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TONAL DIALECTS AND CONSONANT-PITCH INTERACTION IN YUCATEC MAYA*

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1 Introduction

The phonemic inventory of Yucatec Maya includes vowels that contrast on the basis on length, pitch, and glottalization. Though these contrasts have been extensively described in the literature (going back at least to Pike 1946), there is to date no thorough acoustic documentation of this system. The first goal of this paper is thus to provide such documentation; the second goal is to measure the effects of different consonant types on the realization of fundamental frequency (F_0, the acoustic correlate of pitch) in adjacent vowels. Again, the literature is generally robust in this area (see Hombert 1978 and Hombert et al. 1979 for early reports), and it has been demonstrated repeatedly that consonants can have a significant effect on vowel pitch. However, there is little known about the effect of implosives on pitch: do they pattern with other voiced sounds (as pitch depressors) or with other glottalized sounds like ejectives (which cause an increase in pitch)?

The results of this acoustic study show that the previous literature has been fairly accurate in its description of the vowel system of Yucatec Maya, though there are some adjustments to be made. One surprising

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result is that tone may be a dialectal feature of Yucatec Maya, as shown by data collected from participants in three different towns in Yucatan, Mexico. Participants from one town (Sisbicchén) do not produce a tonal contrast, while the tonal contrast is clear in the speech of participants from the other two towns (Mérida, Santa Elena). With regard to consonant-pitch interaction, this paper presents evidence that implosives pattern with voiced sonorants in that they are associated with lower F_0 on a following or preceding vowel.

This paper proceeds as follows. I present relevant background information in §1, including details about the phonemic system of Yucatec Maya as well as a discussion of what is known about implosives and pitch. Experimental methods are presented in §2. Results with regard to the vowel system in general (vowel length, glottalization, and pitch) are presented in §3. In §4 I then discuss how adjacent consonants affect pitch. Conclusions follow in §5.

1.1 Language Description

Yucatec Maya (henceforth YM) is a Mayan language spoken by about 700,000 people in Mexico (Yucatan, Quintana Roo, and Campeche) and Belize (Gordon 2005). The consonantal phonemes of the language are shown in Table 1; here we see that YM has voiceless stops, affricates, fricatives, and ejectives, as well as voiced sonorants and an implosive. Note that the language has no plain voiced obstruents and that [ɓ] is represented by an unadorned <b> in the orthography.[1]

Five vowel qualities are contrastive in YM. Additionally, YM utilizes a four-way contrast on the basis of length, tone, and glottalization. I will refer to contrasts based on this set of suprasegmental features as *vowel shape*.[2] In (2), we see the four vowel shapes (SHORT, LOW TONE, HIGH TONE, and GLOTTALIZED) as commonly described in the literature. Throughout this paper small capital letters denote the specific vowel shapes of YM so that these vowel shapes are not confusable with general

[1] In general, the orthography of YM accurately reflects the pronunciation of a word. All vowel initial spellings denote words that actually begin with a glottal stop, e.g. *ook* 'foot' is pronounced [ʔook]. Note the following correlations between IPA and the orthography of the language (as adopted by the communities who use and teach YM): [ɓ] = b; [ʔ] = '; [tʃ(')] = ch('); [ʃ] = x; [h] = j; [j] = y.

[2] "Vowel complexity" (Roffe 1946) has been used to refer to suprasegmental contrasts, but this term is ambiguous because it also refers to diphthongs and triphthongs.

phonological properties (i.e. “HIGH TONE” denotes a YM vowel shape, whereas “high tone” denotes phonological high tone).

		labial	alveolar	post-alveolar	palatal	velar	glottal
stops	voiceless	p	t			k	ʔ
	ejective	p’	t’			k’	
	implosive	ɓ					
affricates	voiceless		ts	tʃ			
	ejective		ts’	tʃ’			
fricatives			s	ʃ			h
nasals		m	n				
lateral approximants			l				
approximants		w			j		

Table 1: Consonantal Phonemes of YM (Bricker et al. 1998)

quality:	shape (applies to any vowel quality):	
i u	v	SHORT: short, unmarked for tone, modal voice
e o	v̀v	LOW TONE: long, low tone, modal voice
a	v́v	HIGH TONE: long, high tone, modal voice
	v́ʔv	GLOTTALIZED: two short vowels (the first with high tone) interrupted by a glottal stop

Table 2: Vocalic phonemes of YM (Bricker et al. 1998)

(1) Minimal quadruplet for vowel shape (Bricker et al. 1998)

	example		orthography
SHORT	chak	‘red’	v
LOW TONE	chaak	‘boil’	vv
HIGH TONE	cháak	‘rain’	v́v
GLOTTALIZED	cha’ak	‘starch’	v’v

This system of vowel contrasts as been thoroughly described in the literature (e.g. Pike 1946, McQuown 1975, Blair and Vermont Salas 1965 (henceforth B&VS), Fisher 1976, Bricker et al. 1998), and there is general agreement about descriptions of pitch contours and glottalization. The SHORT vowel is described as having neutral tone, meaning SHORT vowels do not participate in a tonal contrast (B&VS: 7), while the LOW TONE vowel is described as having low and level pitch (B&VS: 9, Pike

1946: 84). Accounts of HIGH TONE and GLOTTALIZED vowels are more detailed. B&VS claim that HIGH TONE has different realizations depending on the position of the syllable that bears high tone in the word: HIGH TONE vowels in final syllables (including monosyllables) start with high pitch which falls throughout the duration of the vowel, whereas vowels in nonfinal syllables do not fall in pitch in the same way. The GLOTTALIZED vowels are unanimously described as being interrupted by a glottal stop, though B&VS and Bricker et al. (1998) recognize that this glottal stop does not always have a full realization, especially in rapid speech.

Though previous literature is descriptively rich, it is lacking in experimental data. There is thus no thorough acoustic documentation or testing of the vowel system. In the remainder of this section I discuss what acoustic evidence is provided by previous literature.

The oldest source with some acoustic data is Fisher (1976). In his paper, there are some graphs of pitch contours (taken from the language learning tapes of B&VS). These graphs do show HIGH TONE to be realized as described by B&VS: final syllables are distinguished by falling pitch and nonfinal syllables are distinguished by rising pitch. However, Fisher does not supply any numeric data or statistical analysis.

There are several newer sources that have looked at parts of the tonal system of YM: Avelino et al. (2007), Gussenhoven and Teeuw (2008), and Kügler et al. (2007). The narrow scope of these studies means their results are not generalizable to the entire vowel system, but Avelino et al. present some interesting findings that are relevant here. They identify three types of GLOTTALIZED vowels: those with a full glottal stop between two vowels, those with creaky voice that interrupts a vowel with modal voice, and those with modal voice at the beginning that switches to creaky voice until the end. This is a marked contrast with previous literature that identifies [v́ʔv] as the canonical realization of GLOTTALIZED vowels. B&VS: 96 allude to the use of creaky voice (“a squeezed voice quality”), but Avelino et al. are the first to show acoustic documentation of GLOTTALIZED vowels. The results of this study closely match those of Avelino et al. with respect to glottalization. For this reason, I propose that /v́v̰/ is a better phonological representation of the GLOTTALIZED vowel.

1.2 Implosives and F_0

Consonant-pitch interaction has been studied for (more than) thirty years, and yet there is controversy about implosives in this regard. Recently, Tang (2008) showed that, cross-linguistically, implosives can pattern with either high or low tone in phonological consonant-tone interaction. But what are the phonetic underpinnings of this interaction?

The majority opinion of the literature is that implosives are correlated with high F_0 (Hyman and Schuh 1974, Ohala 1973, Odden 2005, Demolin 1995). However, the only work, to my knowledge, that studies the interaction between implosives and pitch through experimentation and statistical analysis is Wright and Shryock (1993), who found that, in SiSwati, the implosive [ɓ] is associated with significantly lower F_0 (in the following vowel) than the voiceless aspirated stop [p^h] but with significantly higher F_0 than the nasals [m] and [m̤]. The results of the present study will show that in YM, implosives are again associated with lower pitch than voiceless sounds, though they behave identically to voiced sonorants.

