CHAPTER 4

Consonant-Tone Interactions: A Phonetic Study of Four Indigenous Languages of the Americas

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1 Introduction

The effect of consonants on the fundamental frequency of adjacent vowels is well documented both on a diachronic level in tonogenesis as well as on a synchronic phonetic level (see Hombert et al. 1979, Bradshaw 1999, Tang 2008 for surveys). The most familiar consonant-tone interaction involves the lowering effect of voiced consonants on F0 in adjacent vowels. Less well studied and less consistent based on available data are the effects of other types of laryngeal features on F0. In an extensive cross-linguistic survey of consonant-tone interactions, Tang (2008) includes a discussion of the typology of consonant-F0 interactions not related to voicing. She observes that virtually all of the observations about the relationship between glottalization and F0 relate to glottal stop rather than ejectives and that glottalization may either raise or lower F0 depending on the language. Strikingly, even closely related languages, as in the northern branch of Athabaskan (Kingston 2005), may vary in their diachronic tonal reflexes of glottalization. Similarly, aspiration may either raise or lower F0 in adjacent vowels depending on the language and even the individual speaker. Implosive obstruents also display cross-linguistic variation in their effect on F0.

Typological research indicates other interesting patterns related to consonant-tone interactions. One is that the phonetic effect of consonant laryngeal features on an adjacent vowel is typically shorter in languages with an existing

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phonemic contrast in tone. Thus, Hombert et al. (1979) found that the duration of the pitch perturbations caused by prevocalic consonants on Fo in a following vowel is limited to the 40 to 60 millisecond range in Yoruba, which has phonemic tone on vowels, whereas in English the effect exceeds 100 milliseconds. They offer a compelling explanation for this difference based on the functional role of tone in the two languages. Yoruba speakers localize the phonetic perturbations to the immediately post-consonantal phase of the vowel in order to leave the bulk of the vowel available for conveying phonemic tone. English speakers, on the other hand, need not confine pitch perturbations to the portion of the vowel directly after the consonant since there is no threat of interfering with the perceptibility of phonemic contrasts in tone.

There also appears to be an asymmetry both diachronically in terms of tonogenesis patterns as well as on a synchronic phonetic level in the direction of the effect of consonantal laryngeal features on tone in adjacent vowels. Whereas vocalic tonal contrasts have commonly developed from laryngeal contrasts in prevocalic consonants, tonogenesis triggered by post-vocalic consonants appears to be a considerably rarer phenomenon (Hombert et al. 1979). Hombert et al. (1979) suggest that this diachronic asymmetry is attributed to a combination of factors observed on a phonetic level in some studies: the decreased magnitude of a consonant's effect on Fo in a preceding vowel relative to a following vowel coupled with the greater inconsistency in Fo differences in a pre-consonantal vowel as opposed to a post-consonantal vowel.

The current study seeks to expand upon our typological knowledge of the effects of different consonant laryngeal features on Fo by examining phonetic data from four languages of the Americas differing along two dimensions: the nature of their laryngeal contrasts in consonants and the phonemic role of tone. Along the dimension of tone, two languages (Pirahã and Western Apache) with phonemic tone and two lacking phonemic tone (Banawá and Hupa) are examined. Along the dimension of laryngeal contrasts, two of these languages (Pirahã and Banawá) have a two-way contrast between voiced and voiceless obstruents, while the other two (Hupa and Western Apache) exploit a three-way laryngeal distinction among stops between voiceless unaspirated, voiceless aspirated, and ejective stops.

Systematic phonetic study of the effect of consonants on Fo in the four targeted languages promises to enhance our understanding of three issues in the study of consonant-tone interactions. First, comparing tonal Pirahã and Western Apache with non-tonal Banawá and Hupa allows for study of the relationship between phonemic tone in vowels and subphonemic variations in Fo triggered by adjacent consonants. Second, examination of Hupa and Western Apache, both of which have aspirated and ejective stops in addition to plain unaspirated stops, contributes to our typological understanding of the less well studied effects of aspiration and glottalization on F0. Finally, a comparison of the effect of the consonant on the preceding vs. the following vowel will increase our knowledge of directional asymmetries in the phonetic realization of consonant-tone interactions.

2 Methodology

2.1 *Data*

Data from the four languages consisted of words belonging to a larger corpus designed to examine phonetic properties as part of the UCLA endangered language phonetic documentation project conducted during the 1990s. Data from three of the four languages (all except Hupa) were recorded using a DAT record at a sampling rate of 44.1 kHz via a high quality headmounted microphone (Shure SM10), while data from Hupa were recorded using an analog cassette recorder via a handheld microphone. The Hupa data were subsequently digitized at a sampling rate of 16Hz in preparation for analysis. The words were uttered twice in isolation by each speaker in each language. Data from four speakers were examined for Pirahã, Western Apache (two male and two female in each), and Banawá (four males), whereas data from two speakers (one male and one female) were analyzed for Hupa.

A nasal sonorant, a voiceless fricative, and stops differing in their laryngeal specification were examined for their effect on F0 in each language. A voiceless and voiced stop were targeted in Banawá and Pirahã, and a voiceless unaspirated, voiceless aspirated, and ejective stop were examined in Hupa and Western Apache. Within each language, place of articulation was controlled for among the stops and nasals to the extent the data allowed.

Target sounds occurred in prevocalic position and, with few exceptions, occurred after a vowel as well. The vowel following the target consonant was systematically varied between a high front vowel and a low central vowel except for Western Apache, for which the following vowel was consistently a high vowel. Tone was systematically cross-classified with the following vowel quality in the two languages with lexical tone. In both tone languages, the vowels in syllables adjacent to the one containing the measured vowel consistently carried a low tone in order to control for possible tone sandhi effects. In the three languages for which stress has been reported (all except Western Apache), the location of the target consonant relative to stress was held constant, occurring in the onset of a stressed syllable in Hupa and in the onset of an unstressed syllable in Banawá and Pirahã. In two of the languages, Hupa and Banawá, data allowed for the quality of the preceding vowel to be held constant, which allowed for comparison of the effect of the consonant on Fo in the preceding as well as the following vowel. The corpus examined for each language appears in the appendix.

2.2 *Measurements*

A series of Fo measurements were generated using a script within Praat (Boersma and Weenink 2010). Measurements of Fo were taken at ten millisecond intervals in the vowel following the target consonant and, in the case of Hupa and Pirahã, in the vowel preceding the target consonant. In addition, three average measurements encompassing different portions of the target vowel(s) were taken, one constituting the third of the vowel closest to the target consonant (the proximal third), another the middle third (the medial third), and another composed of third of the vowel farthest removed from the target consonant (the distal third).

In the case of the vowel following the target consonant, the initiation of voicing following the release of the consonant as diagnosed from a waveform with a time-aligned spectrogram was used as the demarcation point for the onset of the vowel. The cessation of voicing was taken as the endpoint of the measurement in the following vowel. In the two languages in which the preceding vowel was also analyzed, the release of the consonant preceding this vowel was taken as the start point while the beginning of the consonant constriction was used as the demarcation for the end of the preceding vowel. Data collected using the Praat script were imported into a spreadsheet for coding of variables in preparation for statistical analysis.

2.3 *Predictions*

It was hypothesized that the difference between languages in the phonemic role of tone correlates with differences in the effect of the consonant on the Fo in the following vowel, where this difference might be in magnitude and/or in the temporal domain. It is thus expected that Fo consonant-induced Fo perturbations will be durationally shorter and/or smaller in magnitude in the two languages with phonemic tone, Pirahã and Western Apache, than in the two languages without phonemic tone, Banawá and Hupa.

The relationship between particular consonant laryngeal features and their effect on Fo, lowering or raising, is more difficult to predict. It is hypothesized that voiced stops will lower Fo relative to voiceless ones in the two languages with voiced stops, Banawá and Pirahã. However, it is not clear how laryngeal features associated with consonants will interact with Fo in Hupa and Western Apache, both of which lack voiced stops and possess three types of voiceless stops: voiceless unaspirated, voiceless aspirated, and ejective stops. Voiceless stops cross-linguistically are associated with raising of F0, but most of the data on which this observation is based come from languages contrasting voiced and voiceless stops. Carrier, an Athabaskan language related to Hupa and Western Apache that also makes an aspiration rather than a voicing contrast in stops, is reported by Tang (2008) to contradict this pattern in displaying an affinity between voiceless stops and low tone (Pike 1986). It is also unclear how ejectives will impact F0 in the present experiment since there is little cross-linguistic data bearing on this issue. Frazier (2009) shows that ejectives trigger slightly lower F0 in a following vowel compared to plain voiceless obstruents in Yucatec Maya but higher F0 relative to sonorants and glottal stop. In the vowel preceding an ejective, however, F0 is higher than before a voiceless obstruent in one dialect but not in the other dialect. Glottal stop more consistently triggers lowering of F0 in a preceding vowel. The lowering of F0 triggered by glottal stop in Yucatec Maya is observed in many languages, although many others display the opposite pattern of F0 raising in the vicinity of glottal stop (Hombert et al. 1979, Kingston 2005). In his discussion of the variation between closely related Northern Athabaskan languages in their tonal reflexes of glottalization, Kingston (2005) hypothesizes how different articulatory mechanisms associated with glottalization account for this variation. Cross-linguistic results for fricatives and for sonorants are likewise split between languages evincing F0 raising and those displaying F0 lowering.

