

An acoustical study of phonation in Santiago Laxopa Zapotec¹

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1 Introduction

Most of the work on languages that contain tone and phonation has been based on descriptions of Southeast and Far East Asian languages, which has lead to strong claims being made about what is possible for languages that contain tone and phonation (Masica 1976, Thurgood 2002, Yip 2002, Enfield 2005, Michaud 2012, Brunelle & Kirby 2016). The main claim from many of these authors is that tone and phonation are codependent (i.e., certain tones only appear with certain phonations or certain phonations only appear with certain tones).

An example for this type of co-occurrence between tone and phonation is Mandarin's Tone 3 which is frequently associated with creaky voice (Hockett 1947). This claim has also been made in the reverse that certain phonation types are associated with specific tonal patterns. Breathy voice stereotypically appears with high pitch and creaky voice stereotypically appears with low pitch (Esling et al. 2019).

Research into Mesoamerican languages, however, shows that these claims are too strong or exaggerated (Suárez 1983, Campbell, Kaufman & Smith-Stark 1986, Silverman 1997, DiCanio 2008, Esposito 2010, E. W. Campbell 2017a,b). Most languages of the Oto-Manguean language family exhibits independent tone and phonation. This has lead some researchers to propose that tone and phonation is phased/ordered with respect to each other (Silverman 1997, Blankenship 1997, 2002). A summary of this proposal, which I call the Laryngeal Complexity Hypothesis, is discussed in Section 2.

In order to test the validity of the Laryngeal Complexity Hypothesis, one first needs to establish what the phonation types are and their correlating acoustic measurements. Often these acoustic measurements take the form of the relative amplitude of different harmonics in the acoustic signal or by looking at the relative amplitude in the certain domains.

This paper presents novel data on tone and phonation in Santiago Laxopa Zapotec, an Oto-Manguean language spoken in Santiago Laxopa, Ixtlán, Oaxaca, Mexico. This language has five

¹I am grateful to Fe Silva-Robles and Raúl Díaz Robles for sharing their time and language expertise. I am also grateful to Grant McGuire, Jaye Padgett, Rachel Walker, Maziar Toosarvandani, Ben Eischens, Kim Tan, and Zach Horton for their help and discussions during all stages of this project. This project branched off from a collaboration with Jack Duff and Maya Wax Cavallaro. Various parts of this project were previously shared in joint presentations with Jack Duff and Maya Wax Cavallaro.

This work was supported in part by the National Science Foundation under Grant No. 2019804, the Humanities Institute at UC Santa Cruz, and the Jacobs Research Funds.

tones and four phonations which are contrastive. The results of this analysis shows that breathy phonation is best characterized by the acoustic measurement of H1-A3 and checked and laryngealized phonation are best captured by when there is a decrease in CPP. The result of a statistical analysis shows that these phonation types are best captured by those measurements.

2 The Laryngeal Complexity Hypothesis

The LARYNGEAL COMPLEXITY HYPOTHESIS (LCH) has its origins in the work from Silverman (1997) and Blankenship (1997, 2002). The basic premise of the LCH is that in languages that have both tone and phonation there needs to be an ordering between the two laryngeal gestures for tone and phonation for optimal perceptibility. This premise comes from the understanding that the same mechanism that is responsible for tone is also responsible for the production of phonation: the vocal folds and glottis. The rate that vocal folds vibrate is responsible for changing the fundamental frequency, perceived as pitch, which is grammaticalized as tone in lexical tone languages. The faster the vocal folds vibrate the higher the pitch and the slower the vocal folds vibrate the lower the pitch.

The vocal folds are also the primary articulator for phonation. Ladefoged (1971) and Gordon & Ladefoged (2001) treated phonation as a by-product of how open or closed the glottis is during vocal fold vibration. This is schematized by Figure 1. The more open the glottis is the breathier the sound to the point where the sound becomes the sound [h]. The more closed the glottis is the creakier the sound is to the point where the sound becomes [?].

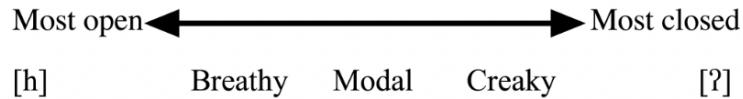


Figure 1: Simplified one-dimensional model for phonation. Based on Ladefoged (1971) and Gordon & Ladefoged (2001)

The LCH assumes that phonation and tone are both produced at the vocal folds and glottis. Because these same organs are responsible for these two different phenomena there is a mismatch in trying to produce both at the same time. It is assumed by the LCH that because of this issue there needs to be a strict ordering in the glottal gestures. This means that the tonal gesture needs to be produced either before or after the phonation gesture. The reason for this is that if the gestures were overlapped there will be a perturbation of the tone and the listeners will not be able to reliably differentiate what the tone is. The LCH assumes that there is a close link between production and perception. This assumption places the responsibility on making sure the acoustic cues are the most perceptually salient on the speaker and the speaker is responsible

to produce both tone and phonation in such a way that the listener can clearly differentiate the different acoustic cues for both tone and phonation. These assumptions can best be represented by Figure 2.

In Figure 2, which is taken from DiCanio (2012), the cue for tone is represented by the Pitch Target and the Glottal Gesture represents the gestures needed to produce phonation. When the Pitch Target is not co-articulated with the Glottal Gestures, then there is the greatest perceptual recoverability for the listener. This is argued for by the LCH as the tones are the most recoverable on modal vowels. This modal portion is then ordered or phased relative to the non-modal portion. This ordering is then the responsibility of the speaker to accommodate for the listeners perceptibility. If, however, the Pitch Target and the Glottal Gesture were overlapping, as represented by lower half in Figure 2, then the cues for pitch and phonation would be overlapping and making it perceptually more difficult for

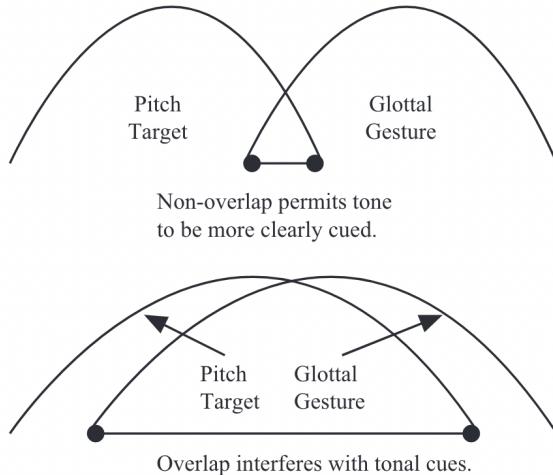


Figure 2: Representation taken from DiCanio (2012).

Some work has been done into investigating this in other languages, most notably DiCanio's (2012) investigation into glottals in Itunyoso Trique, which is also an Oto-Manguean language. DiCanio in his study found that when the magnitude of coarticulation for glottal consonants occurs on the vowels there is a strong correlation between the magnitude of overlap and the amount of perturbation in the f0 signal. If, however, the degree of overlap was minor then the acoustic signal had little to no perturbation. These results were found by consulting the spectral tilt of the vowels with the f0 measures and performing a generalized linear mixed effects model with speaker treated as a random effect.