2 Experimental Methods

2.1 Participants

Twenty-four participants were recruited from three cities in Yucatan, Mexico: Mérida (capital of Yucatan), Santa Elena (about 65 km south of Mérida), and Sisbicchén (about 160 km east of Mérida). Table 3 provides more information about the participants.

<table>
<tr><th></th><th></th><th>ages</th><th>additional languages</th></tr>
<tr><td rowspan="2">Mérida</td><td>6 males</td><td>33, 39, 40, 41, 47, 47</td><td rowspan="2">fluent in Spanish, one male also proficient in English</td></tr>
<tr><td>1 female</td><td>39</td></tr>
<tr><td rowspan="2">Santa Elena</td><td>5 males</td><td>22, 25, 43, 63, 68</td><td rowspan="2">fluent in Spanish, one male and one female also fluent in English</td></tr>
<tr><td>7 females</td><td>19, 20, 25, 30, 33, 35, 63</td></tr>
<tr><td rowspan="2">Sisbicchén</td><td>2 males</td><td>30, 41</td><td>fluent in Spanish</td></tr>
<tr><td>3 females</td><td>24, 29, 30</td><td>understand Spanish, but do not use it</td></tr>
</table>

Table 3: Participant data

2.2 Stimuli

Participants were recorded while they read 100 words. The wordlist was composed of mostly C_1VC_2 words (C_1 and C_2 were sometimes identical) and was balanced on the basis of vowel shape and consonant type.[3] The consonant types were glottal stop [ʔ], ejective [p’, t’, k’, ts’, tʃ’], implosive [ɓ], voiceless obstruent [p, t, k, ts, tʃ, s, ʃ], and voiced sonorant [m, n, l, w, j]. All four vowel shapes were used. Each word matched one possible combination of C_1 type, V shape, C_2 type (5 x 4 x 5), giving 100 words. The full wordlist is in Appendix A. For ease of exposition, I will henceforth refer to C_1 as the onset consonant and C_2 as the coda consonant (even though not all C_2’s are actually codas, due to some polysyllabic target words, as discussed below).

The wordlist was balanced on the basis of C_1 type, vowel shape and C_2 type to eliminate potential confounds. For example, effect of onset can be evaluated independently of vowel shape and coda type because each onset type occurs with the other types equally. In order to maintain the balanced wordlist, some nonce forms were used. Though all 100 forms required to complete the wordlist utilize legal phonotactics, there are lexical gaps that were filled in with nonce forms. For example, there is no existing monosyllabic YM word of the form glottal stop - GLOTTALIZED vowel - glottal stop, so the nonce form *a’a’* [ʔáa̰ʔ] is used. When more than one existing word of a certain form could be found, the word used in the study was chosen on the basis of the following criteria (in order of importance): grammatical category (nouns and adjectives preferred, then nonclitic function words (e.g. *ich* ‘in’, *bíin* ‘*future aspect*’); verbs avoided due to grammatical tone (Avelino et al. 2007))[4], familiarity of word (highly familiar words, as rated by a native speaker, chosen over less familiar words), consonant type (stops chosen over affricates (for both ejectives and voiceless obstruents), [p’] avoided (because it is a weak ejective), [w, j] avoided (for ease of segmenting the speech stream into phones)). All words appear in Bricker et al. (1998) and/or *Diccionario Maya Popular* (2004). Furthermore, all words chosen for the wordlist were

[3] All participants said the word *k’aaba’* ‘name’, where measurements were taken from the final syllable [ɓaʔ]. This was the only disyllabic word used for all participants. It was included because there was no existing monosyllable of the form implosive - SHORT vowel - glottal stop, and because the relevant syllable is in final position.

[4] When no other common word could be found, a verb was used if it was a frequent lexical item (as judged by a native speaker) and had an easily identifiable root (see Bevington 1995 for a brief description of YM verbal morphology and Briceño Chel 2006, Ayres and Pfeiler 1997 for detailed discussion). All verbs used in this study meet this criteria: *e’es* ‘show’, *a’al* ‘say’, *éem* ‘descend’, *u’ub* ‘hear’, *maan* ‘buy’, *beet* ‘make, do’, *bin* ‘go’.

deemed to be in common usage by a native speaker (Santiago Domínguez, from Santa Elena).

There is an aspect of the dialect spoken in Santa Elena (and other areas nearby) that affected the wordlist used for this group of speakers. In this dialect, the implosive is banned in coda position, and so words such as *ta'ab* 'salt' are pronounced with a glottal stop in place of the implosive ([tá̰a̰ʔ]). The implosive is produced when followed by a vowel, and so *ta'abo'* 'that salt' is pronounced [tá̰a̰ɓoʔ]. For this reason, the wordlist for speakers from Santa Elena was amended such that words ending in the implosive are affixed with a vowel initial suffix (if possible), i.e. the form CVɓ becomes CVɓVC. For most words, which are nouns, the far deixis marker *-o'* provides a suitable addition. In some cases, other affixes are used, and in other cases, no affix was available (and so a nonce form had to be used). Additionally, if there was no CVɓ form of a certain type, sometimes there was a monomorphemic CVɓVC form that could be used in the Santa Elena wordlist. For these reasons, there are cases where the Santa Elena wordlist contains a nonce form where the general wordlist contains an existing form and vice versa. (The Santa Elena wordlist contains 16 nonce forms and the general wordlist contains 14 nonce forms.)

Given the claims from previous literature that pitch has a different realization in final syllables than in nonfinal syllables, the wordlist for Santa Elena speakers includes a potential confound. However, statistical analysis of the data collected from Santa Elena speakers yields mostly nonsignificant results when pitch in final syllables (for a particular vowel shape) is compared to pitch in nonfinal syllables (for the same vowel shape).[5] For this reason, syllable position will be ignored in the discussions of pitch in §3 and §4.

2.3 Recording Procedures and Extraction of Measurements

Participants read each word from the wordlist in isolation and in a random order. A frame sentence was not used because the goal of this study is to analyze the phonetics of the "citation" forms of the four vowel shapes and

[5] SHORT vowels did show a significant effect of syllable position, with final syllables having higher pitch than nonfinal syllables. However, since all and only nonfinal syllables end with the implosive, this fact is likely explained as an effect of consonant type and not an effect of syllable position. See §4 for discussion of the effect of the implosive on pitch.

in order to extract away from all other prosodic and syntactic factors. Each word was printed on a note card. For an existing form, the card contained the target word in standard orthography in large print with the Spanish equivalent of the word in smaller print below. The Spanish translation was given because most participants had more reading experience with Spanish and in order to prevent orthographic misunderstandings. For example, a reader should be less likely to mistake *k'a'an* (with a GLOTTALIZED vowel) for *k'áan* (with HIGH TONE) if *k'a'an* is printed alongside *fuerte* 'strong' (as opposed to *k'áan* 'hammock'). With nonce forms, each card contained the target word in standard orthography in large print with an existing word containing the same vowel shape in smaller print below. This format was again designed to prevent misinterpretation.

There was a brief training and practice session before recording began. The participant reviewed the correlation between orthography and vowel shape and then read a few test note cards, containing both existing and nonce forms. The recording session was divided into two sections: existing forms were presented first, followed by a break during which the participant was asked if they had any questions, and then nonce forms were presented. Throughout the session, participants were encouraged to ask questions if necessary and to repeat the word as many times as they wished if they were not happy with the original pronunciation. In all, participation took about 20 minutes and participants were compensated for their time.