A final prediction relates to the directionality of the effect of consonant laryngeal features on F0 in adjacent vowels. Given the typology of tonogenesis patterns, it is hypothesized that a consonant will induce a greater effect, temporally and/or in magnitude, on the F0 of a following vowel than a preceding vowel in the two languages, Hupa and Banawá, for which data from both the preceding and following vowel were analyzed.

3 Results

3.1 *Banawá*

Banawá is a non-tonal Arawan language of Brazil spoken by approximately 70 people (Buller et al. 1993). Target words for measurement in Banawá contained one of the consonants /m/, /s/, /d/, /t/ in disyllabic words in two intervocalic contexts: between /a/ and between /i/. In all tokens, the first vowel was stressed and the second vowel unstressed.

Figure 4.1 depicts mean F0 values at three positions in the vowels adjacent to the four target consonants: a point ten milliseconds removed from the consonant, a window over the third of the vowel closest to the consonant,

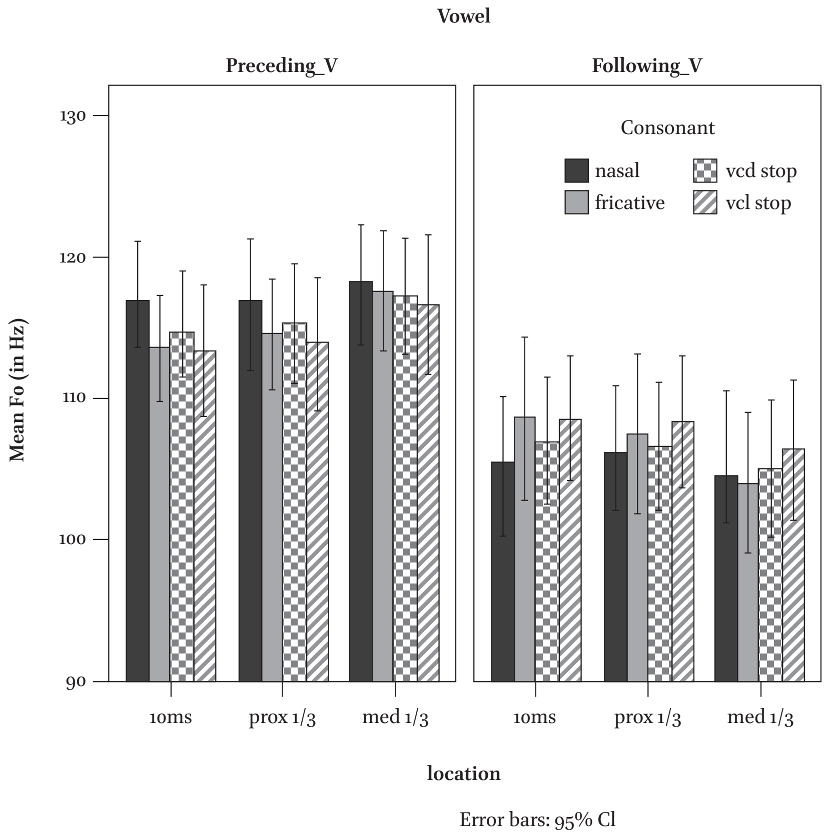

FIGURE 4.1 *Fo values (in Hertz) averaged over four male Banawá speakers at three points during the vowel preceding and following four consonant types. Error bars represent 95% confidence intervals.*

and a window over the medial third of the vowel. To provide a sense of the time windows associated with the proximal and medial third measurements, Figure 4.2 provides average duration values for vowels both preceding and following the different consonants.

As Figure 4.1 shows, there is little difference in Fo values (< 5 Hz) as a function of consonant type at any of the measurement points. The most striking result is the lowered Fo of the vowel following the consonant compared to the vowel preceding the consonant, a result that is likely attributed to a terminal pitch fall at the end of the words, all of which were uttered in isolation. This utterance-final vowel was often realized with creaky phonation, which is associated with lowered Fo that might create a baseline effect transcending

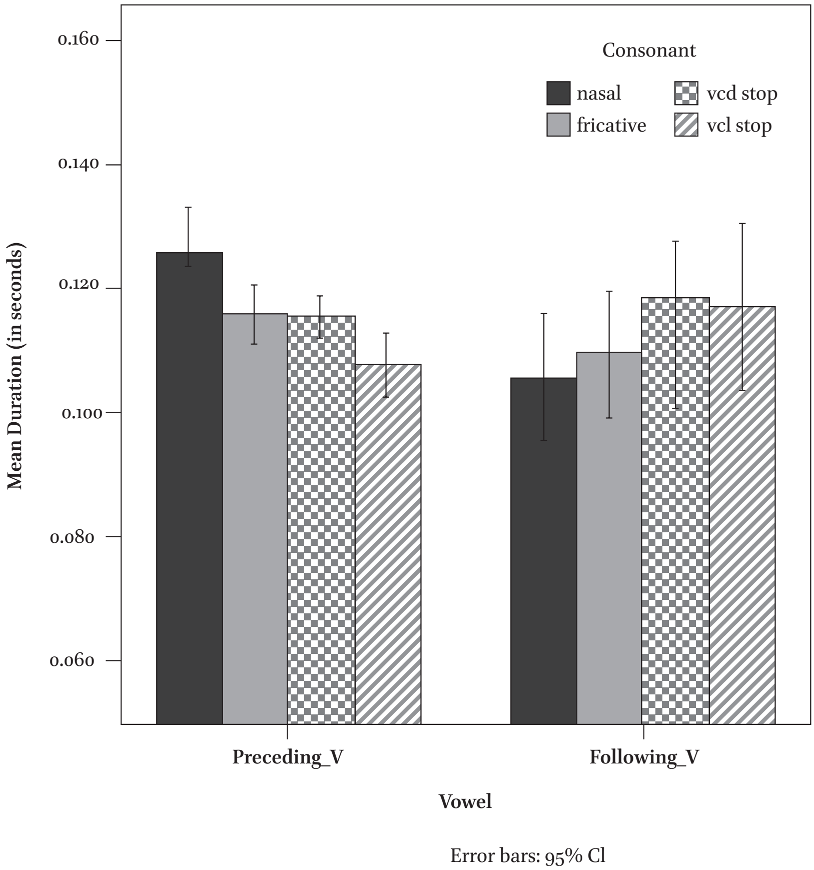

FIGURE 4.2 *Duration values (in seconds) for the vowel preceding and following four different consonant types averaged over four Banawá speakers. Error bars represent 95% confidence intervals.*

differences in the preceding consonant. A difference in stress between the first (stressed) syllable and the second (unstressed) syllable likely also contributed to the difference in Fo between the two vowels.

A series of mixed-effects regression models were fitted to the data with Fo values serving as the dependent variable and consonant (voiced stop vs. voiceless stop vs. fricative vs. nasal) and location of the vowel relative to the target consonant (preceding vs. following vowel) serving as the predictor variables. Speaker was included as a random factor. Separate analyses were performed for the vowel preceding the target consonant and the vowel following the consonant and for different windows in time over which Fo values were calculated.

These included points at ten millisecond intervals at increasing distances from the targeted consonant ranging from ten to fifty milliseconds, i.e. ten milliseconds removed from the consonant, twenty milliseconds removed, and so on up to fifty milliseconds away from the consonant. In addition, analyses were run for each of the windows comprising equal thirds of the measured vowels, i.e. the third of the vowel closest to the target consonant, the middle of the vowel, and the third farthest away from the consonant.

Results of the analysis indicated that, in contrast to the location of the vowel relative to the target consonant, the consonant itself failed to act as a reliable predictor of F0 values at any of the time points in keeping with the results shown graphically in Figure 4.1. However, the random effect of speaker did act as a robust predictor of F0 values.

Figure 4.3 depicts individual speaker results for mean F0 values ten milliseconds removed from the target consonant. It can be seen that speaker 3 and, to a lesser extent, speaker 1 display the expected lowering of F0 following a voiced stop. In the case of speaker 1, the effect is more accurately described as a slight raising of F0 following a voiceless stop. The lowering of F0 adjacent to a voiced stop for speaker 3 is also observed to a lesser degree in the preceding vowel. Note that the slight raising of F0 in the vowel after a voiced stop for speaker 4 is unlikely to reflect a reliable effect.

As the F0 values averaged over the third of the vowel closest to the target consonants show in Figure 4.4, the effect of voicing on F0 for speakers 1 and 3 is observable throughout the third of the following vowel proximal to the target consonant, although it is absent by the medial third of the vowel.

In summary, the Banawá data evince only a weak effect of consonant on F0 values for adjacent vowels and this effect is limited to only certain speakers. One speaker showed a lowering of F0 in adjacent vowels, more notably the following vowel, triggered by voiced stops. For another speaker, the difference between voiced and voiceless stops in their effect on F0 is better characterized as raising following a voiceless stop. In keeping with predictions discussed earlier, the F0 perturbations are more salient on a following vowel than a preceding vowel for those speakers that display any consonant-induced effects on F0.

3.2 *Pirahã*

Pirahã is the only extant language of the Mura family and is spoken by approximately 360 people in the Amazonas region of Brazil (Lewis 2009). The Pirahã consonant inventory is similar to that of Banawá in the respects crucial for this paper except for not contrasting voiced oral and nasal stops (Everett 1986).