Another study on Jalapa Mazatec (Garellek & Keating 2011) also investigated the interaction of tone and phonation. Jalapa Mazatec is a language with both contrastive tone and phonation and Garellek & Keating (2011) validated the claims made by the LCH, in that tone and phonation seemed to be ordered with each other when it comes to at least one of the phonation types.

In testing the claims made by the LCH, this paper describes the tonal and phonation inventories in Santiago Laxopa Zapotec. This language is ideal for testing the viability of the LCH because of its use of both contrastive tone and phonation. The rest of the paper will provide a description of the language in Section 3 with special emphasis on the tone and phonation systems. In order to best investigate these interactions, we need to first determine what characterizes and correlates to the tonemes and phonation contrasts. Describing these characteristics and correlates is the focus of this paper. The interaction of tone and phonation in Santiago Laxopa Zapotec will be explored in greater detail in a future paper.

3 Santiago Laxopa Zapotec

Santiago Laxopa Zapotec (SLZ; *Dilla'xhonh Laxup*) is a Northern Zapotec language spoken by approximately 1000 people in the municipality of Santiago Laxopa, Ixtlán District in the Sierra Norte of Oaxaca, Mexico (Adler & Morimoto 2016, Adler et al. 2018, Foley, Kalivoda & Toosarvandani 2018, Foley & Toosarvandani 2020). It is closely related to San Bartolomé Zoogocho Zapotec (Long & Cruz 2005, Sonnenschein 2005) and is mutually intelligible with this variety according to native speakers. As is common among Zapotecan languages, SLZ distinguishes between lenis and fortis consonants (e.g., Nellis & Hollenbach 1980, Jaeger 1983, Uchihara & Pérez Báez 2016) and has a fairly standard five-vowel inventory, see Table 1 and Table 2.²

Table 1: Consonant inventory for Santiago Laxopa Zapotec

		bilabial	alveolar	retroflex	alveo-palatal	palatal	velar	labio-velar	uvular
nasal	lenis		n						
	fortis	m:	n:						
stop	lenis	b	d				g	g ^w	
	fortis	p	t				k	k ^w	
fricative	lenis		z	ʐ~ʈ	ʒ	ç			χ~ʂ
	fortis		s	ʂ	ʃ				
affricate	lenis		dz						
	fortis		ts		tʃ				
lateral	lenis		l~ɻ						
	fortis		l:						
trill			r						
approximate							w		

²The consonant and vowel inventories was previously established by the Zapotec Language Project at UCSC (<https://zapotec.ucsc.edu/>)

Table 2: Vowels inventory in Santiago Laxopa Zapotec.

	front	central	back
high	i		u
mid	e		o
low		a	

In addition to the contrasts in both consonants and vowels, SLZ additionally has a phonation and tonal contrast. I will first talk about the tonal contrasts in Section 3.1 followed by the tonal phonation in Section 3.2.

3.1 Tone in SLZ

As is common among Oto-Manguean languages, SLZ is a tonal language (Suárez 1983, Campbell, Kaufman & Smith-Stark 1986, Silverman 1997, E. W. Campbell 2017a,b). Previous to **brinkerhoffDownstepSant** there was no detailed description of the tonal system for SLZ presented. This paper represents the first time that such a detailed description of the tone system has been presented in writing. Previous studies on the tonal system were heavily based on the closely related San Bartolomé Zoogocho Zapotec (Long & Cruz 2005, Sonnenschein 2005). San Bartolomé Zoogocho Zapotec has been previously described as having as few as 6 tones (Sonnenschein 2005) and as many as eleven tones (Long & Cruz 2005). In order to determine the exact number of tones in SLZ a combination of Pike's (1948) method for discovering tonal contrasts and Snider's (2014) method of compiling a database full of words and their tonal patterns in different phrases and contexts was used by myself and two other researchers starting the summer 2020. This led to the discovery of five surface tones which appear on a syllable, see Table 3.

Table 3: Examples of the five tonal patterns observed in the Santiago Laxopa Zapotec words.

High	a^H	<i>xha</i>	[<i>za^H</i>]	'clothing.POSS'
Mid	a^M	<i>lhill</i>	[<i>ri^M</i>]	'house.POSS'
Low	a^L	<i>yu'</i>	[<i>çu^L</i>]	'earth'
Rising	a^{MH}	<i>yu'u</i>	[<i>ju'u^{MH}</i>]	'quicklime (Sp. cal)'
Falling	a^{HL}	<i>yu'u</i>	[<i>ju'u^{HL}</i>]	'house'

Following discussion from Brinkerhoff, Duff & Wax Cavallaro (2022) these tones appear to be limited in their distribution. It is true that all five patterns can surface on a syllable but there is a restriction in what tonal patterns are allowed to surface on words that are larger than bimoraic. The patterns that we observe on bimoraic nominals are: HL, MH, and LL.

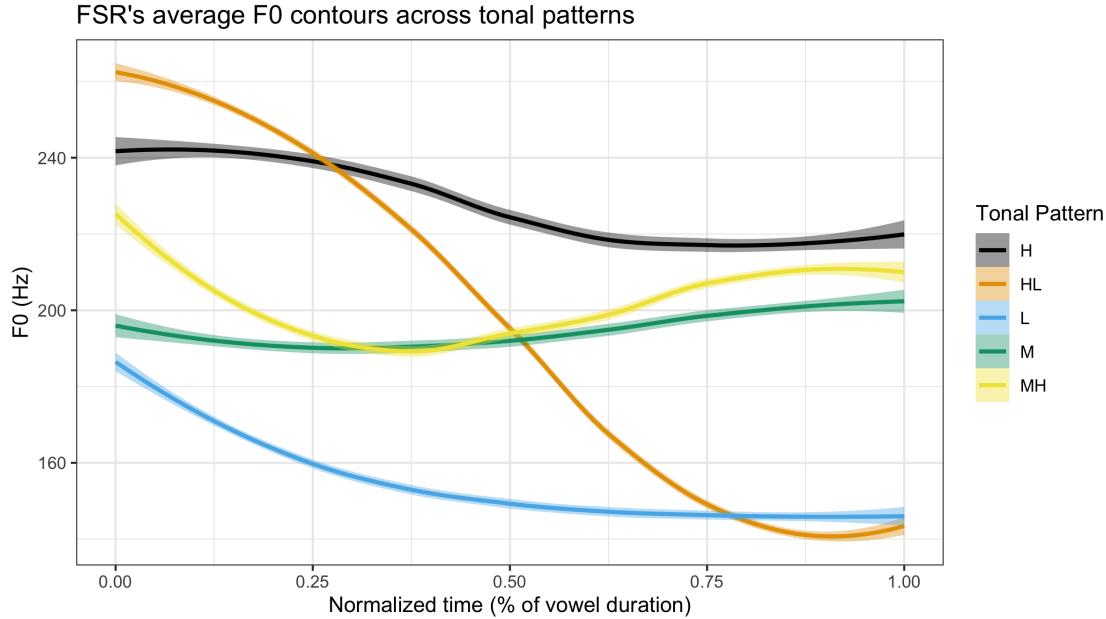


Figure 3: Tonal contrasts for FSR averaged and time normalized. Each line in this graph represents the average of approximately 10 syllables for each tonal pattern.