Recordings were made with an IBM laptop (running PRAAT (Boersma and Weenink 2006)) and a head-mounted microphone (Radio Shack product 33-3012) at a sampling frequency of 44.1 kHz. All measurements were extracted from the recordings using PRAAT. For each target word, the boundaries of the vowel were demarcated so that length could be calculated, and pitch values were extracted at 10 ms intervals for the duration of each vowel. Each vowel was coded for glottalization type. Vowels were produced with modal voice (no glottalization), creaky voice (during some portion of the vowel), or a full glottal stop. The coding of a vowel as one of these categories was based on observance of a spectrogram and waveform (see Gordon and Ladefoged 2001). A full glottal stop was evidenced by a period of (relative) silence greater than 20 ms, while creaky voice was evidenced by widely spaced (and often irregularly spaced) pitch periods with relatively weak intensity (see Fig. 1 for examples).

3 Description of the Vowel System

3.1 Vowel Length

In Table 4 we see the average vowel lengths for the four vowel shapes. It is clear from this table that the HIGH TONE, LOW TONE, and GLOTTALIZED vowels are all long vowels, each almost twice as long as the SHORT vowel. All differences in vowel length between two vowel shapes are statistically significant ($p < .0001$) except GLOTTALIZED vowels vs. HIGH TONE vowels.[6] Cross-linguistically, low tone tends to be associated with longer vowel duration than high tone, and contour tones tend to be associated with longer vowel duration than level tones (Gandour 1977). It is therefore interesting that both GLOTTALIZED and HIGH TONE vowels (those vowels that start with relatively high F_0) are significantly longer than LOW TONE vowels. The lengths of these vowels in YM fit with the general pattern if we consider that they are indeed contour tones – starting with high F_0 and ending with low F_0 – while the LOW TONE vowel is produced with level pitch.

vowel shape	mean length (ms)	standard deviation
GLOTTALIZED	216	71.8
HIGH TONE	212	73.0
LOW TONE	198	77.0
SHORT	113	51.7

Table 4: Mean vowel length by vowel shape

	mean length (ms)			
vowel shape	nonce form	existing form	t	p
GLOTTALIZED	256	203	9.3	<.0001
HIGH TONE	255	201	9.4	<.0001
LOW TONE	245	190	8.0	<.0001
SHORT	146	109	7.0	<.0001

Table 5: Mean vowel length for nonce forms vs. existing forms

Vowel length is not influenced by gender, and it is only marginally influenced by location. The only significant differences for

[6] Two types of statistical tests are used in this a paper. In this case, and any time the null hypothesis is that there is no difference between two means, a linear mixed regression model is used to account for multiple observations within subjects. When percentages are compared, the Rao-Scott χ^2 is used to account for multiple observations within subjects.

location are that SHORT vowels are longer in Santa Elena ($\bar{x}$ = 119 ms, t = 2.4, p = .02) and Sisbicchén ($\bar{x}$ = 130 ms, t = 2.6, p = .01) than in Mérida ($\bar{x}$ = 88 ms). Vowel length is influenced by whether or not a word exists in the language or is a nonce form. As shown in Table 5, for each vowel shape, vowels are longer in nonce forms than in existing forms.

In Table 6 we see that GLOTTALIZED vowels are longer in final position than in nonfinal position but that SHORT vowels are longer in nonfinal position. The latter is surprising given the well-documented phenomenon of phrase final lengthening (see Selkirk 1984). The data suggests that, in YM, each vowel shape retains its canonical realization in final position and that differences of vowel length are not as robust in nonfinal position (i.e. SHORT vowels are longer and long vowels are shorter).

	mean length (ms)			
vowel shape	nonfinal	final	t	p
GLOTTALIZED	182	229	-4.1	<.0001
HIGH TONE	198	218	-1.9	.06
LOW TONE	191	198	-.7	.49
SHORT	139	114	3.6	.0003

Table 6: Mean vowel length for final vs. nonfinal syllables (Santa Elena speakers only)

As discussed in §3, only the Santa Elena speakers read polysyllabic words, and so these are the only speakers represented in Table 6. Recall that all nonfinal syllables in this wordlist are of the form CVɓ. This means that these vowel length differences could reflect a difference of position or a difference of coda type ([ɓ] vs. all other sounds) or a combination of the two. For speakers from Mérida and Sisbicchén, there is not a robust effect of coda type on vowel length. When testing vowel length in syllables that end with an implosive as compared to those that do not, the only significant result is that LOW TONE vowels are shorter when followed by an implosive than when not (t = -4.1, p < .0001). Based on this result, I conclude that Table 6 most likely indicates a difference of position and not a difference of coda type.

3.2 Glottalization

Generalizing over all participants, 70% of GLOTTALIZED vowels are produced with glottalization. Glottalization is marginally present in other vowel shapes: 17% of HIGH TONE vowels show some form of glottalization, 5% of LOW TONE vowels, and 6% of SHORT vowels. In the rest of this section, I discuss glottalization in only the GLOTTALIZED vowels.

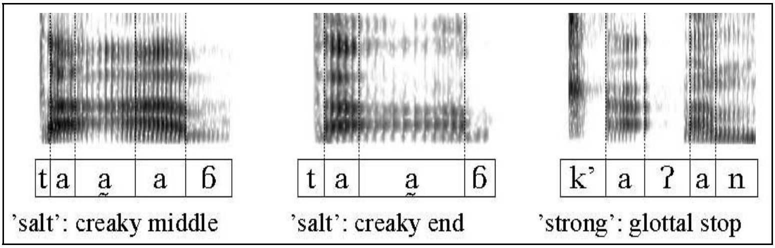

Figure 1: Three common types of glottalization: creakiness in the middle, towards the last half of the vowel, and as a glottal stop. All tokens were spoken by males from Mérida.

The most common types of glottalization match those noted in Avelino et al. (2007): "creaky middle" (modal voice interrupted by creaky voice), "creaky end" (modal voice that changes to creaky voice), and "full glottal stop" (modal voice interrupted by a glottal stop). These three types of glottalization are illustrated with spectrograms in Fig. 1. A small percentage of vowels are produced with creaky voice throughout the duration of the vowel, and some vowels showed glottalization but were not easily classifiable as one of these four types. The distribution of these glottalization types for those GLOTTALIZED vowels that were produced with glottalization is summarized in Table 7.

type of glottalization	
creaky middle	41.2%
creaky end	25.8%
other	18.0%
full glottal stop	12.6%
creaky throughout	2.4%

Table 7: Distribution of glottalization types

Table 8 summarizes the distribution of glottalization type on the basis of gender, location, and existence of word. The effect of gender is not significant. For location, we see some noticeable differences. Mérida speakers are more likely to produce glottalization and more likely to produce a full glottal stop than speakers from Santa Elena or Sisbicchén. About a third of GLOTTALIZED vowels are produced without glottalization in Santa Elena and Sisbicchén. Interestingly, when glottalization is produced, there is a preference for the "creaky middle" type in all locations. The effect of existence of word is also significant: a full glottal stop is more likely to be produced with a nonce form than with an existing form.

		type of glottalization				
		none	creaky middle	creaky end	full ʔ	other
gender	males	28%	28%	21%	8%	14%
	females	31%	30%	15%	9%	15%
	for gender: Rao-Scott $\chi^2 = 1.1$; $p = .89$					
location	Mérida	12%	36%	27%	17%	9%
	Santa Elena	39%	21%	18%	7%	15%
	Sisbicchén	31%	38%	7%	2%	22%
	for location: Rao-Scott $\chi^2 = 26.9$; $p = .0007$					
existence of word	nonce form	26%	23%	17%	19%	16%
	existing form	30%	30%	23%	6%	10%
	for existence of word: Rao-Scott $\chi^2 = 22.6$; $p = .0002$					
		row totals may not equal 100% due to rounding				

Table 8: Type of glottalization by gender, location, and existence of word

The presence of glottalization is correlated with both onset type and coda type, as shown in Table 9. In onset position, implosives, obstruents, and sonorants are more likely to be followed by a vowel with glottalization than ejectives and glottal stops. In coda position, the glottal stop is the most likely to be preceded by glottalization, while ejectives are the least likely. A similar pattern holds for the other vowel shapes: for HIGH TONE, LOW TONE, and SHORT vowels, the vowel is most likely to be produced with glottalization when followed by a glottal stop.

