distribution of noise peaks and overall spectral diffuseness. This acoustic variation points to concomitant articulatory differences in the production of /ɬ/, following observed cross-linguistic variation in the production of lateral approximants (see Ladefoged and Maddieson's 1996 discussion).

4.4. Formant transitions

Formant transitions proved useful in discriminating between velar and uvular fricatives and in distinguishing degrees of rounding among the back fricatives. In Hupa and Montana Salish, rounding is generally associated with lowering of the first two formants. Thus, the rounded velars and uvulars in Montana Salish have lower F1 and F2 values in their vowel transitions than the unrounded uvulars. In Hupa, which observes a three way rounding contrast among the velars, unrounded /x/, rounded /xʷ/ and more rounded /x̹ʷ/, the greater the degree of rounding of the velar, the lower F2 values are in the adjacent vowel transition. Rounding also triggers lowering of F1 in adjacent vowels although this effect is limited to low vowels as predicted by vocal tract models (see discussion of Hupa in 3.6.4). The lowering effect of rounding on formant transitions, particularly F2, parallels an effect observed in center of gravity (section 4.3): increasing the length of the cavity anterior to the constriction lowers the natural resonating frequencies of the front cavity, F2 especially and to a lesser extent F1 in low vowels, not only during the fricative but also during the transitions into adjacent vowels.

In Western Aleut and Salish, uvulars trigger a lowering of the second formant of the immediately adjacent vowel suggesting a backing of vowels adjacent to uvulars. Furthermore, in Western Aleut, the first formant is also raised in the vicinity of uvulars, suggesting a lowering effect of the uvular consonant on the tongue. In fact, lowering of high vowels adjacent to uvulars is a salient feature of Inuktitut, a language related to Western Aleut (Schultz-Lorentzen 1945). The raising effect of uvulars on the first formant parallels an effect observed in low vowels: lowering the tongue body narrows the cavity behind the constriction and thus raises the frequency of the first resonance during consonant-vowel transitions. That the difference in F1 between vowels adjacent to uvulars and those adjacent to velars does not extend to Montana Salish plausibly reflects a ceiling effect attributed to the rounding of the uvular fricative in Montana Salish. Rounding triggers lowering of the first formant in the adjacent vowel, leaving little room for the rounded uvular to trigger additional lowering of the first formant.

Formant transitions also were useful in discriminating the non-sibilant fricatives /f/ and /θ/ in Toda, but only for the male speakers, for whom neither gravity center values, duration, nor spectral characteristics proved reliable discriminators of /f/ and /θ/. F2 values were substantially higher in the vowel preceding /θ/ than in the vowel before /f/, a difference attributed to the coronal articulation of the /θ/. This difference did not extend to the female speakers, for whom /f/ and /θ/ were reliably differentiated in terms of duration.

Retroflexion also had substantial effects on formant transitions. F3 values were lower in vowels adjacent to retroflex consonants relative to their non-retroflex counterparts in Toda (see Stevens and Blumstein 1975, Dave 1977, Jongman et al. 1985, Dart 1991 for discussion of this effect in other languages). F2 values served to differentiate /ʃ/ from other coronal sibilants in Toda: values were higher for /ʃ/, suggesting a higher tongue body (cf. Recasens 1984, Dart 1991, 1998 on the relationship between tongue body height and F2).

5. Discussion

In general, differences in spectral shape and center of gravity distinguished most of the fricatives in the seven examined languages. Formant transitions also proved useful in differentiating fricatives with similar spectra and gravity center frequencies. Duration was the least informative parameter for discriminating the fricatives.

Many of the spectral properties observed in the diverse set of examined languages offer confirmation of a number of predictions made by vocal tract models. Constriction location acted as a reliable predictor of the distribution of the greatest concentrations of noise in all of the examined languages: the more posterior the constriction, the greater the weighting of noise toward lower frequencies, as predicted given the prominence of front cavity resonances in fricative spectra. Like backing, rounding was also shown to trigger a shift in noise toward lower frequencies in the spectrum due to its additional lengthening effect on the cavity in front of the constriction. The effects of fricative constriction on adjacent vowel formants fit in with those predicted from theoretical models and existing data: retroflexion triggers lowering of the third formant due to the additional sublingual resonance, rounding induces lowering of the second formant (and the first formant in low vowels) owing to the lengthening of the front cavity, uvulars differ from velars in raising the first formant (in addition to lowering the second formant) of adjacent vowels due to their lower tongue body position.