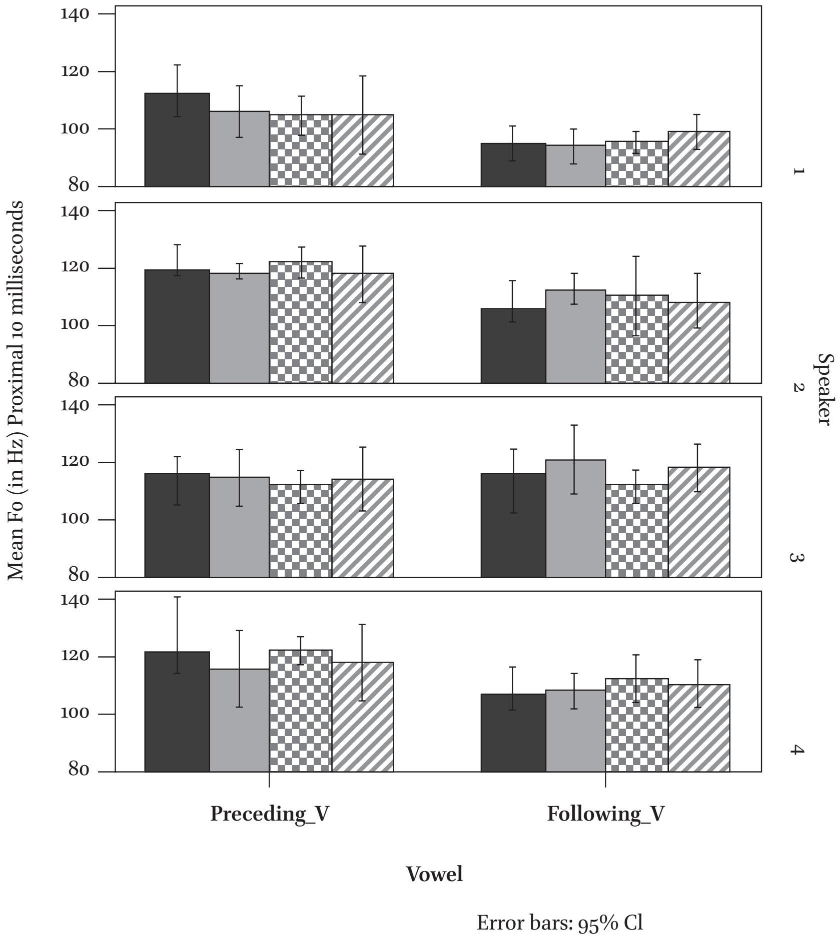

FIGURE 4.3 *Fo values (in Hertz) for four male Banawá speakers at a point in the vowel ten milliseconds before and after four different consonant types. Error bars represent 95% confidence intervals.*

A crucial difference between the two languages, however, lies in the role of Fo: Pirahã has a lexical contrast between high and low tone, while Banawá does not. Comparison of the two languages thus allows for testing of the hypothesis that a higher functional load associated with Fo will constrain the magnitude of Fo perturbations induced by consonants. The vowels /a/ and /i/, both high and low tone, following the consonants /s/, /p/ and /b/ were targeted for measurement in Pirahã. All of the measured vowels appeared in unstressed syllables and the preceding vowel was low-toned. The corpus thus included two

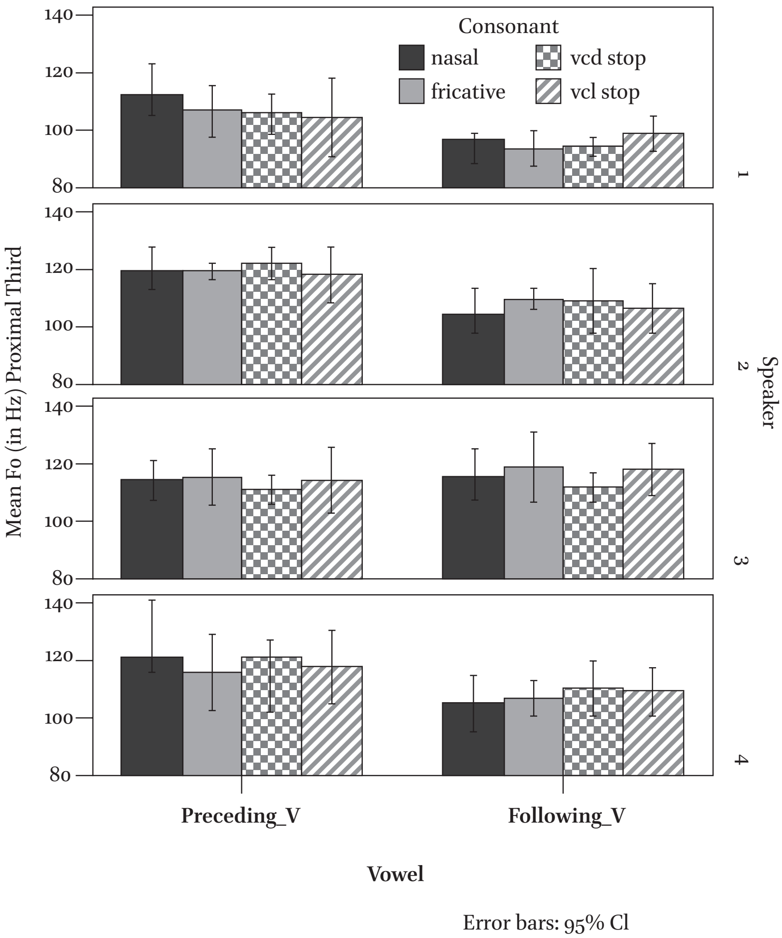

FIGURE 4.4 *Fo values (in Hertz) for four male Banawá speakers computed over the third of the preceding and following vowel proximal to four different consonant types. Error bars represent 95% confidence intervals.*

of the four logically possible tone patterns over two syllables: low + low and low + high. Vowels adjacent to /b/ were omitted from the analysis in tokens in which /b/ was either realized as the nasal /m/ or if it was lenited to a fricative or approximant. A few tokens of /i/ following /p/ were devoiced and thus not analyzed. Some instances of /s/ were realized as a glottal fricative but this did not affect the measurements.

The Pirahã data were separated into two groups according to the gender of the speakers. Figure 4.5 depicts mean Fo values separated for phonemic tone as a function of the preceding consonant for the male speakers at three

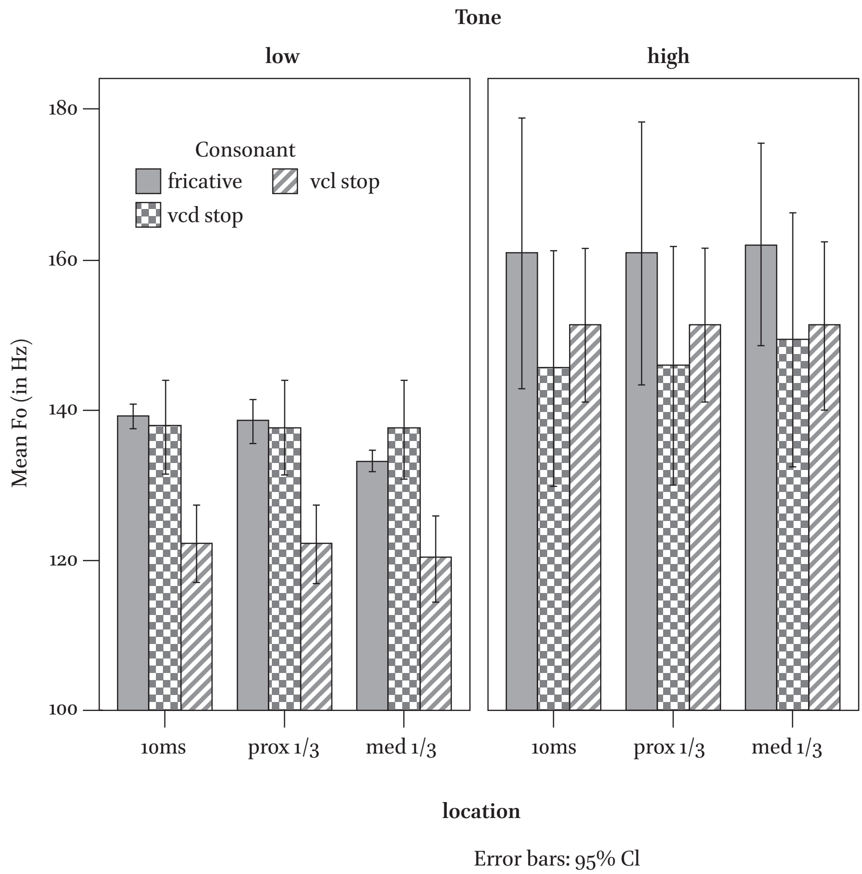

FIGURE 4.5 *Fo values (in Hertz) averaged over two male Pirahã speakers at three points during low tone and high tone vowels following three consonant types. Error bars represent 95% confidence intervals.*

different time points: ten milliseconds following the consonant, the third of the vowel immediately following the consonant, and the medial third of the vowel. Results for the female speakers appear in Figure 4.6. Results in both figures are for the vowel following the target consonant. It may also be noted in Figure 4.7, which shows duration values for vowels averaged over both male and female speakers, that the time windows comprising the proximal and medial thirds of the vowel are shorter for the vowels following a voiceless stop relative to the other two consonant contexts.