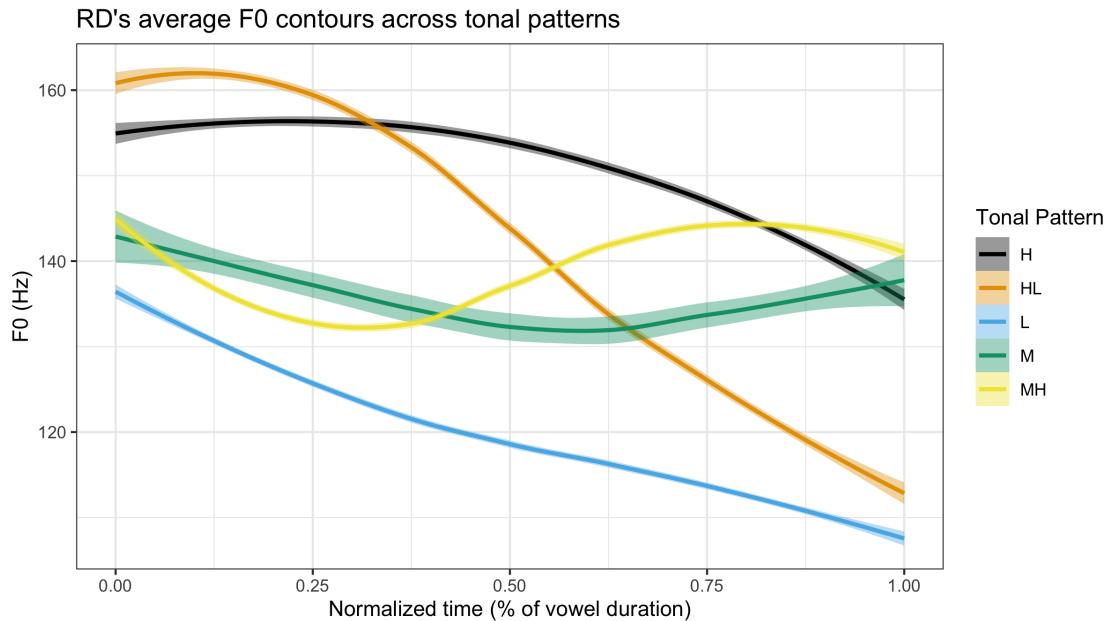


Figure 4: Tonal contrasts for RD averaged and time normalized. Each line in this graph represents the average of approximately 10 syllables for each tonal pattern.

3.2 Phonation in SLZ

Among Zapotecan languages it is quite common for languages to make use of contrastive phonation (e.g., Avelino 2004, Long & Cruz 2005, Avelino 2010, López Nicolás 2016, Chávez-Péon 2010).

SLZ, in addition to the five vowel qualities, has four contrastive phonation types which are: modal, breathy, checked, and laryngealized. These contrasts are exemplified in the minimal quadruple in (1). In representing the checked and laryngealized vowels, I follow the same procedure as other authors (e.g., Avelino (2010) and Uchihara (2016)) in representing the ‘glottal stop’ element as a superscripted glottal stop in the IPA transcription (i.e., [a']). This is primarily done as a way of standardizing the variable pronunciation of the glottal element in Zapotec ranging from a full glottal stop (i.e., [a?]) to creaky voice on a portion of the vowel (i.e., [aa̯]).

(1) Four-way near minimal phonation contrast

- a. *yag* [çag^L] ‘tree; wood; almúd (unit of measurement approximately 4kg)’
- b. *yah* [ça^L] ‘metal; rifle’
- c. *yu'* [cu^{'L}] ‘earth’
- d. *ya'a* [ça^{'a}^L] ‘market’

Breathy phonation on vowels is characterized by a raspy quality throughout the whole vowel or a portion toward the end of the vowel, see Figure 5.

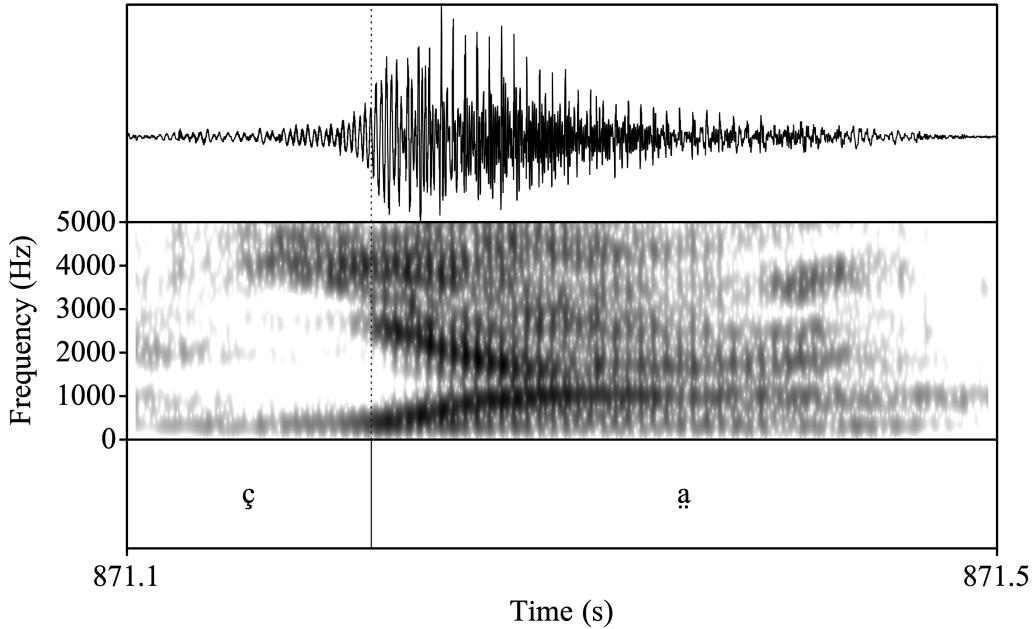


Figure 5: Breathy vowel in the word *yah* ‘metal; rifle’

Checked vowels on the other hand are characterized by an abrupt glottal closure which cuts the vowel short. This phonation is sometimes only realized as a very short period of creakiness at the end of the vowel, see Figure 6.