	onset	coda
ejective	63%	48%
glottal stop	62%	86%
implosive	78%	67%
vcls. obstruent	72%	74%
vcd. sonorant	78%	77%
	Rao-Scott $\chi^2 = 20.4$ $p = .0004$	Rao-Scott $\chi^2 = 37.9$ $p < .0001$

Table 9: Percentage of GLOTTALIZED vowels produced with glottalization by onset type and coda type

3.3 Pitch

Fig. 2 shows the average pitch contours (as defined by five normalized time points: initial, 25% of vowel duration, medial, 75% of vowel duration, and final) for groups of participants divided by location and gender (numerical values for means and standard deviations are given in Appendix B). When males are compared to females within each location, there are few differences in the general shape of the pitch contours and the relationships among the pitch contours of different vowel shapes. For example, with Mérida females and males, both SHORT and LOW TONE vowels show low steady pitch, HIGH TONE vowels start with higher pitch and end with the same pitch as LOW TONE vowels, and GLOTTALIZED vowels start with even higher pitch and end with low pitch. The only striking differences based on gender are SHORT vowels in Santa Elena (which have relatively high pitch for females and relatively low pitch for males) and GLOTTALIZED vowels in Sisbicchén (which show a dramatic decrease in pitch in the middle for females but not for males[7]). Because gender does not seem to heavily influence the shapes of and relations among the pitch contours, future graphs will show both genders averaged together.

The pitch contours for Mérida and Santa Elena are very similar, but Sisbicchén presents a marked contrast to both of these locations. All vowel shapes in Sisbicchén show roughly the same rising contour. The distinctions between Mérida/Santa Elena and Sisbicchén are made clear in Fig. 3, where we see graphs that make use of data averaged among all speakers from Mérida and Santa Elena on one hand and Sisbicchén on the other. In the following discussion, I will first address the Mérida/Santa Elena speakers and then the Sisbicchén speakers. For ease of exposition, I will refer to the former group as the "western dialect" and to the latter as the "eastern dialect". These labels are for convenience only and should not be taken as an indication that we can generalize the data presented here to all speakers in the western or eastern part of the peninsula.[8]

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[7] The pitch differences in GLOTTALIZED vowels between males and females from Sisbicchén are related to glottalization, as will be discussed in more detail below (see Fig. 5).

[8] In Frazier (2009), I show that additional speakers from Sisbicchén as well as speakers from two other towns in the eastern part of Yucatan, México (Xocén and Yax Che) produce either the same pitch contours for "LOW TONE" and "HIGH TONE" vowels or produce higher pitch for "LOW TONE" than for "HIGH TONE" vowels. The full details of this study are beyond the scope of this paper, but they suggest that "eastern" and "western" may be somewhat accurate for describing tonal dialects.

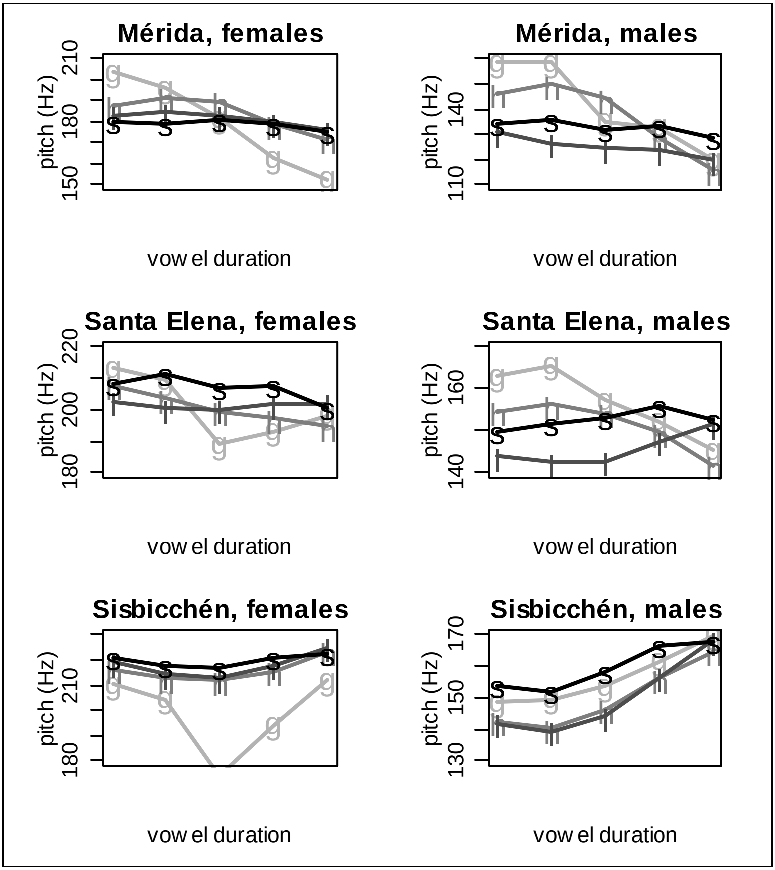

Figure 2: Pitch contours by location and gender.
'g' = GLOTTALIZED; 'h' = HIGH TONE; 'l' = LOW TONE; 's' = SHORT
Vowel duration is normalized.

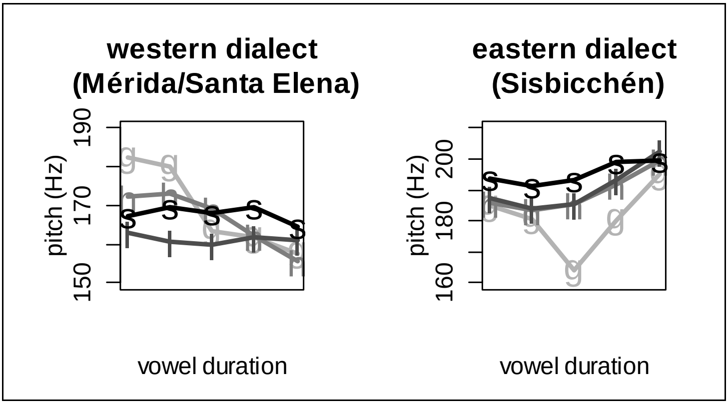

Figure 3: Pitch contours for western and eastern dialect groups
'g' = GLOTTALIZED; 'h' = HIGH TONE; 'l' = LOW TONE; 's' = SHORT
Vowel duration is normalized.

For speakers in the west, we see that each vowel shape is associated with a unique pitch contour, regardless of whether or not that contour is itself contrastive, i.e. tonal. Table 10 summarizes the statistically significant differences among the vowel shapes for each time point. In the table, the "greater than" sign denotes that the vowel shape(s) to the left has an average F_0 (at that particular point) that is significantly greater than the vowel shape(s) to the right. The symbol is used transitively, e.g. for initial pitch, GLOTTALIZED vowels have a significantly higher F_0 than all three other vowel shapes. To summarize Table 10, each vowel shape starts with a distinct F_0, but all vowel shapes end up with some sort of low F_0. The SHORT vowels do not fall in pitch in the same way the long vowels do.

time point	statistically significant differences (p <.01)
initial	GLOTTAL > HIGH > SHORT > LOW
25%	GLOTTAL > HIGH > SHORT > LOW
mid	HIGH, SHORT > GLOTTAL, LOW
75%	SHORT > HIGH, LOW, GLOTTAL
final	SHORT, LOW > GLOTTAL, HIGH

Table 10: Statistical analysis of pitch in western dialect

The high F_0 of GLOTTALIZED vowels is not a correlate of following glottalization. In Fig. 4 we see a comparison between GLOTTALIZED vowels that are produced with glottalization and those that are not. In both cases, the vowel starts with high F_0. This high F_0 is retained when glottalization does not occur, otherwise the glottalization results in characteristic lower F_0.[9] This pattern suggests that GLOTTALIZED vowels are indeed marked for high tone at the phonological level because high pitch cannot simply be a phonetic correlate of following glottalization.