A series of mixed effects regression models were fitted to the data following, with certain modifications, the procedure adopted in the analysis of Banawá. As in the analysis of Banawá, separate models were fitted to data points

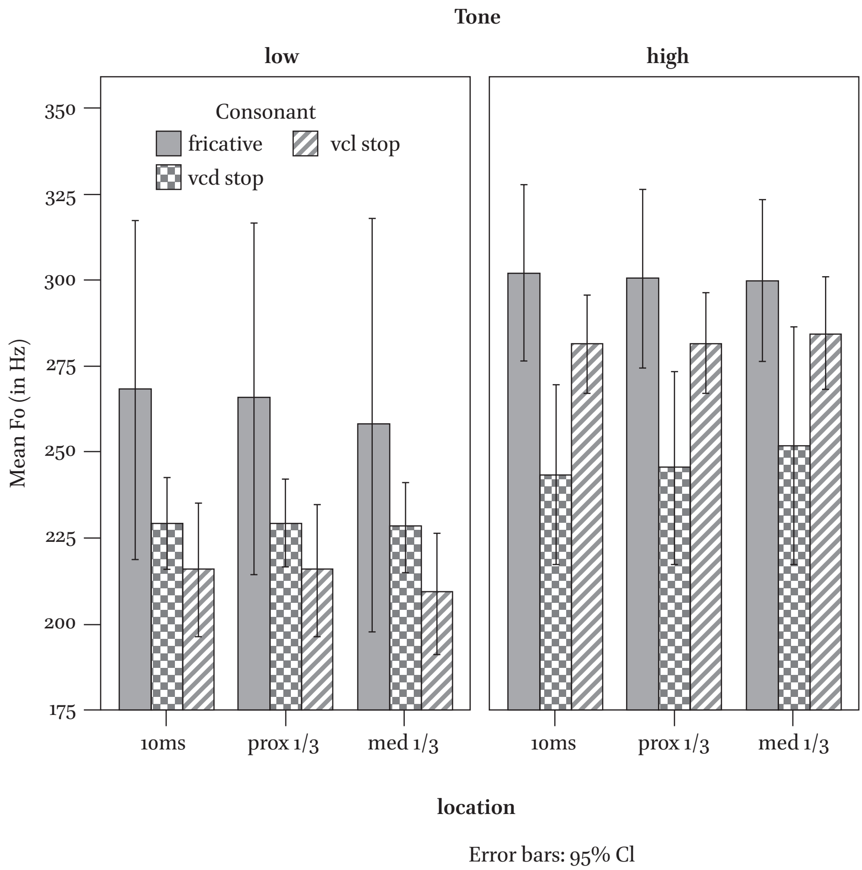

FIGURE 4.6 *Fo values (in Hertz) averaged over two female Pirahã speakers at three points during low tone and high tone vowels following three consonant types. Error bars represent 95% confidence intervals.*

corresponding to different time points at which Fo values were calculated. However, tone (high vs. low) replaced vowel location as the second fixed variable in addition to consonant (voiceless stop vs. voiced stop vs. fricative). An additional difference between the Piraha analysis and the Banawá one was the incorporation of separate analyses for the two genders.

In the case of the male speakers, the analyses failed to show any effect of consonant type on Fo at any of the measurement points. The most salient effect for the male speakers is the higher Fo values for vowels carrying a phonemic high tone compared to those associated with a phonemic low tone. The most salient effect attributed to a consonant appears to be the lowering of Fo in low-toned vowels following a voiceless stop relative to low-toned vowels after other consonants.

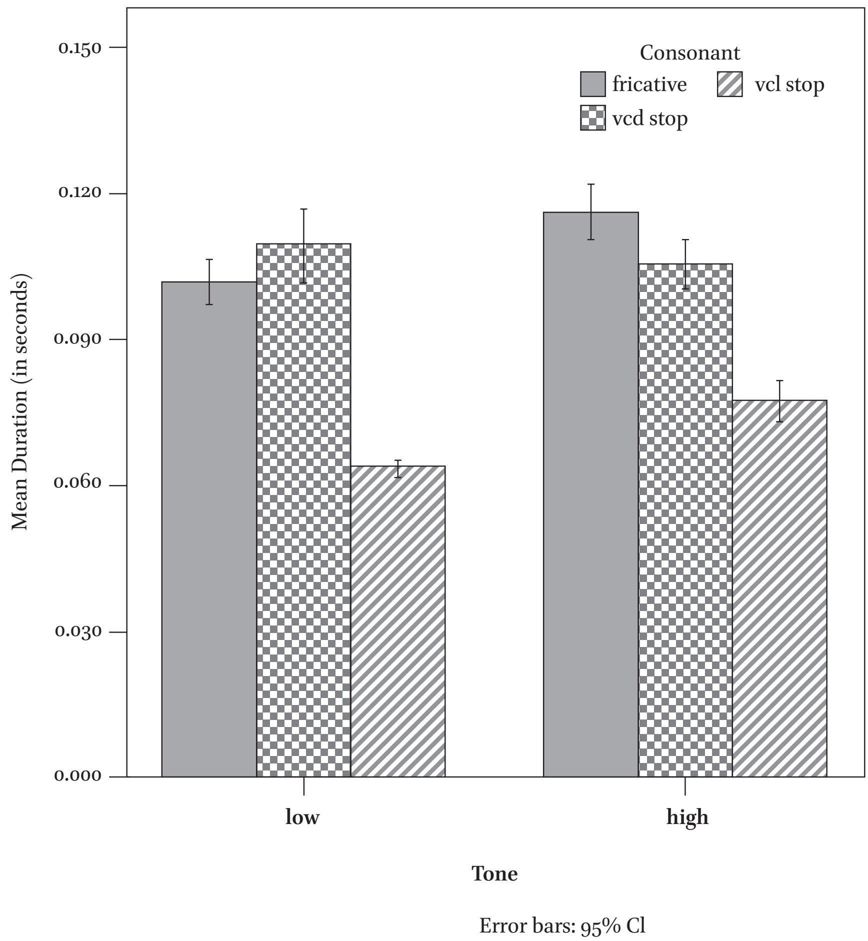

FIGURE 4.7 *Duration values (in seconds) for low tone and high tone vowels following four different consonant types averaged over four Pirahã speakers. Error bars represent 95% confidence intervals.*

Results for the two female speakers were statistically more robust. Not only tone level but also consonant preceding the vowel acted as reliable predictors of F0 values for all time points and windows throughout the vowel. In addition, there was an interaction between consonant and tone. Table 4.1 shows summary results of the regression model at the three time points corresponding to those in Figure 4.6: ten milliseconds after the vowel, the beginning third of the vowel and the middle third of the vowel. The estimate for CONSONANT$_{\text{fricative}}$ and CONSONANT$_{\text{voiced stop}}$ are in relation to CONSONANT$_{\text{voiceless stop}}$ and the estimate for TONE$_{\text{low}}$ is in relation to TONE$_{\text{high}}$, both of which serve as the intercept.

TABLE 4.1 *Log likelihood ratios, fixed effect coefficient estimates, standard error, t-values and p- values in mixed effects models for two female speakers conducted at three time points*

Parameter	Estimate	Std. Error	t-value	p-value
Time = 10 milliseconds				
Log Likelihood = 260.8				
Intercept	281.452500	7.532873	37.363	< .001
CONSONANT$_{fricative}$	20.650000	13.047318	1.583	.125
CONSONANT$_{voiced\ stop}$	−38.298750	10.653091	−3.595	.001
TONE$_{low}$	−65.689167	11.506653	−5.709	< .001
CONSONANT$_{fricative}$ * TONE$_{low}$	31.540000	19.930108	1.583	.125
CONSONANT$_{voiced\ stop}$ * TONE$_{low}$	51.515417	16.731345	3.079	.005
Time = proximal third				
Log Likelihood = 262.8	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	281.846250	7.805975	36.106	< .001
CONSONANT$_{fricative}$	18.706250	13.520345	1.384	.177
CONSONANT$_{voiced\ stop}$	−36.675000	11.039315	−3.322	.002
TONE$_{low}$	−66.096250	11.923823	−5.543	< .001
CONSONANT$_{fricative}$ * TONE$_{low}$	31.017083	20.652668	1.502	.144
CONSONANT$_{voiced\ stop}$ * TONE$_{low}$	50.099000	17.337935	2.890	.007
Time = medial third				
Log Likelihood = 280.5	**Estimate**	**Std. Error**	**t-value**	**p-value**
Intercept	284.567500	9.039163	31.482	< .001
CONSONANT$_{fricative}$	15.082500	15.656289	.963	.343
CONSONANT$_{voiced\ stop}$	−32.790000	12.783307	−2.565	.016
TONE$_{low}$	−75.823214	13.231980	−5.730	< .001
CONSONANT$_{fricative}$ *TONE$_{low}$	33.869881	23.587754	1.436	.162
CONSONANT$_{voiced\ stop}$ * TONE$_{low}$	52.161714	19.685581	2.650	.013

The most apparent effect is the raising of F0 adjacent to the voiceless fricative relative to the vowel following other consonants, a difference that is especially apparent for low-toned vowels. Pairwise comparisons indicated that F0 following a voiceless stop was significantly higher (at $p < .01$) than following other consonants. Voiced stops are also associated with lowering of F0, most notably in the case of high-toned vowels. The pattern seen in high tone vowels for the female speakers is essentially an exaggerated mirror of the pattern seen for the male speakers. In low tone vowels, on the other hand, the higher F0 observed in fricatives relative to voiced stops for the female speakers was not found for the male speakers. It is also interesting to note that, for the female speakers, the mean F0 value for a low tone vowel following a fricative is actually higher in absolute terms than the mean F0 for a high tone vowel after a voiced stop suggesting that listeners are able to normalize F0 judgments as a function of the consonantal context.