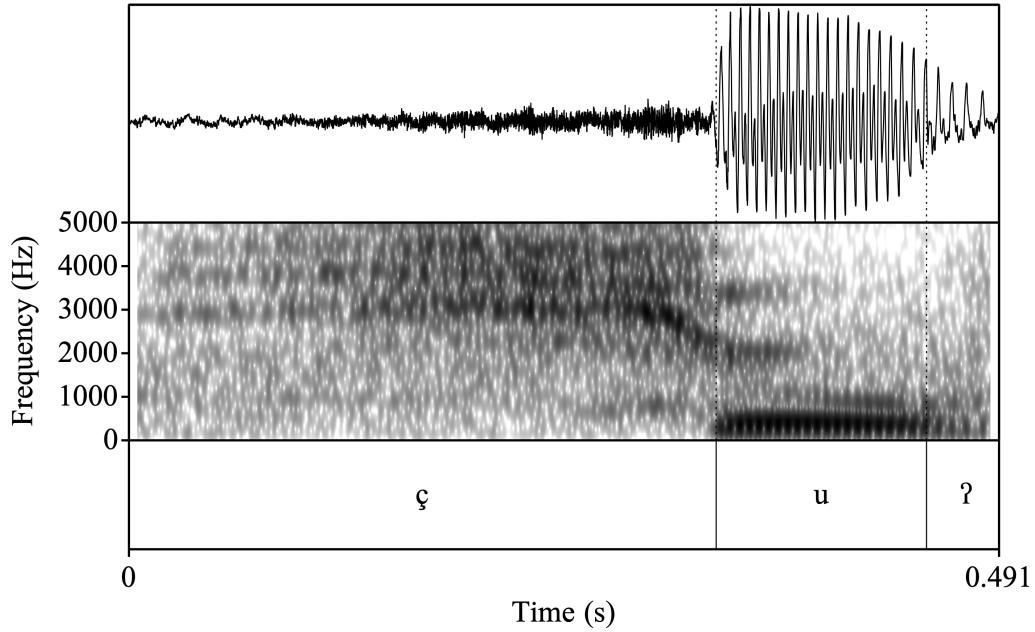


Figure 6: Checked vowel in the word *yu'* ‘earth’

Laryngealized vowels are quite common in Zapotecan languages and have received a wide number of different names. Previous descriptions have used terms such as broken, rearticulated, interrupted, and creaky (Long & Cruz 2005, Avelino 2004, 2010, Sonnenschein 2005, Adler & Morimoto 2016). In order to avoid confusion, I will use the term laryngealized following Avelino (2010). In addition to a wide number of different names these vowels also exhibit a wide range of allophones.

Avelino (2010) found in the closely related Yalálag Zapotec that among his consultants there were at least four different pronunciations as seen in Table 4. In SLZ, each of the consulted

Table 4: Laryngealized Vowels in Yalálag Zapotec

$/V'V/$	$[V?V]$
	$[VV\check{V}]$
	$[V\check{V}:V]$
	$[V\check{V}V]$

language experts would produce this vowel differently. One consultant would do rearticulation, where there is a full glottal stop in the middle of the vowel, or creaky voice. This alternation seemed to be in free variation but there was a greater tendency to creak in low toned words, such

as *xa'ag* [sa:g] ‘topil’³, see Figure 7 for a comparison between this consultant’s pronunciation of the laryngealized vowels.

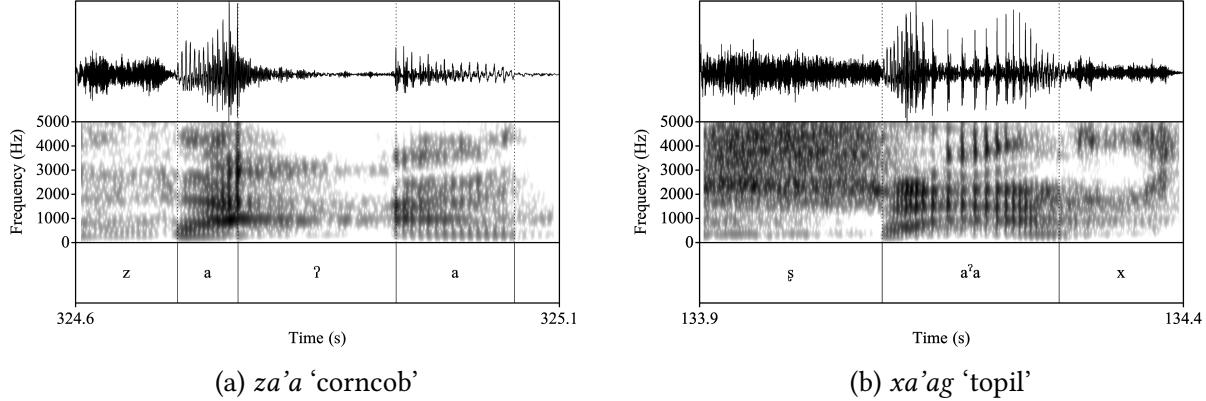


Figure 7: Comparison of FSR’s laryngealized vowels in *za'a* ‘corncob’ and *xa'ag* ‘topil’

The other consultant only ever produces creaky voice for these vowels regardless of the tone with the word. During one of the elicitation sessions, we conducted a perceptual check that these were in fact the same vowels and both consultants reliably identified the words and produced laryngealized vowels according to their own idiosyncrasies. However, a more detailed perception study is beyond the scope of this paper.

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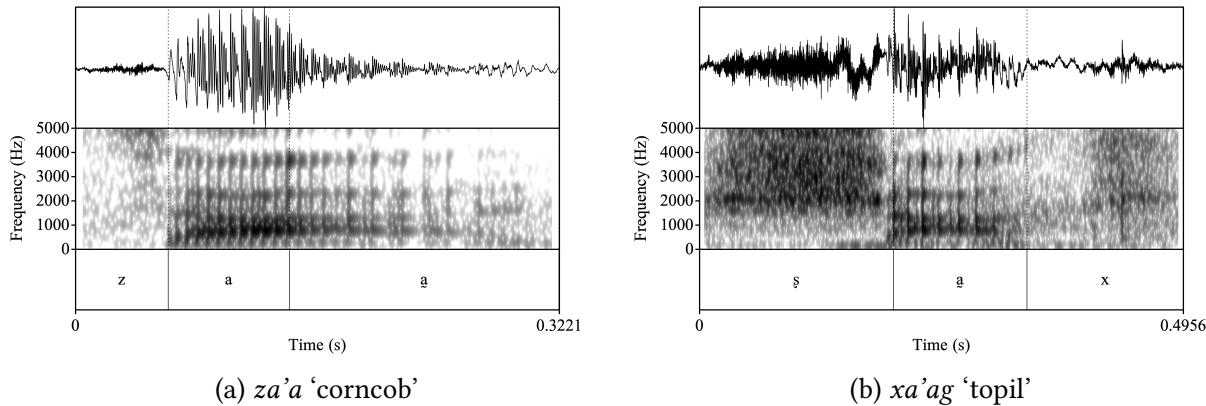


Figure 8: Comparison of RD’s laryngealized vowels in *za'a* ‘corncob’ and *xa'ag* ‘topil’

³A *topil* is a type of government office in traditional Oaxacan communities somewhat akin to a sheriff.