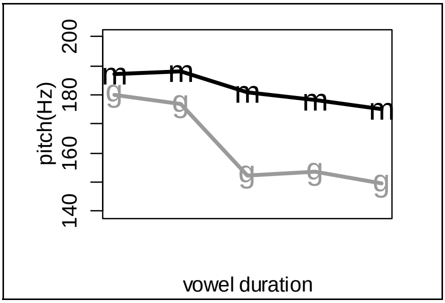

Figure 4: Pitch contours for GLOTTALIZED vowels in western dialect as produced with and without glottalization
'm' = modal voice only (no glottalization); 'g' = with glottalization
Vowel duration is normalized.

time point	statistically significant differences ($p < .05$)
initial	SHORT > GLOTTAL, HIGH
25%	SHORT > GLOTTAL, HIGH, LOW
mid	SHORT > HIGH, LOW > GLOTTAL
75%	SHORT > HIGH > GLOTTAL; LOW > GLOTTAL
final	LOW > GLOTTAL

Table 11: Statistical analysis of pitch in eastern dialect

Pitch contours in the eastern dialect certainly look different than those in the western dialect (see Fig. 3). As is made clear in Table 11, there are few significant differences among the pitch values of different vowel shapes for the eastern dialect. In general, SHORT vowels have a higher F_0 than the long vowels. Most interesting is the fact that there are no statistically significant differences in the pitch of "LOW TONE" and "HIGH TONE" vowels. It appears that, in Sisbicchén, tone is not

[9] In the production of creaky voice, the tenseness of the vocal folds often results in slower vibration and hence lower F_0 (Johnson 2003:138).

phonemic.[10] GLOTTALIZED vowels do display a different pitch contour than the other long vowels, but this difference in pitch is due to glottalization, as shown in Fig. 5. GLOTTALIZED vowels that are not produced with glottalization display the same pitch contour as the other long vowels. There seems to be a strong preference in the eastern dialect to produce long vowels with a specific rising pitch contour. The only deviation from such production occurs when creaky voice forces a lower F_0.

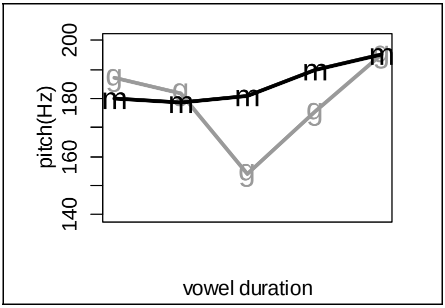

Figure 5. Pitch contours for GLOTTALIZED vowels in eastern dialect as produced with and without glottalization
'm' = modal voice only (no glottalization); 'g' = with glottalization
Vowel duration is normalized.

3.4 Local Summary

This section has provided detailed acoustic description of length, glottalization, and pitch in the vowel system of YM. Some of this information is in conflict with descriptions from previous literature, and some has shown previously undocumented dialectal differences. I emphasize these points in the discussion below.

The canonical realization of GLOTTALIZED vowels (for speakers from all three locations) is that of a long vowel with modal voice interrupted by creaky voice. The production of a full glottal stop only has a marginal distribution. This is especially significant when we consider that these measurements are taken from recordings of careful speech – the participants are producing what can be considered the citation form of

[10] It remains to be established whether or not a tonal contrast has been replaced by another type of contrast (i.e. whether or not a merger has actually occurred). See Frazier (2009) for evidence that a three-way length contrast has replaced (or at least supplemented) a tonal contrast in Sisbicchén and other eastern towns.

each word. It can be assumed that in rapid and/or casual speech the full glottal stop is even less likely to be produced (as noted by Bricker et al. 1998; see Frazier 2009 for the effect of phrase position on the production of glottalization). It is appropriate to call these vowels "GLOTTALIZED" but it is not necessarily appropriate to represent them as /v́ʔv/ at the phonemic level.

Speakers of the western dialect produce pitch contours that closely match those described in previous literature. This is not true of speakers of the eastern dialect. For these speakers, it appears that pitch is not phonemic. This point is made especially clear when we see that even GLOTTALIZED vowels follow the same pitch contour as other long vowels when they are produced without glottalization.

4 Influence of Adjacent Consonants on Pitch

As discussed in §1.2, though we know much about the effect of consonant voicing on the F_0 of adjacent (especially following) vowels, we do not know much about the effects of other consonant characteristics. Ejectives are associated with higher F_0 (Gessner 2003), but they are voiceless, so it is hard to tell if this is an effect of voicing or an effect of other laryngeal maneuvers. Data on implosives is thus crucial for a better understanding of the effect of consonant features on vowel F_0. Implosives involve a constricted glottis, like ejectives, but they are voiced. As the results in this section will show, in YM, implosives are virtually indistinguishable from voiced sonorants with regard to their effect on vowel F_0. In the following, I first discuss the actual realization of the implosive [ɓ]. I then discuss the effect of this implosive (and other consonants) separately for onset and coda position.

4.1 The Phonetic Realization of [ɓ] in Yucatec Maya

Because we have already seen that descriptions from previous literature do not always match the acoustic reality of the production of certain segments, it is important to verify that the voiced bilabial obstruent of YM is indeed an implosive. This question is crucial because we want to be sure we are analyzing the effect of an implosive and not the effect of a plain voiced obstruent.

Implosives are "stops that are produced with a greater than average amount of lowering of the larynx..." and have a waveform that is characterized by an increase in amplitude until the burst (Ladefoged and

Maddieson 1996: 82-4). As Fig. 6 shows, [ɓ] has this characteristic waveform in the western dialect. Auditory perceptions are in agreement – the segment sounds like an implosive. It seems safe to assume that speakers of the western dialect use [ɓ] and not [b] or some other phone.

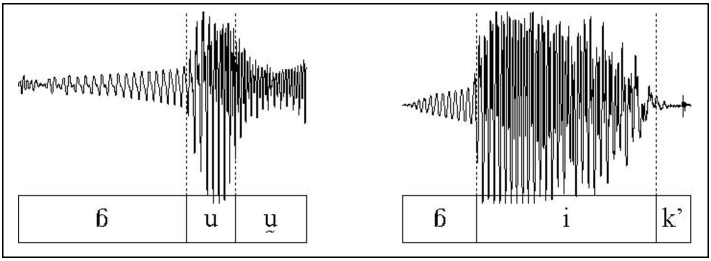

Figure 6: Evidence of bilabial implosive in western dialect
Waveforms show only first 300 ms of word. *Left: bu’ul* ‘bean’ spoken by a male from Mérida; *right*: *bi’ik’* ‘wiggle’ spoken by a male from Santa Elena.

The situation in the eastern dialect is a bit more complex, as shown in Fig. 7. The waveforms are not canonical for either implosives or plain voiced stops. When we look at the spectrograms, there are signs of prenasalization, especially for the males. Auditorily, the segment does sound like an implosive, and there are also hints of nasalization. It is clear that the voiced bilabial obstruent has a different realization in the two dialects (providing further evidence for dialect differentiation). Even though it is not a canonical one, I will continue to assume that this sound is an implosive in Sisbicchén, i.e. it is produced with “greater than average” larynx lowering.[11] Measurements of oral and nasal airflow are needed before a more conclusive statement can be made about the realization of this sound.

[11] It is recognized that there is wide variation in the production of implosives, especially in terms of degree of larynx lowering and degree of voicing (Lindau 1984).