Another salient finding holding for both males and females is that the vowel following voiced stops is affected less by the phonemic tone of the vowel than the vowel after either voiceless stops or fricatives. This result suggests that voiced stops may have an intrinsic F0 target that is less mutable than other consonants as a function of a vowel's tone.

3.3 *Hupa*

Hupa is a Pacific Coast Athabaskan language of Northern California (Golla 1970) spoken by eight people as of 1998 (Lewis 2009). Hupa differs from both Banawá and Pirahã in possessing a larger inventory of consonants whose effects on F0 can be evaluated. Of particular interest is the three-way laryngeal contrast in the stop series between voiceless unaspirated, voiceless aspirated and ejective stops. Both the preceding vowel and the following vowel (either a high mid /e/ or a low high /ɪ/ vowel) were examined for two Hupa speakers, one male and one female. Targeted consonants were /t/, /tʰ/, /t'/, /s/, and a nasal, which was /m/ in the pre-high vowel context and /n/ preceding the low vowel. All of the vowels preceding the target consonants were unstressed, while all those following the consonant were stressed. Figure 4.8 (male speaker) and Figure 4.9 (female speaker) show average F0 values for the pre-consonantal and post-consonantal vowel at three different time points (ten milliseconds removed from the consonant, the third of the vowel adjacent to the consonant, and the medial third of the vowel) as a function of the target consonant. Non-modal phonation in the vowel preceding the ejective for the female speaker precluded accurate F0 extraction for the pre-ejective vowel. Figure 4.10 depicts mean duration values for the pre- and post-consonantal vowels collapsed over both speakers.

Although the F0 measurements were not subjected to statistical analysis due to the paucity of data points, there are several similarities for both speakers. Most conspicuous are the following effects: first, the raising of F0

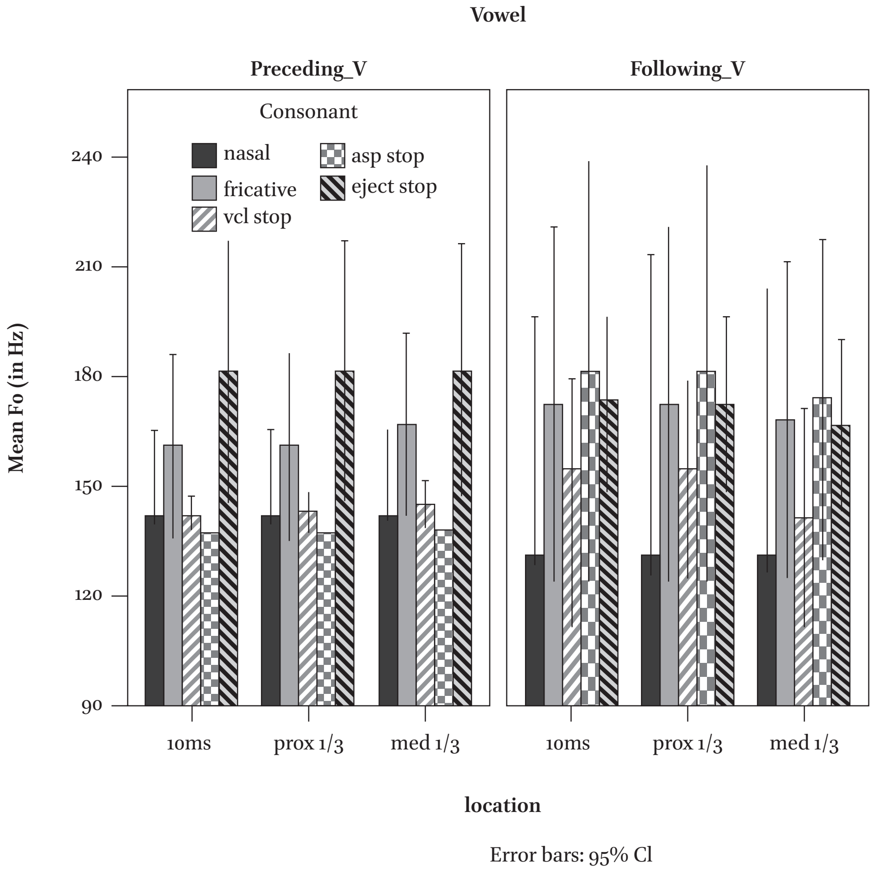

FIGURE 4.8 *Fo values (in Hertz) averaged over a male Hupa speaker at three points during the vowel preceding and following five consonant types. Error bars represent 95% confidence intervals.*

following both the ejective and the aspirated stop, second, the lowering of Fo in vowels adjacent to the voiceless unaspirated stop and in the vowel preceding the aspirated stop, and third, the raising of Fo preceding the ejective for the one speaker for whom data was available. These effects persist throughout the medial third of both the preceding and following vowel, though they are less pronounced by the medial third in the case of the female speaker.

Fricatives and nasals differ in their effect on Fo as a function of their context and the speaker. The male speaker shows a lowering of Fo in vowels adjacent to nasals and raising of Fo in vowels next to fricatives. The female speaker, on the other hand, displays raising of Fo in the vowel preceding but not following

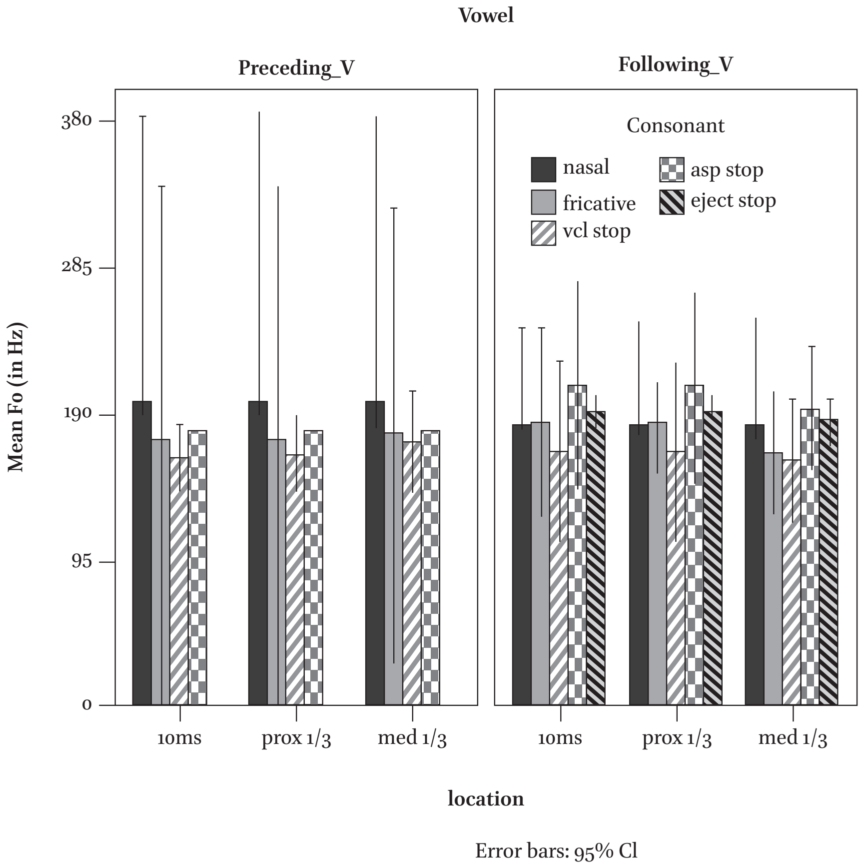

FIGURE 4.9 *Fo values (in Hertz) averaged over a female Hupa speaker at three points during the vowel preceding and following five consonant types. Error bars represent 95% confidence intervals.*

a nasal, and the fricative exerts a similar effect to the nasal on the following vowel, while Fo values in the vowel preceding a fricative are similar to those associated with a following aspirated stop.

3.4 *Western Apache*

Western Apache belongs to the Apachean branch of Athabaskan and is spoken by a population of 12,700 according to the 1990 census (Lewis 2009). It possesses the same laryngeal contrasts as Hupa but crucially differs in having a phonemic contrast between high and low tone. Fo was measured for four Western Apache speakers (two male and two female) in the vowel /i/, both