4 Interaction of Tone and Phonation

Most previous work on the interaction of tone has been focused on the languages of East and Southeast Asia (e.g., Masica 1976, Thurgood 2002, Yip 2002, Enfield 2005, Michaud 2012, Brunelle & Kirby 2016). What has been found in these descriptions is that certain tones and phonations are codependent. For example Smalley (1976) and Ratliff (1992) both describe White Hmong’s -g tone as being a mid-low tone with breathy phonation and Mandarin’s tone 3 is often associated with creaky phonation (Hockett 1947). Brunelle (2009) found that creaky phonation plays an important role in the production of certain tones. Additionally, work on S’gaw Karen has found that two tones are only differentiated by the presence of some form of non-modal phonation (Boehm p.c.).

However, there has been some observations—especially in Mesoamerica—that tone and phonation are independent from each other (e.g., Silverman 1997, Garellek & Keating 2011). This means that tone can independently occur with any phonation type. This has also been extensively described in multiple Zapotecan languages (e.g., Avelino 2004, 2010, Chávez-Péón 2010, E. Campbell 2011, Villard 2015, López Nicolás 2016)

Chávez-Péón (2010) has a detailed description of the tone and phonation interactions in San Lucas Quiaviní Zapotec (SLQZ), a central valley variety of Zapotec. The distribution of tone and phonation is found in Table 5. We see that in SLQZ, that both low and falling tone have the full range of possible combinations. However, we see gaps in the high tone for breathy and rising tone can only occur with modal phonation.

Table 5: SLQZ tone and phonation interactions (Chávez-Péón 2010).

	Modal	Breathy	Creaky	Interrupted
High	✓	–	✓	✓
Low	✓	✓	✓	✓
Falling	✓	✓	✓	✓
Rising	✓	–	–	–

Based on elicitation data collected from 2020-2022, SLZ has a more expansive distribution of tone and phonation when compared to SLQZ but seems to be very similar to other Northern Zapotec varieties (e.g., Avelino 2004). The distribution of SLZ tonal and phonation interactions are given in Table 6 for the number of tokens that were analyzed.

One of the striking things in this is the lack of high tone with breathy phonation. This gap is interesting because of the long time association of high pitch with breathiness (a good overview—of this association and other phonation types—is found in Esling et al. 2019). This gap of breathy phonation and high tone is quite common across the Zapotecan languages (Campbell p.c.). In

Table 6: Number of unique syllables for each interaction of tone and phonation in the data.

	Modal	Breathy	Checked	Laryngealized
High	12	–	5	3
Mid	7	1	2	1
Low	17	5	9	3
High-Low	9	1	2	1
Mid-High	1	1	–	1

the case of breathy phonation in SLQZ, Uchihara (2016) offers some convincing evidence that the phonation originated in syllables with low tone and then spread to other tones via analogy. If this is also true for SLZ then we should be able to find similar distributions that Uchihara observes when we compare SLZ to its closest relative San Bartolomé Zoogocho Zapotec, which lacks a breathy phonation. Such an investigation would be important in understanding how breathy vowels originated in the Zapotecan family, but is beyond the scope of this paper.

5 Acoustic investigation into the phonation

One of the primary ways to measure and investigate phonation is using spectral measures. The most frequent type of measurement is spectral-tilt. Spectral-tilt measurements are conducted by comparing the relative amplitude of different harmonics in the acoustic signals, which has primarily been the difference in the relative amplitude of the first and second harmonics. Other measurements make use of higher harmonics which are closest to the different formants, see Figure 9. These spectral-tilt measurements have been found to be particularly useful in languages such as Green Hmong (Huffman 1987, Andruski & Ratliff 2000) and Jalapa Mazatec (Silverman et al. 1995, Blankenship 1997).

The spectral-tilt measurements that are used in this study are: H1-H2 and H1-A3. H1-H2 is the difference in amplitude between the first harmonic (H1) and the second harmonic (H2) and is the prototypical spectral-tilt measure that is reported in most studies. The other spectral-tilt measurement of H1-A3 is the difference in amplitude between the first harmonic and the harmonic closest to the third formant. These measurements were selected for this study based on the Esposito's (2010) investigation into the phonation of a Central Valley Zapotec variety. She reports that H1-H2 best represents female speakers only. Male speakers, however, were best characterized by H1-A3.

When conducting spectral-tilt measurements, there are two types of measurements that can be made: corrected and uncorrected. The status of corrected or uncorrected refers to whether or not the influence of formants are taken into account (Garellek 2019 provides a good overview

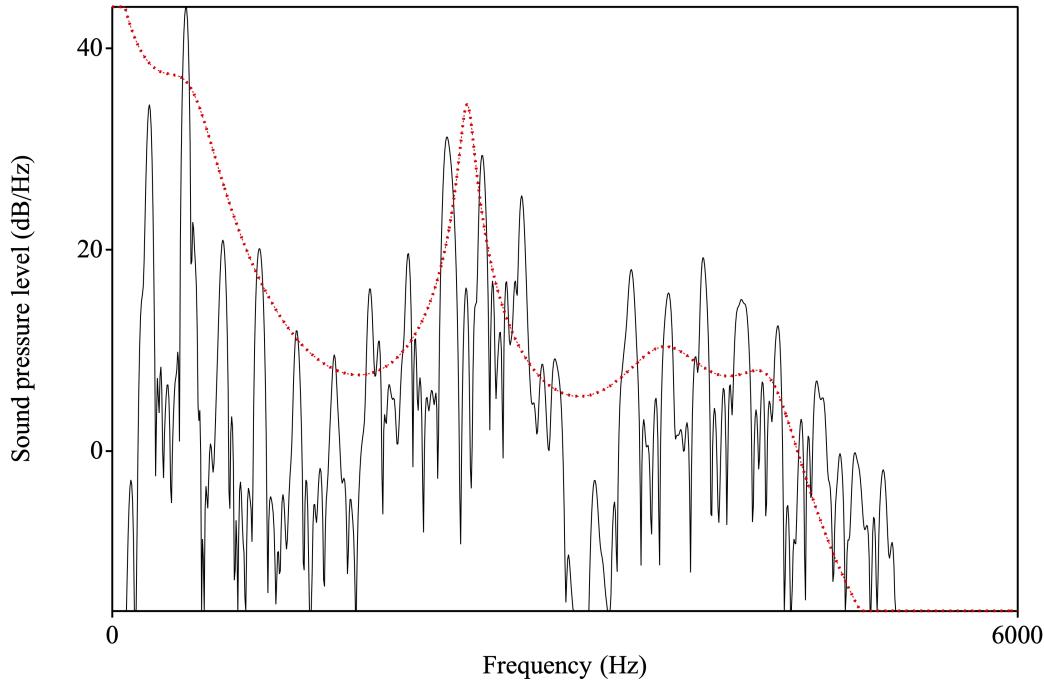


Figure 9: Spectral slice with LPC smoothed line overlaid for the vowel [e]. The harmonics in the spectral slice are represented by each of the dark peaks. The leftmost black solid line peak is the first harmonic (H_1) and each subsequent peak represents the next highest harmonic (H_2 through H_n). The red dotted line represents an LPC smoothed line which identifies the formants by the peaks. Each of the harmonics that are closest to the formant peak is identified as A_1 through A_n .

of the differences). Most previous studies have not used corrected measure but have been focused on a single vowel /a/ because it minimizes the effects of the first formant (Esposito 2010). Corrected measures take the formants into account during calculation and minimizes their influences. Fortunately, most software that is used for calculating the acoustic measurements, such as VoiceSauce (Shue, Keating & Vicenik 2009) and PraatSauce (Kirby 2022), produces both corrected and uncorrected values.