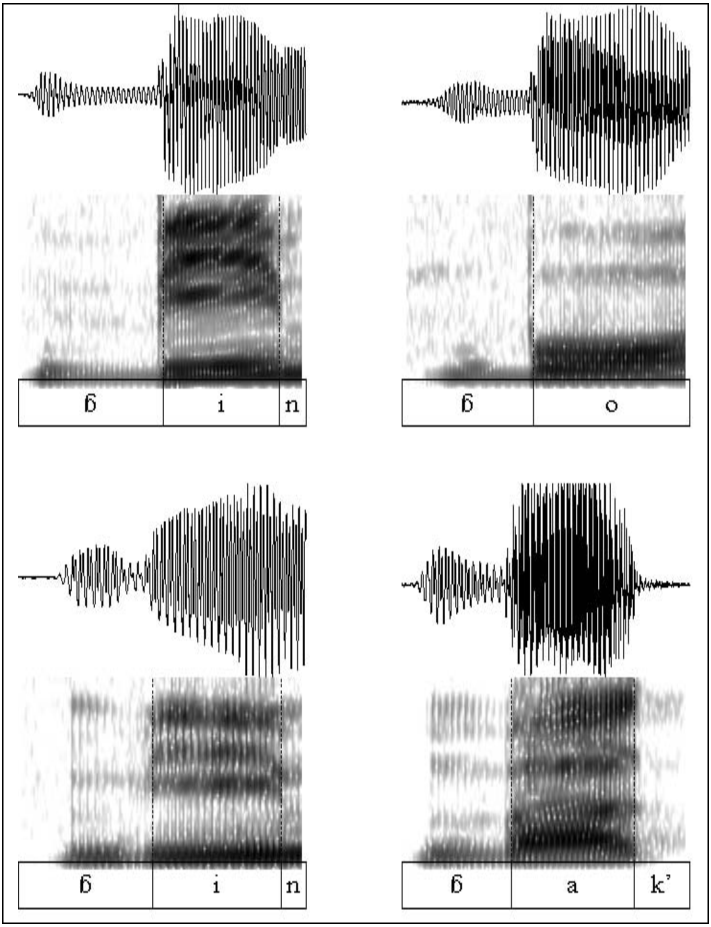

Figure 7. Evidence of bilabial implosive in eastern dialect
Waveforms and spectrograms show only first 300 ms of word. *Top left*: *bin* 'go', spoken by a female; *top right*: *bóoch'* 'shawl', spoken by a female; *bottom left*: *bíin* '*future aspect*', spoken by a male; *bottom right*: *bak'* 'meat', spoken by a male.

4.2 Onsets and Vowel F_0

The average pitch contours for each vowel shape by onset type are shown in Fig. 8 (for the western dialect) and Fig. 9 (for the eastern dialect). For each vowel shape and dialect, the differences between the average pitch values produced at each time point for each pair of onset types were statistically tested (resulting in 400 tests). We can generalize from these tests (across both dialect groups) the following pattern: vcls. obstruent > ejective > glottal stop > implosive, vcd. sonorant (where ">" means "associated with higher F_0 than").[12] The comma between implosives and voiced sonorants means that the data does not show a consistent pattern of one being associated with a higher F_0 than the other. The general pattern is thus one of voicing: voiceless consonants are associated with a higher F_0 in the following vowel than voiced consonants, which is of course already well documented. The overall pattern is seen in each vowel shape in the western dialect (though pitch in GLOTTALIZED vowels is the least affected by onset type). In the eastern dialect, there is less consistency and GLOTTALIZED vowels show few significant effects of onset type.

It is interesting that while implosives and voiced sonorants cannot be distinguished with respect to each other, the three types of voiceless consonants do each show a unique pattern. At this point it is impossible to tell if the pattern of vcls. obstruent > ejective > glottal stop represents a cross-linguistic phenomenon or is distinctive of YM (or is merely distinctive of the data under analysis here). It is at least clear that F_0 can be affected by more than just voicing, though more data (from other languages) is needed before we can develop hypotheses about the nature of these effects.

These results point out another interesting tendency. There were many more significant results for the western dialect (96/200) than for the eastern dialect (53/200). This means that, in a dialect where pitch is contrastive, consonant type affects the realization of vowel F_0 more so

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[12] This generalization was developed in the following way. For each contrast that was significant (e.g. ejective vs. implosive), I summed 1) the number of times a particular onset type was associated with higher F_0 than another onset type, and 2) the number of times a particular onset type was associated with lower F_0 than another onset type. For example, if the contrast of ejective vs. implosive was significant and the mean F_0 with ejectives was greater than the mean F_0 with implosives, this resulted in ejectives gaining one in the "greater than" column and implosives gaining one in the "less than" column. The numbers obtained in this way are given below:

	west		east		total	
	>	<	>	<	>	<
ejective	27	11	14	5	41	16
glottal stop	21	15	10	10	31	25
implosive	2	21	2	24	4	45
obstruent	44	5	25	0	69	5
sonorant	2	34	2	14	4	48

than in a dialect where pitch is not contrastive. This result seems to indicate a phonetics-phonology mismatch, as one might expect there to be stricter control over an acoustic property (i.e. F_0) that participates in a phonemic contrast (i.e. tone) as compared to an acoustic property that does not signify contrast. It would useful for future work to explore the implications of this result for models of the phonetics-phonology interface.

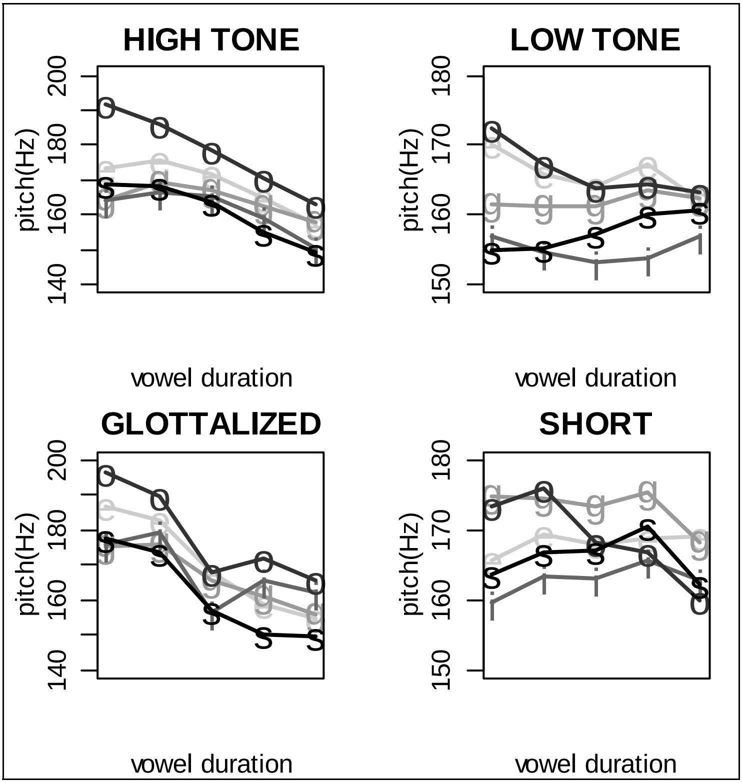

Figure 8: Effect of onset on F_0 by vowel shape in western dialect
Five different consonant types as onsets (ordered from lightest to darkest line): ‘e’ = ejective; ‘g’ = glottal stop; ‘i’ = implosive; ‘o’ = (vcls.) obstruent; ‘s’ = (vcd.) sonorant. Vowel duration is normalized.

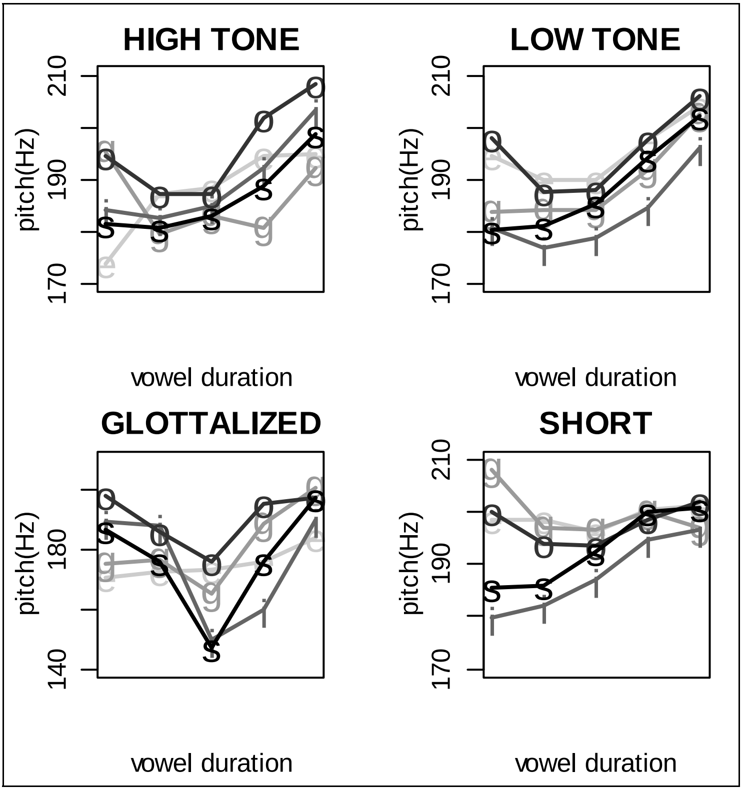

Figure 9: Effect of onset on F_0 by vowel shape in eastern dialect
Five different consonant types as onsets (ordered from lightest to darkest line): 'e' = ejective; 'g' = glottal stop; 'i' = implosive; 'o' = (vcls.) obstruent; 's' = (vcd.) sonorant. Vowel duration is normalized.