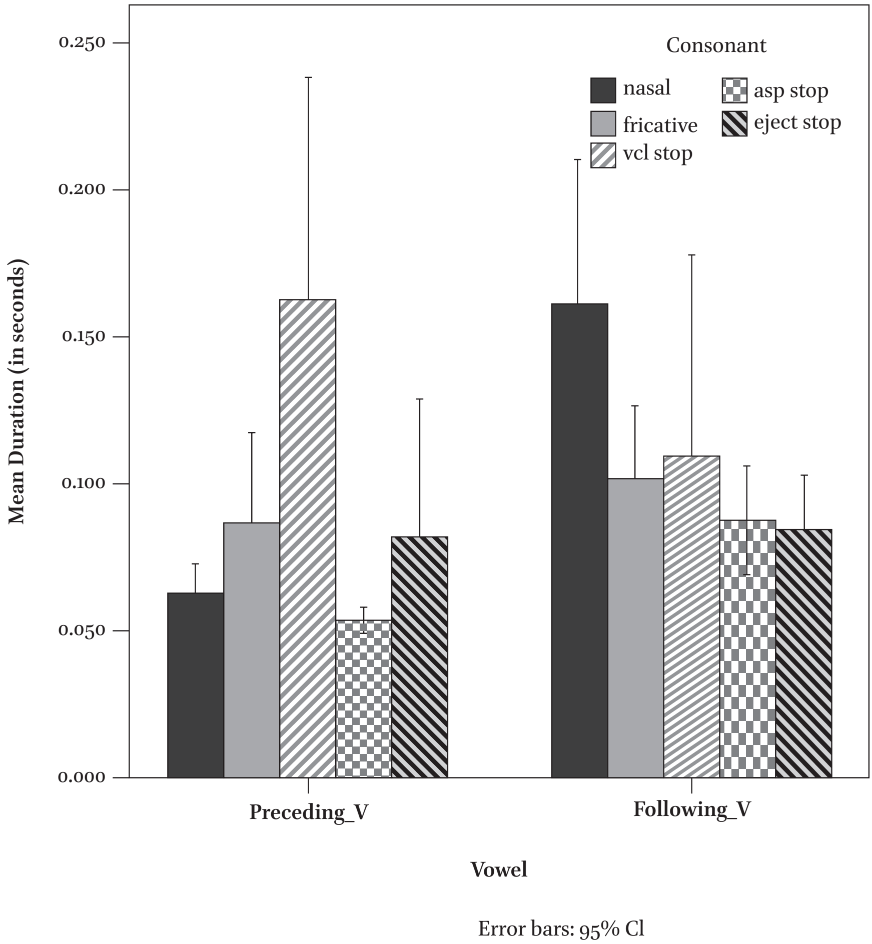

FIGURE 4.10 *Duration values (in seconds) for the vowel preceding and following five different consonant types averaged over two Hupa speakers. Error bars represent 95% confidence intervals.*

high tone and low tone, following voiceless unaspirated /t/, voiceless aspirated /tʰ/, ejective /t'/, fricative /s/, and nasal /n/. All the target vowels appeared in syllables belonging to the stem, which impressionistically is more prominent than affixes, although it is unclear if Western Apache has stress in addition to tone. The vowel preceding the target consonant consistently carried low tone. The corpus thus included the tonal combinations low + low and low + high. There were no instances of high tone /i/ following /n/.

Figure 4.11 (male speakers) and Figure 4.12 (female speakers) depict average F0 values for the post-consonantal vowel at three different time points for

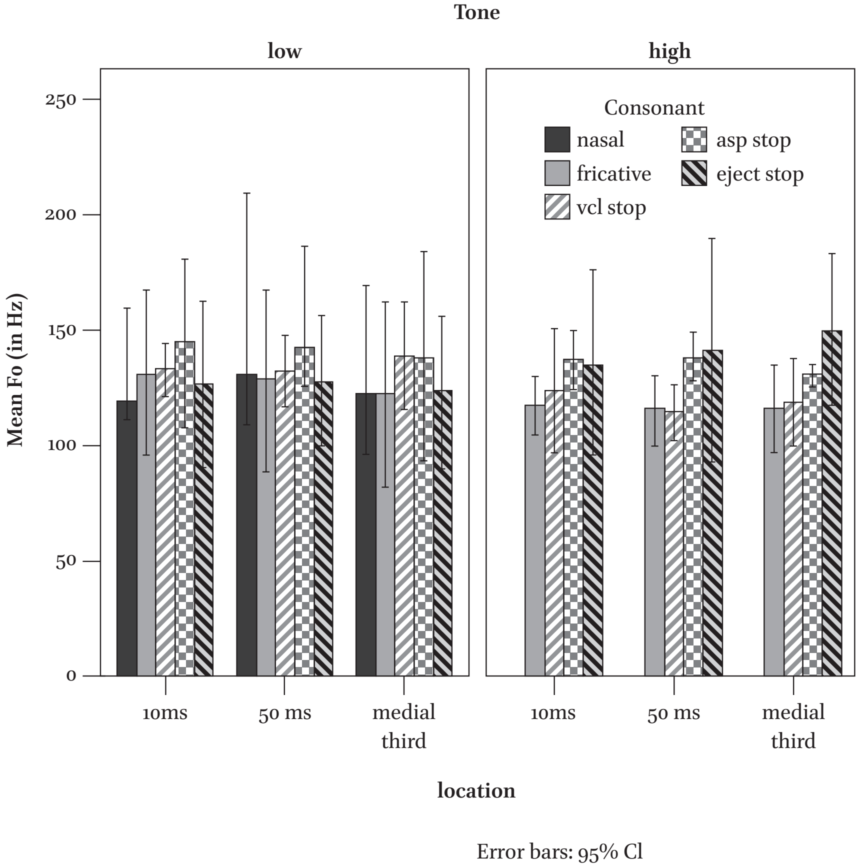

FIGURE 4.11 *Fo values (in Hertz) averaged over two male Western Apache speakers at three points during low tone and high tone vowels following five consonant types. Error bars represent 95% confidence intervals.*

low tone and high tone vowels: ten milliseconds removed from the consonant, fifty milliseconds distanced from the consonant, and over the middle third of the vowel. Figure 4.13 shows mean duration values for the high and low tone vowels collapsed over all four speakers.

Logistic regression models fitted to data points at different distances from the target consonant speakers indicated that only tone but not consonant was a reliable predictor of Fo values for both the male and female speakers. However, for the female speakers, there was an interaction between consonant and tone that approached significance. On high tone vowels, the ejective and aspirated stops triggered raising of Fo with the effect of ejectives persisting

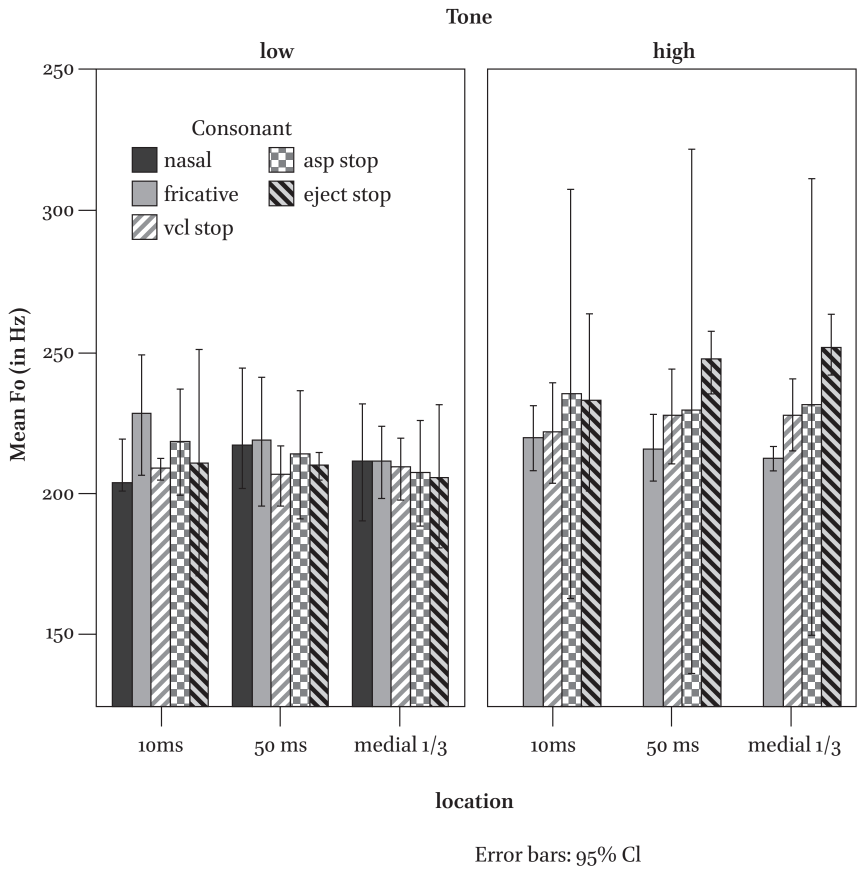

FIGURE 4.12 *Fo values (in Hertz) averaged over two female Western Apache speakers at three points during low tone and high tone vowels following five consonant types. Error bars represent 95% confidence intervals.*

through the middle of the vowel. Voiceless stops and fricatives were associated with lowering of Fo, where the effect of voiceless stops is localized to the very beginning of the vowel. The raising effect of aspirated and ejective stops and the lowering effect of voiceless stops and fricatives for high tone vowels is also observed for male speakers. The effects of the adjacent consonant on vowel Fo is negligible in the case of low tone vowels for both male and female speakers. It is also interesting to note that male speakers do not clearly use Fo to distinguish high and low tone even by the middle of the vowel (except in the case of post-ejective vowels). It is possible that the apparent neutralization of tonal contrasts for the male speakers is due to utterance-final pitch lowering, which might exert a disproportionately large effect on high tone vowels.