A second type of spectral measure that one often encounters are harmonic-to-noise ratios. Frequently these harmonics-to-noise ratios take the form of a Cepstral Peak Prominence (CPP) measurement which measures the difference in amplitude between the harmonic and inharmonic components of the source spectrum, as measured in the cepstral domain (de Krom 1993).

In determining whether or not a given measure corresponds to a given phonation several patterns have been described and validated by many authors. A summary of these findings are given in Garellek (2019) where it is noted that when the values of the spectral-tilt measurement are higher than that of the modal's spectral-tilt measurement and the CPP value is lower than the modal's CPP value this more than likely indicates a vowel with breathy phonation. If, however,

the spectral-tilt measurements are lower than the modal’s spectral-tilt measurements and the CPP value is lower than the modal’s CPP value this more than likely indicates a vowel with creaky phonation. This means that if the acoustic measurements for the SLZ phonation types match these findings we can be fairly confident that we are dealing with breathy and creaky phonation.

The rest of this section will describe the methods, results, and discussion of an acoustic analysis into SLZ’s phonation.

5.1 Methods

Due to the impact of the COVID-19 pandemic, only two native language speakers of SLZ were able to take part in this study (one male; one female). Both speakers live in Santa Cruz, CA and data collection was done remotely using Zencastr⁴, a professional podcasting website, (44.1kHz, 16-bit) or in-person outside in a well ventilated location, using a Zoom H4n handheld recorder (44.1kHz, 16-bit). Participants were recorded saying approximately 100 words in the carrier sentence *shnia’ X chone las* ‘I say X three times’. This phrase was repeated three times. The exact number of tokens that were analyzed are given in Table 6 which is repeated here as Table 7.

Table 7: Number of tokens analyzed in this paper for each interaction of tone and phonation.

	Modal	Breathy	Checked	Laryngealized	Totals
High	72	–	30	18	120
Mid	42	6	12	6	66
Low	102	30	54	18	204
High-Low	54	6	12	6	78
Mid-High	6	6	–	6	18
<i>Totals</i>	276	48	108	54	486

After the elicitations were completed the audio was uploaded into ELAN (Wittenburg et al. 2006) for initial segmentation into sentences. This was then followed by segmenting of the vowel portion in Praat (Boersma & Weenink 2021). These segments were then fed into VoiceSauce (Shue, Keating & Vicenik 2009) where each vowel was resampled at 16kHz for acoustic measurement. The acoustic measurements of VoiceSauce were then analyzed in R (R Core Team 2021). In order to investigate the differences in timing, each vowel was normalized for time and following Garellek & Keating (2011), the resulting measurements were averaged for each third of the vowel.

⁴<https://zencastr.com/>

5.2 Spectral-tilt results

In plotting the spectral-tilt measurements, we find that the results follow some of the established patterns and deviates in others. This section will first discuss the results of the H1-H2 measurements for the both FSR and RD, the H1-A3 measurements for FSR and RD, and the CPP measurements for FSR and RD.

5.2.1 H1-H2 results

The clearest result that was gleaned from the H1-H2 measurements show that the breathy voice is much lower than the measurement for modal vowels throughout much of the vowel. This can be seen in Figures 10a, 11, and 12. This behavior, however, is at odds with the observed patterns that breathy voice should have a higher H1-H2 value than the model's value. This suggests that instead of breathy voice is actually creaky. However, the correct behavior for breathy voice is observed in H1-A3, see Section 5.2.2

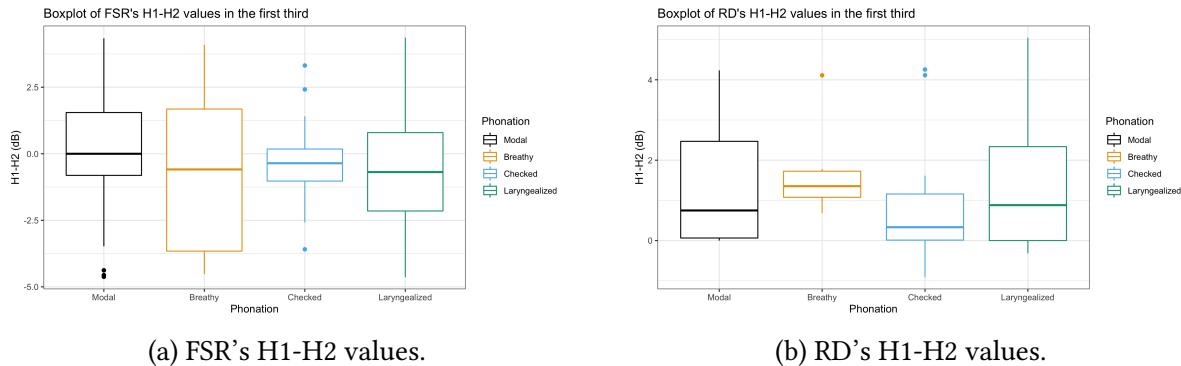


Figure 10: Mean H1-H2 values for the first third of the vowel according to each phonation type.

Additionally, in the first third of the vowel as shown in Figure 10, we see that the mean values for checked vowels are lower than those for modal vowels. This is true for both FSR and RD. In regards to laryngealized vowels the mean value for H1-H2 is nearly identical to that for modal vowels for RD. However, for FSR the value is lower.

In looking at the second third of each vowel, we observe very similar results as that for the first third except that there is a more pronounced decline in values for breathy vowels with them being much lower than modal vowels, see Figure 11. The results for checked and laryngealized vowels are still nearly identical to those in Figure 10.