4.3 Codas and Vowel F_0

The effect of coda type on F_0 in YM is illustrated in Fig. 10 (for the western dialect) and Fig. 11 (for the eastern dialect). In this case a different pattern emerges in the two dialect groups.[13] In the western dialect, all vowel shapes can be generalized with the following pattern: ejective > obstruent > sonorant > glottal stop > implosive. There are few significant effects for the eastern dialect, but the general pattern is obstruent, ejective > glottal stop > implosive, sonorant. There are fewer significant effects for coda type than for onset type (82/200 in the west; 18/200 in east), which is in agreement with the literature that (at least voicing in) a consonant is more influential on the F_0 of a following vowel than a preceding vowel (Hombert 1978).

The voicing dichotomy is not clearly represented in the above generalizations. In the western dialect, coda sonorants are associated with higher pitch than coda glottal stops. It seems possible that this is due to the correlation between coda glottal stops and glottalization of the vowel (see Table 9), such that coda glottal stops are associated with lower F_0 because low F_0 is a correlate of creaky voice. However, similar results are obtained by running the same statistical tests but ignoring all vowels that show some form of glottalization. Even in the absence of glottalization, glottal stops are associated with lower F_0 than sonorants in the preceding vowel (in the western dialect). This is a puzzling result given that Hombert (1978) presents strong evidence that glottal stops are correlated with higher F_0 in the preceding vowel. In the eastern dialect, voiceless codas are generally associated with higher pitch than voiced codas, but there are few significant results for this dialect (even though, again, pitch is not contrastive).

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[13] These generalizations were extracted via the same method discussed in footnote 12:

	west		east	
	>	<	>	<
ejective	24	3	3	0
glottal stop	13	24	3	2
implosive	10	30	3	6
obstruent	20	10	7	1
sonorant	15	15	2	9

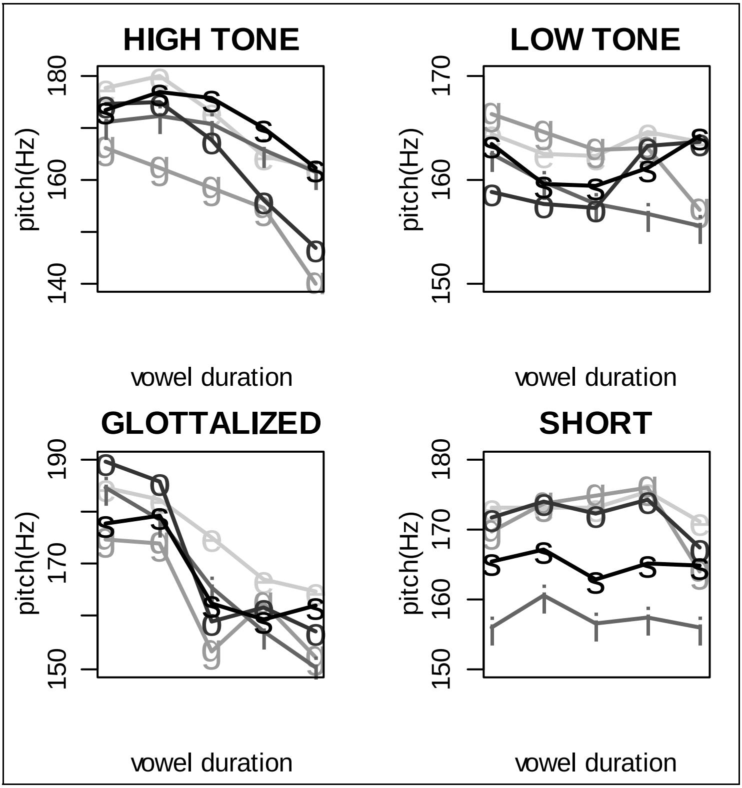

Figure 10: Effect of coda on F_0 by vowel shape in western dialect
Five different consonant types as codas (ordered from lightest to darkest line): ‘e’ = ejective; ‘g’ = glottal stop; ‘i’ = implosive; ‘o’ = (vcls.) obstruent; ‘s’ = (vcd.) sonorant. Vowel duration is normalized.

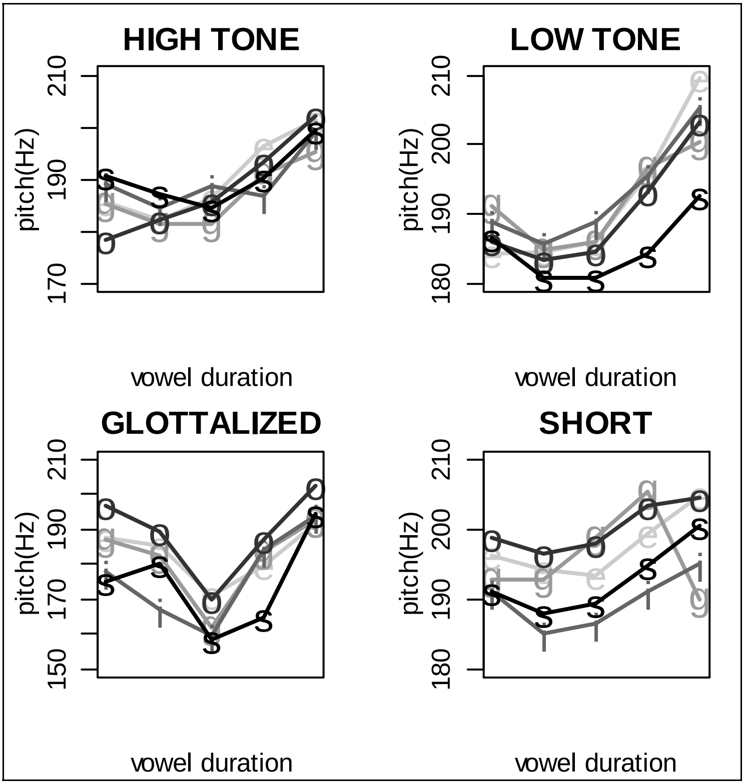

Figure 11: Effect of coda on F_0 by vowel shape in eastern dialect
Five different consonant types as codas (ordered from lightest to darkest line): ‘e’ = ejective; ‘g’ = glottal stop; ‘i’ = implosive; ‘o’ = (vcls.) obstruent; ‘s’ = (vcd.) sonorant. Vowel duration is normalized.

4.4 Local Summary

Implosives are clearly associated with lower F_0 (than that of voiceless consonants) in both onset and coda positions in YM, but the evidence is inconclusive with regard to how implosives compare to voiced sonorants. With respect to voicing, the results of this study are in agreement with previous literature: voicelessness is associated with higher F_0, and consonants are more influential on the F_0 of a following vowel than of a preceding one. A surprising result is that consonant type is less influential on the production of F_0 in the eastern dialect, where a tonal contrast has been neutralized.