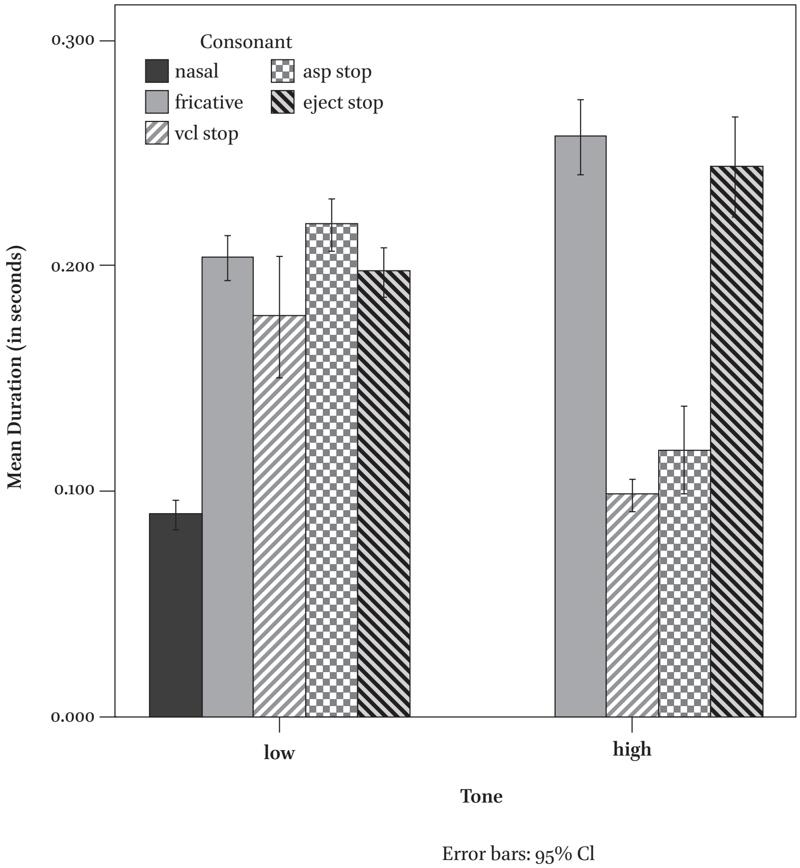

FIGURE 4.13 *Duration values (in seconds) for low tone and high tone vowels preceding and following five different consonant types averaged over four Western Apache speakers. Error bars represent 95% confidence intervals.*

4 Discussion

While some of the hypotheses introduced earlier in the paper were confirmed in the present experiment, at least to some extent, other results are somewhat surprising in light of expectations based on other studies.

4.1 *Consonant Type and Fo*

Looking first at the relationship between consonant type and Fo, the predicted lowering of Fo in the vicinity of voiced stops relative to voiceless ones was observed only in a rather limited capacity. In Pirahã, this effect was apparent only for female speakers on high tone vowels. Male speakers of Pirahã failed to show Fo lowering induced by voiced stops. Nor was there any voicing-induced lowering of Fo on low tone vowels for Pirahã female speakers. Only two of the four Banawá speakers displayed any interaction between voicing and Fo with two speakers showing higher Fo values on vowels after voiceless stops compared to voiced ones and only early in the following vowel and not in the preceding vowel.

A more robust and consistent effect on Fo was associated with spread glottis consonants including fricatives and, in the two languages possessing them, aspirated stops. Pirahã showed a raising of Fo on both high tone and low tone vowels following fricatives for female speakers, although not for male speakers. The Hupa male speaker also displayed a raising effect of fricatives on Fo. The female Hupa speaker had higher Fo values following a fricative than following a voiceless unaspirated stop for the third of the vowel closest to the fricative. The female speakers of Western Apache also displayed higher Fo values adjacent to a fricative compared to after a voiceless stop, although this effect was limited to low tone vowels and diminished by a point fifty milliseconds removed from the fricative. Only the Banawá data failed to show raising of Fo by fricatives. A trend was observed for voiceless aspirated stops to exert a raising effect on Fo in the two languages with these two consonant types, Hupa and Western Apache. This effect was not found, however, in low tone vowels for the female Western Apache speakers and not in the preceding vowel for the male Hupa speaker.

The tendency for aspirated stops to raise Fo in adjacent vowels is consistent with results from Korean (Kim, Beddor, and Horrocks 2002, Silva 2006) and with Cantonese data presented by Zee (1980). There are at least two possible explanations for the raising of Fo triggered by aspirated stops and fricatives. Stevens (1998) suggests that increased vocal fold stiffness is necessary at the beginning of aspirated consonants to counteract the vocal fold abduction triggered by the increased intraoral pressure associated with aspirated consonants. Silva (1988) hypothesizes that increased transglottal airflow associated with aspiration is responsible for the raising effect on Fo by aspirated consonants.

These accounts are compatible with the raising effect on Fo associated with fricatives in the data examined here. Like aspirated stops, fricatives are also produced with high transglottal airflow due to the abducted glottis, which could trigger antagonistic vocal tensing gestures to allow voicing of the vowel(s) adjacent to the fricative. The fact that aspirated stops are characteristically associated with greater raising of Fo in adjacent vowels than fricatives in Hupa and Western Apache suggests a higher rate of transglottal airflow for aspirated stops in these two languages. If true, this would not be surprising given that stops but not fricatives participate in an aspiration contrast in both languages.

The raising effect of fricatives and aspirated stops on Fo is not consistent, however, either in the data examined here, as discussed above, or even cross-linguistically. Xu and Xu (2003) find that aspirated stops trigger lowering of F0 in a following vowel in Mandarin, while Cantonese data in Francis et al. (2006) indicate a similar lowering effect on F0 associated with aspirates, in contradiction to Zee's (1980) Cantonese results. Downing and Gick (2001) cite Mathangwane's (1999) study of Botswana Kalang'a showing a link between greater aspiration duration and tone-depressor effects. Similarly, Erickson (1975) observes interspeaker variation in the effect of aspiration on F0 in Thai: certain speakers display higher F0 values following aspirated stops relative to unaspirated ones, while others show the opposite effect. As Downing and Gick (2001) suggest, the interspeaker and the interlanguage variation in the relationship between spread glottis consonants like fricatives and aspirated stops indicates the possibility of different articulatory and aerodynamic conditions being involved in the production of these two consonant types. Tang (2008) suggests that lowered air pressure, presumably below the glottis, may be responsible for the lowering effect on F0 by spread glottis sounds found in some data. The interaction between aspiration and phonemic tone found in the Western Apache female speaker data such that aspirated stops raise F0 only in high tone vowels point to the complexity of the relationship between the spread glottis configuration associated with aspirated consonants and the laryngeal gestures associated with a vowel's tonal target.

Ejectives also tended to trigger raising of F0 in the two examined languages with ejectives, Hupa and Western Apache. The one exception to this generalization is the finding that low tone vowels adjacent to ejectives were realized with *lowered* F0 by Western Apache male speakers, although it should be borne in mind that there was no statistically robust effect on F0 by consonant type in the Western Apache data for the male speakers. Kingston (2005) offers an articulatory explanation for this variation in the relationship between F0 and ejectives, which has led to salient divergences in tonogenesis patterns even between closely related languages in the Athabaskan family. On the one hand, glottalization may be articulated with increased tension of the vocal folds, which can trigger raising of F0. On the other hand, another realization of glottalization, characteristically described as "creak", may not be associated with this compression and may instead trigger lowering of F0. The interaction between phonemic tone on the vowel and ejectives in the Western Apache data from male speakers suggests that different articulatory and perhaps aerodynamic strategies might be employed by the same speaker in different tonal contexts in order to accommodate the realization of lexically contrastive tonal information. More generally, the observed differences across languages and across speakers within languages suggest considerable variation in the phonetic implementation strategies employed in the production of consonants.

4.2 *Directionality*

Directionality was not a particularly important factor in predicting the effect of consonant type on F0 in the examined data. There was a slight asymmetry in the Banawá data such that voicing affected the following more than the preceding vowel for the two speakers showing any effect of consonant on F0. In Hupa, the other language for which both the preceding and following vowel were measured, there were not any clear differences in the relative magnitude of the influence of consonant on the following vowel as opposed to the preceding vowel. The most interesting directional asymmetry involved aspiration in Hupa, which was associated with F0 raising in the following vowel but lowering in the preceding one. This result is perhaps not surprising given the different aerodynamic conditions present going into a consonant constriction as opposed to at the release. The effect of a spread glottis gesture on a preceding vowel is that of breathiness, which is consistently associated with lowered F0 cross-linguistically (Hombert et al. 1979). During the constriction, on the other hand, pressure builds up potentially creating the aerodynamic and articulatory conditions discussed above that may give rise to heightened F0.

4.3 *Phonemic Tone vs. Subphonemic F0 Perturbations*

The present experiment yielded other results that were not predicted a priori. First, there was no consistent tendency for consonant-induced F0 perturbations to be smaller in the two languages with phonemic tone than in the two without despite expectations that the high functional load of F0 in conveying phonemic contrasts in tone might inhibit subphonemic effects attributed to consonants. The language displaying the least effect of consonant on F0, Banawá, lacks phonemic tone, while Pirahã, which possesses tone contrasts on vowels, evinced the most robust effect of consonant on F0. This lack of a difference between languages as a function of the role of tone is rather unexpected given Hombert et al.'s (1979) finding that the temporal duration of F0 perturbations triggered by a preceding consonant is shorter in tonal Yoruba compared to non-tonal English. However, the present results mirror data presented in Frazier (2009) for two dialects of Yucatec Maya. She found that consonants actually tended to be differentiated more in terms of their effect on F0 in adjacent vowels in the western dialect, which has contrastive tone, than in the eastern dialect, which lacks tone. The fact that phonemic tone appears not to inhibit consonant-triggered F0 perturbations suggests that speakers are adept enough at normalizing F0 as a function of consonant context to allow for a sufficiently perceptible realization of tonal contrasts. On the other hand, certain interactions between phonemic tone and consonant-induced effects on F0 observed in the present work and the Frazier (2009) study suggest some sensitivity of speakers to the relationship between vowel tone category and the effect of consonants on F0. Thus the effect of consonant type on F0 differed for some consonants depending on tone type in both of the tonal languages examined here. For examples, voiceless stops induced a stronger lowering effect on F0 in low tone vowels than in high tone vowels in Pirahã, and ejectives induced F0 lowering on low tone vowels but F0 raising on high tone vowels for male speakers of Western Apache. Further research on F0 in a broader cross-section of tonal and non-tonal languages could shed more light on the nature of the relationship between phonemic tone and consonant-induced F0 perturbations.