In the final third of the vowel, we continue to see breathy vowels having a lower H1-H2 value than modal vowels, which runs against our expectations for breathy vowels. Breathy vowels should have a higher value for H1-H2 than modal vowels. In FSR's values for checked and laryngealized vowels, the values are still roughly the same as they were for previous portions of the

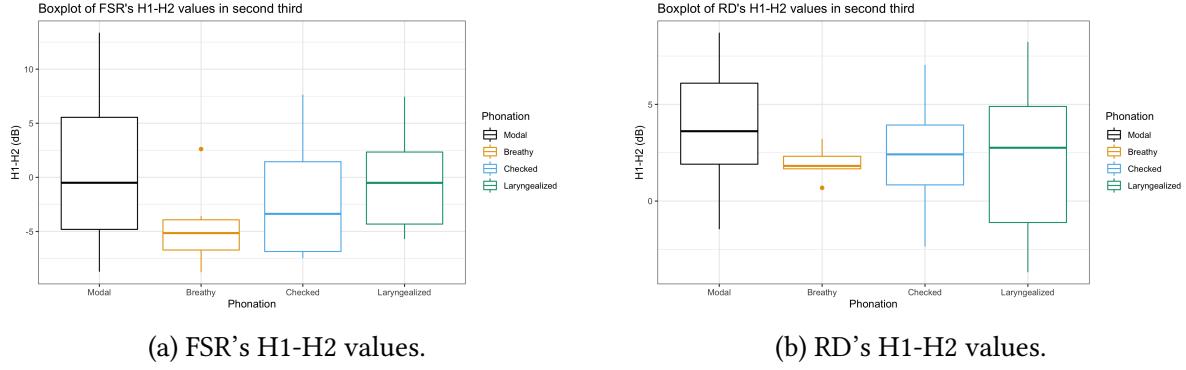


Figure 11: Mean H1-H2 values for the second third of the vowel according to each phonation type.

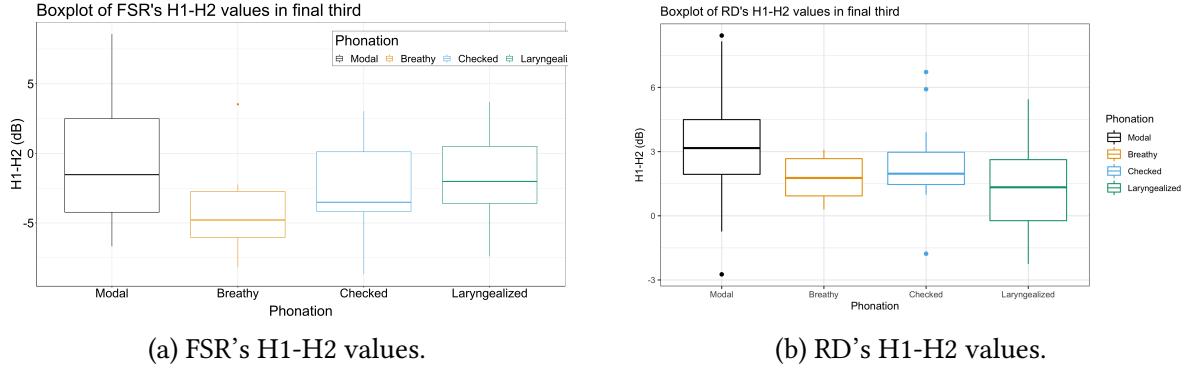


Figure 12: Mean H1-H2 values for the final third of the vowel according to each phonation type.

vowel. RD, however, shows H1-H2 values for checked and laryngealized vowels that are lower than the values for the modal vowel.

5.2.2 H1-A3 results

In turning to the H1-A3 spectral-tilt measurement that Esposito (2010) found useful for Central Valley Zapotec, several observations quickly become apparent. The most striking is the higher H1-A3 value found for breathy vowels in all portions of the vowel. This observation is true for both FSR and RD.

In the first third of the vowel, RD's mean value for H1-A3 is lower than the modal's H1-A3 value. However, there is a large degree of overlap between modals, checked, and laryngealized H1-A3 values, as evidenced by the boxes covering the same regions, see Figure 13.

In the second third of the vowel, Figure 14, the breathy vowel continues to be higher than the modal vowel. The checked and laryngealized vowels H1-A3 values for FSR are uninformative because of the large degree of overlap. For RD, these same measurements show a lower H1-A3 value than the modals which is consistent with creakier productions of vowels. This lower H1-A3

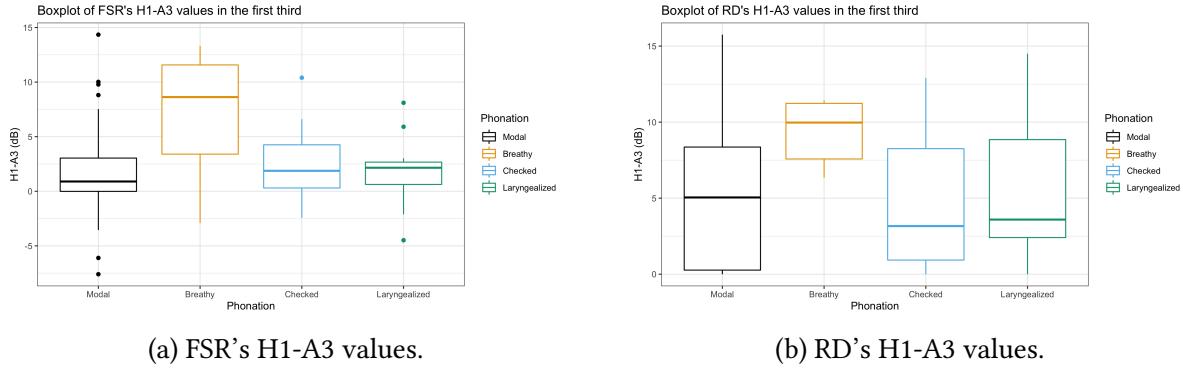


Figure 13: H1-A3 values for FSR (a) and RD (b) for the first third of the vowel.

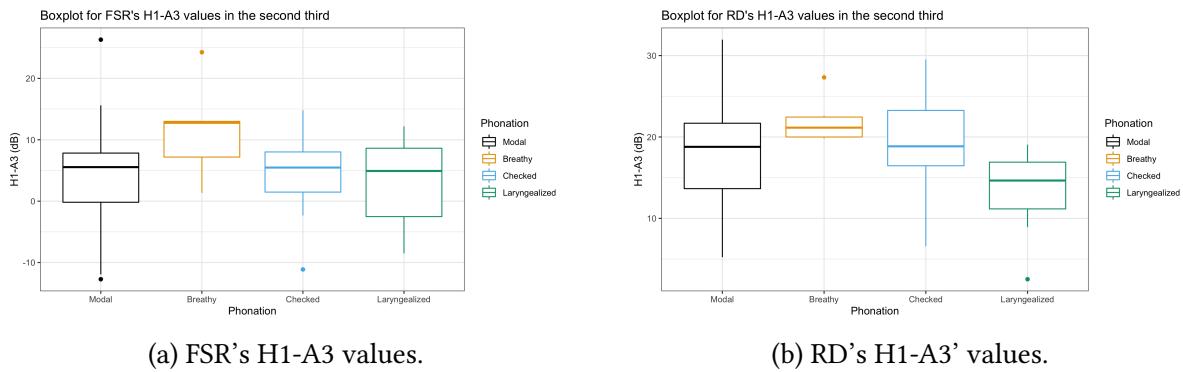


Figure 14: H1-A3 values for FSR (a) and RD (b) for the second third of the vowel.

continues throughout the rest of the vowel for laryngealized vowels, see Figure 15b. This behavior is consistent with the observation that RD performs creaky voice throughout their production of laryngealized vowels. For the checked vowels, the measurements are very similar to those of the modal vowel.