5 Conclusions

This paper has provided the first detailed acoustic account of the suprasegmental vowel contrasts of YM. Speakers from Mérida and Santa Elena (the western dialect) produce the four vowel shapes mostly as described in the literature. However, speakers from Sisbicchén (the eastern dialect) do not: they do not utilize a tonal contrast and all vowel shapes are marked by the same rising pitch contour. In both dialects, GLOTTALIZED vowels are most commonly produced with creaky voice and not with a full glottal stop. With regard to consonant-pitch interaction, the results of this paper clearly show that implosives are associated with lower F_0 than voiceless sounds in YM. Those who work on consonant-tone interaction now have two sources (this one and Wright and Shryock 1993) which show that implosives pattern with other voiced sounds on the phonetic level.

It is apparent that much more work is needed in order to better understand the sound system of YM. This paper has shown that this language is not homogeneous with respect to suprasegmental features, but how heterogeneous is it? I used the terms "eastern" and "western" dialect for simplicity, but we do not know which geographical locations utilize a tonal contrast and which do not. There is also the matter of the acoustics of the implosive. More detailed measurements (of oral and nasal airflow) are needed in order to determine the nature of the implosive in Sisbicchén (and surrounding areas).

The literature has been in agreement for sixty years (since Pike 1946) about the production of pitch and glottalization in YM, but new acoustic data has shown that the literature was not exactly right. Furthermore, a majority of sources claim implosives to be associated with higher F_0, though no evidence for this claim has been found. This means that the field of linguistics would benefit immensely from acoustic documentation and testing for languages (and phonological phenomena) where no such documentation exists.

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Appendix A: Wordlist

The following wordlist includes each Yucatec Maya target word used in the production study and its English and Spanish translation (the latter was printed below the Yucatec Maya word on the stimuli). All words are used in both wordlists unless otherwise noted (SE = Santa Elena speakers only, nonSE = all other speakers). Nonce forms are denoted by ".." in place of English/Spanish translations; underlining denotes the CVC context from which measurements were taken in polysyllabic forms.

	i'	**a'a'**	**aa'**	**áa**
	hawk	..	..	..
	gavilán	..	..	..
	ich	**e'es**	**ook**	**óox**
	in	show	foot	three
	en	mostrar	pie	trés
	am	**a'al**	**oon**	**éem**
	spider	speak	avocado	descend
	araña	hablar	aguacate	descender
	uk'	**a'ak'**	**eek'**	**éets'**
	louse	..	star	echo
	piojo	..	estrella	eco
nonSE:	**ab**	**u'ub**	**iib**	**áab**
	..	listen	bean	..
	..	escuchar	frijol	..
SE:	**abal**	**u'ubik**	**iibil**	**áabil**
	plum	hear it	bean	grand-child
	ciruela	escucharlo	frijol	nieto
	ka'	**ti'i'**	**tsuu'**	**tsáa'**
	metate	there	aguti	rattle
	metate	allí	agutí	cascabel
	chak	**tso'ots**	**tsaap**	**cháak**
	red	hair	fuzz that causes itching	rain
	rojo	pelo	cosa áspera (que causa comezón)	llueve
	kan	**xi'im**	**tseem**	**chéel**
	four	corn	chest	rainbow
	cuatro	maíz	pecho	arco iris

	pak' wall pared	**pi'its'** slightly (sweet) ligeramente (dulce)	**peek'** dog perro	**púuts'** needle aguja
nonSE:	**chab** anteater oso hormiguero	**ta'ab** salt sal	**xiib** man hombre	**píib** underground roasting pit horno hecho bajo tierra
SE:	**chabo'** that anteater eso oso hormiguero	**ta'abo'** that salt eso sal	**xiibo'** that man eso hombre	**píibo'** that underground roasting pit eso horno hecho bajo tiera
	ni' nose nariz	**na'a'** ..	**laa'** old viejo	**náa'** ..
	lak clay cup taza hecha de barro	**na'at** intelligent entendimiento	**miis** cat gato	**máak** person hombre
	nal corn elote	**mo'ol** paw pata de los felinos	**maan** buy compra	**néen** mirror espejo
	mak' * cork corcho	**ma'ats'** hull (corn) hollejo	**neek'** seed semilla	**láak'** other otro
nonSE:	**nab**	**ya'ab** a lot mucho	**yeeb** fog niebla	**náab** hand span cuarta
SE:	**nabo'**	**ya'abo'** a lot mucho	**yaabilaj** love amor	**náabo'** that hand span cuarta
	ch'o' mouse ratón	**k'a'a'**	**t'uu'** side (of hammock) lado (de hamaca)	**k'áa'** .. ..

	k'at clay barro	**p'u'uk** jaw, cheek mejilla	**k'aas** ugly feo	**k'áax** forest bosque
	k'an ripe maduro	**k'a'an** strong fuerte	**k'iin** day, sun día,sol	**k'áan** hammock hamaca
	ch'och' cicada cigarra	**k'i'ik'** blood sangre	**t'uut'** parrot loro	**k'áak'** fire fuego
nonSE:	**k'ab** arm brazo	**k'a'ab**	**k'aab**	**ts'íib** writing escritura
SE:	**k'abo'** that arm eso brazo	**k'a'abéet** necessary necesario	**k'aaba'** name nombre	**k'óoben** kitchen cocina
	k'aaba' name nombre	**ba'a'**	**baa'**	**báa'** .. ..
	bix how como	**ba'ax** what que	**beet** make, do hacer	**báat** axe hacha
	bin go ir	**bu'ul** bean frijol	**beel** road camino	**bíin** *future aspect* *el futuro*
	bak' meat carne	**bi'ik'** wiggle culebrear	**beech'** quail codorniz	**bóoch'** shawl rebozo
nonSE:	**bab**	**be'eb** a type of vine un tipo de planta	**baab**	**báab** swim nadar
SE:	**babo'**	**ba'abo'**	**baabo'**	**báabo'** .. ..

* Not all speakers recognized this word (*mak'*), and so for some it was a nonce form.

Appendix B: Numeric Data on Pitch

mean (Hz) and standard deviation by gender, location, and vowel shape for pitch at five points during vowel production

		Mérida				Santa Elena			
		females; 1 participant		males; 6 participants		females; 7 participants		males; 5 participants	
		mean	sd	mean	sd	mean	sd	mean	sd
GLOTTALIZED	init	203	29	159	28	213	39	163	26
	25%	196	32	158	29	209	41	165	32
	mid	182	49	135	27	189	48	157	31
	75%	163	38	133	30	193	45	152	31
	fin	152	33	119	24	198	41	145	30
HIGH TONE	init	188	24	146	26	208	34	155	22
	25%	191	24	150	30	204	37	156	26
	mid	190	24	144	29	199	38	154	26
	75%	179	30	129	25	197	38	150	28
	fin	172	13	116	22	195	38	142	29
LOW TONE	init	183	16	131	22	202	29	144	20
	25%	184	15	126	19	200	29	142	24
	mid	183	16	124	18	200	29	143	25
	75%	180	14	124	18	202	33	147	30
	fin	176	14	119	19	202	36	152	34
SHORT	init	180	26	134	22	208	29	150	21
	25%	179	26	136	20	211	27	151	23
	mid	181	14	132	20	207	33	153	26
	75%	179	14	133	19	208	32	156	31
	fin	175	13	129	28	201	35	153	32

		Sisbicchén females; 3 participants		Sisbicchén males; 2 participants	
		mean	sd	mean	sd
GLOTTALIZED	init	210	41	149	21
	25%	204	43	149	18
	mid	174	56	154	20
	75%	194	55	161	27
	fin	212	42	170	30
HIGH TONE	init	216	29	143	17
	25%	213	19	140	15
	mid	212	18	146	18
	75%	215	21	156	22
	fin	223	25	165	32
LOW TONE	init	219	27	142	18
	25%	214	17	139	16
	mid	213	15	144	18
	75%	218	16	156	23
	fin	225	18	168	29
SHORT	init	221	24	154	24
	25%	217	22	152	22
	mid	217	22	158	25
	75%	221	23	167	27
	fin	222	28	168	27