4.4 *Gender*

Another finding of the present study is that female speakers generally had a stronger effect of consonant on F0 than male speakers. Thus, consonant type had an overall statistically robust effect on F0 for female speakers but not for male speakers in Pirahã and, to a lesser extent, in Western Apache. Nor did consonant reliably influence F0 for the male speakers in Banawá, although it is impossible to determine whether this result is an effect of language or gender since all the Banawá speakers in the present experiment were male. In general, it is difficult to assess the robustness of the observed divergence between male and female speakers in all the examined languages for which data from both genders were collected since the F0 trends are largely similar for the two genders even if the effect of consonant on F0 is more pronounced for the female speakers. The most salient difference between genders appears to be the lowering of F0 in low tone vowels after ejectives for male speakers in Western Apache contrasted with the raising of F0 in the same context for female speakers. This difference plausibly reflects a genuine difference between genders since creakiness, which is often associated with vowels adjacent to ejectives, has a lowering effect on F0 and also is known to be gender dependent, where creak traditionally is more canonically associated with male speech (Henton and Bladon 1988; but see Yuasa 2010 and Podesva and Lee 2010 for contrary results). The gender-dependence of the effect of creakiness on F0 is demonstrated by results of Frazier's (this volume) study of glottalization in Yucatec Maya. She finds that glottalized vowels, which contrast with modal voiced vowels, are variably realized with different degrees of creakiness. In tokens without creakiness, F0 values are comparable between female and male speakers whereas, in tokens with a creaky realization, F0 patterns diverge between the two genders. In the case of Western Apache, low tone might be articulatorily compatible with creak, which might be more characteristic of male speech than female speech in Western Apache. This speculative hypothesis warrants further investigation for a larger number of speakers.

5 Conclusion

Data from four languages examined in this chapter is consistent with recent research demonstrating the non-universality of F0 perturbations induced by consonants. The most consistent effect on F0 attributed to consonants was the raising of F0 by ejectives and by spread glottis consonants such as aspirated stops and fricatives. Even this result, however, was subject to counterexamples dependent on factors such as language, gender, directionality, and tone. Female speakers generally displayed greater F0 perturbations triggered by consonants than males, although this result was also sensitive to interactions with other properties such as tone and the location of the vowel relative to the consonant. Interestingly, the hypothesis that microprosodic effects on F0 would be smaller in languages with phonemic tone was not confirmed, at least not in its simplest form. Rather, results suggest a more complex relationship between phonemic tone and subphonemic F0 perturbations. Overall the considerable variation in the F0 data both within and across languages is consistent with the view that the both phonemic tone and consonants may be phonetically implemented in different ways with correspondingly varied effects on fundamental frequency.

References

Boersma, P. and D. Weenink. 2010. *Praat: Doing phonetics by computer* (version 5.1.42) (www.praat.org).

Bradshaw, M. 1999. *A Crosslinguistic Study of Consonant-Tone Interaction*. PhD diss., Ohio State University.

Buller, B., Buller, E. and Everett, D. 1993. Stress placement, syllable structure, and minimality in Banawá. *International Journal of American Linguistics* 59, 280–293.

Downing, L.J., and Gick, B. 2001. Voiceless tone depressors in Nambya and Botswana Kalang'a. *Proceedings of Berkeley Linguistics Society* 27, 65–80.

Erickson, D. 1975. Phonetic implications for a historical account of tonogenesis in Thai. In *Studies in Tai Linguistics in Honor of W.J. Gedney*, ed. J.G. Harris and J.R. Chamberlain, 100–111. Bangkok: Central Institute of English Language Office of State Universities.

Everett, D. 1986. Pirahã. In *Handbook of Amazonian Languages* vol. 1, ed. D. Derbyshire and G. Pullum, 200–325. New York: Mouton.

Francis, A.L., Ciocca, V., Wong, V.K.M., and Chan, J.K.L. 2006. Is fundamental frequency a cue to aspiration in initial stops? *The Journal of the Acoustical Society of America* 120, 2884–2895.

Frazier, M. 2009. Tonal dialects and consonant-pitch interaction in Yucatec Maya. In *New Perspectives in Mayan Linguistics*, ed. H. Avelino, J. Coon, and E. Norcliffe, 59–82. WPLMIT 59: Cambridge, MA.

———. this volume. Pitch and glottalization as cues to contrast in Yucatec Maya.

Golla, V. 1970. *Hupa Grammar*. PhD diss., University of California, Berkeley.

Henton, C.G. and Bladon, R.A.W. 1988. Creak as a sociophonetic marker. In *Language, speech, and mind: Studies in Honor of Victoria A. Fromkin*, ed. L. Hyman, V. Fromkin and C. Li, 3–29. Beckenham, Routledge.

Hombert, J.-M., Ohala, J., and Ewan, W. 1979. Phonetic explanations for the development of tones. *Language* 55, 37–55.

Kim, M.-R., Beddor, P.S., and Horrocks, J. 2002. The contribution of consonantal and vocalic information to the perception of Korean initial stops. *Journal of Phonetics, 30*, 77–100.

Kingston, J. 2005. The phonetics of Athabaskan tonogenesis. In *Athabaskan Prosody*, ed. S. Hargus and K. Rice, 137–184. Amsterdam: John Benjamins.

Lewis, M. Paul (ed.). 2009. *Ethnologue: Languages of the World, Sixteenth edition*. Dallas, TX: SIL International. Online version: http://www.ethnologue.com.

Pike, E.V. 1986. Tone Contrasts in Central Carrier (Athapaskan). *International Journal of American Linguistics* 52, 411–418.

Podesva, R. and Lee, S. 2010. Voice quality variation and gender in Washington, DC. Paper presented at NWAV 39. San Antonio, Texas.

Silva, D.J. 1998. The effects of prosodic structure and consonant phonation on vowel F0 in Korean: An examination of bilabial stops. In J.R.P. King and S.R. Ramsey (eds.), *Progress in Korean linguistics*, pp. 1–23. Ithaca, NY: Cornell University Press.

Stevens, K.N. 1998. *Acoustic Phonetics*. Cambridge: MA: MIT Press.

Tang, K.E. 2008. *The Phonology and Phonetics of Consonant-Tone Interaction*. PhD diss., UCLA.

Xu, C. and Xu, Y. 2003. Effects of consonant aspiration on Mandarin tones. *Journal of the International Phonetic Association* 33, 165–181.

Yuasa, I.P. 2010. Creaky voice: a new feminine voice quality for young urban-oriented upwardly mobile American women. *American Speech* 85, 315–337.

Zee, E. 1980. The effect of aspiration on the F0 of the following vowel in Cantonese. *UCLA Working Papers in Phonetics* 49, 90–97.

Appendix: Corpora for the Four Languages (Measured Vowels in Bold)

Banawa

Cons	Word	Gloss
t	bat**a**	'rotten'
	kit**i**	'small'
d	bad**a**	'name'
	bid**i**	'small'
m	bam**a**	'catfish'
	kim**i**	'corn'

s	b**a**s**a**	‘to put a stick up high’
	k**i**s**i**	‘to descend’

Pirahã

Cons	Word	Gloss
p	p**á**ˈʔai	‘fish’
	ʔáːp**a**ˈhai	‘bird arrow’
	kohoˈaip**í**	‘eat’
	hoˈaip**i**	‘name’
b	b**á**giˈái	‘thief’
	ab**a**ˈgi	‘toucan’
	ˈsab**í**	‘angry, mean’
	kaiˈtiab**i**	‘buzzard’
s	ʔíˈsiːs**í**	‘fat, body oil’
	taːˈhoas**i**	‘sand’

Hupa

Cons	Word	Gloss
t	n**a**ˈt**ɪ**l	‘they go about’
	ʍ**ɪ**ˈt**a**ʔ	‘my mouth’
tʰ	m**ɪ**ˈtʰ**ɪ**s	‘through it’
	ʍ**ɪ**ˈtʰ**a**ʔ	‘my father’
t’	t’**e**	‘blanket’
	ʍ**ɪ**ˈt’**a**h	‘my pocket’
s	ʍ**ɪ**ˈs**ɪ**ts’	‘my skin’
	n**ɪ**ˈs**a**t	‘it is deep’
n/m	tʃ**ɪ**ˈm**e**l	‘lizard’
	ʍ**ɪ**ˈn**aː**ʔ	‘eye’

Western Apache

Cons	Word	Gloss
t	p**ɪ**ʔ**aː**t**í**	‘it’s female’
	p**ɪ**t**ɪ**ɬ	‘his blood’
tʰ	nagotʰ**íː**h	‘I hope it will rain’
	pɪhastʰ**iː**n	‘her old man’
t’	hat’**íː**ko	‘he wants’
	pɪt’**iː**s	‘cottonwood tree’
s/x	j**ɪ**z**ɪ**sx**íː**	‘He killed it’
	h**ɪ**s**iː**	‘I missed it’
n	p**ɪ**n**ɪ**ʔ	‘his land’