Fricatives predicted on the basis of other studies to display relatively substantial variation in their production showed considerable variation in their concomitant acoustic properties in the present work. Thus, /s/ and laterals, both of which are known to differ significantly from language to language and speaker to speaker in their articulatory and acoustic properties, provided the greatest source of variation in the current study, suggesting interspeaker and interlanguage differences in location of constriction, constriction length, and tongue body height. It is hoped that a better understanding of this variation in fricatives will be achieved in future studies combining articulatory and acoustic data.

Acknowledgments

The authors wish to thank Wiktor Jassem, Allard Jongman, and Peter Ladefoged for comments on earlier drafts of this paper and audiences at UCSB and UCLA for their feedback on the research on which this paper is based. The original collection of the data reported here was supported by a grant from the National Science Foundation to Peter Ladefoged and Ian Maddieson. Analysis of the data was partially funded by a UCSB Academic Senate Grant. The authors wish to thank the researchers involved in making the original recordings: Peter Ladefoged [Western Apache, Western Aleut, Chickasaw, Gaelic, Montana Salish, Toda]; Alice Taff, Lorna Rozelle, Taehong Cho, Moses Dirks, Jacob Wegelin [Western Aleut]; Brian Potter, Willem de Reuse, John Dawson [Western Apache]; Pamela Munro [Chickasaw]; Jenny Ladefoged, Alice Turk, Keven Hind, St.

John Skilton [Gaelic]; Edward Flemming, Sarah Thomason [Montana Salish]; Michael Shalev, Peri Bhaskararao [Toda], as well as the many speakers who generously shared their voices. Portions of this research were presented at the 140th meeting of the Acoustical Society of America in Newport Beach, California.

Appendix

Tables AI-AVII give the corpora containing the examined fricatives in the seven languages. The measured fricatives are in bold.

Table AI. Western Aleut

sa**s**	birds
ɬaχ	boy
çal	tide
hiza**x**	almost
tʃiːða**χ**	baby animal

Table AII. Western Apache

tʃ’ɪʔkotɪ**ɬ**an	centipede
ʃɪ**s**ánɛ́	my old lady
pɪ**ʃ**aʃ	her/his bear
pɪ**x**aɬ	her/his club

Table AIII. Chickasaw

aɬtʃi**f**a	S/he’s late
pi**s**a	S/he looks at it
bi**ʃ**aɬtʃi	‘it’s milked’
hi**ɬ**a	S/he dances

Table AIV. Gaelic

fani	stay (future)
fʲanˠəɣ	flaying
satəɣ	throwing
ʃaxət	past
çanˠiç	bought
xatʲil	slept

Table AV. Hupa

jajlq’aː**s** (speaker M1)	I threw it
mɪt^{h}ɪ**s** (speaker F1)	through it
ala̜**ʃ**	nasty
hajaː**ɬ**	then
nḁː**x**	two
ma**x**^{w} (speaker M1)	It stinks
tɬ’u**x**^{w} (speaker F1)	river eel
nɪk^{jh}aː**x̹**^{w} (speaker M1)	in a big way
naːt^{h}ɪnu**x̹**^{w} (speaker F1)	Hupa (where the trail leads back)

Table AVI. Montana Salish

saχ^{w}	split wood
ʃalː	he got bored
ɬaq’t	wide, shovel
x^{w}altʃst	reach (for something)
χ^{w}aq’^{w}	grind or file something
χaq’	pay

Table AVII. Toda

pɔː**f**	swelling
tɔː**θ**	powdery, soft
kɔ**s̪**	money
pɔː**s**	milk
pɔː**ʃ**	language
pɔː**ʂ**	clan name
ka**ɬ**	study
a**ɬ̣**	rice put in ghee to clarify it
pɔː**x**	blood

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