In looking at the final portion of the vowels, Figure 15, the measurements continue to show similar behavior to the second portion for both FSR and RD. However, one exception is the lower H1-A3 value for FSR's checked vowels, suggesting that FSR produces a period of creakiness in the last portion of the vowel.

5.2.3 CPP results

As previously mentioned at the start of Section 5, another measurement that is frequently encountered with spectral-tilt measurements is a Cepstral Peak Prominence (CPP) measurement (Hillenbrand, Cleveland & Erickson 1994), which is a type of harmonics-to-noise ratio and indicates whether or not there is any aperiodicity in the signal.

A CPP measurement for any vowel with non-modal phonation should be lower than the CPP measurement for modal vowels. When evaluating the CPP measurements for the same vowels

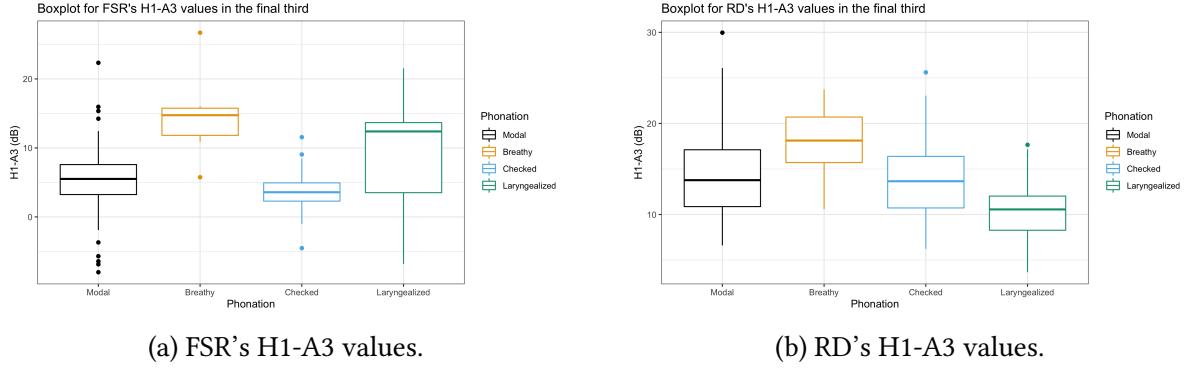


Figure 15: H1-A3 values for FSR (a) and RD (b) for the final third of the vowel.

and portions of a vowel, there are several observations that readily become apparent. The most noticeable observation is that for both speakers the breathy vowel's CPP value is consistently higher than the modal vowel's CPP value, which is opposite what is typically observed for non-modal phonation. When evaluating the checked vowel's CPP values, FSR had a lower value in the first third but the rest of the vowel shows values that are comparable to the modal vowel. For RD's checked vowels, the CPP shows that the mean is in fact lower than the modals in Figures 16b, 17b, and 18b but there is a large overlap in values.

Laryngealized vowels show a different pattern. For FSR, the laryngealized vowel's CPP value is lower than the modal's CPP value in the second-third of the vowel only. For RD, however, the laryngealized vowels have the roughly the same values as the modal vowels throughout the thirds.

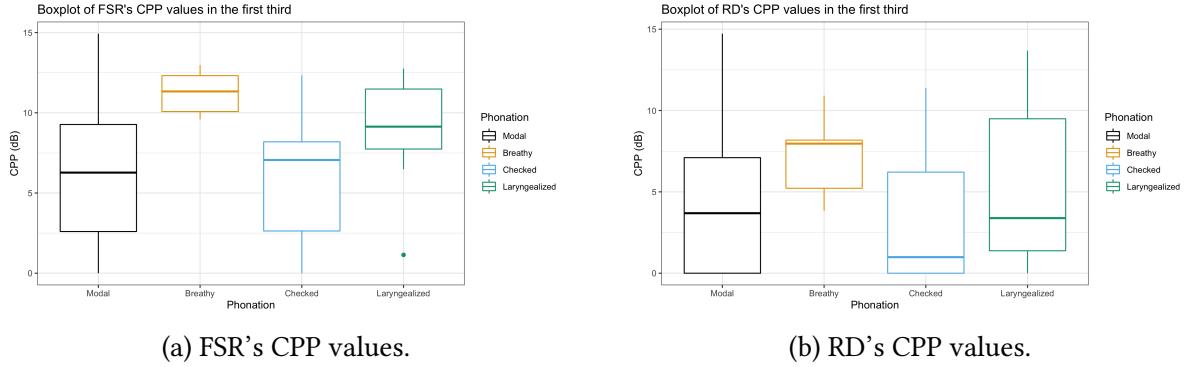


Figure 16: CPP values for FSR (a) and RD (b) for the first third of the vowel.

5.3 Statistical results

In order to determine whether or not the different acoustic measurements were effective at capturing the different phonation types, a mixed-effects linear regression analysis was performed

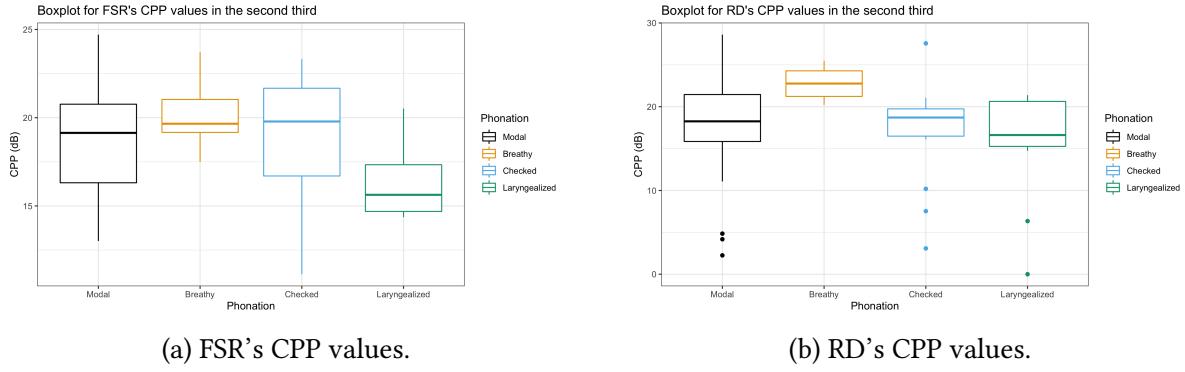


Figure 17: CPP values for FSR (a) and RD (b) for the second third of the vowel.

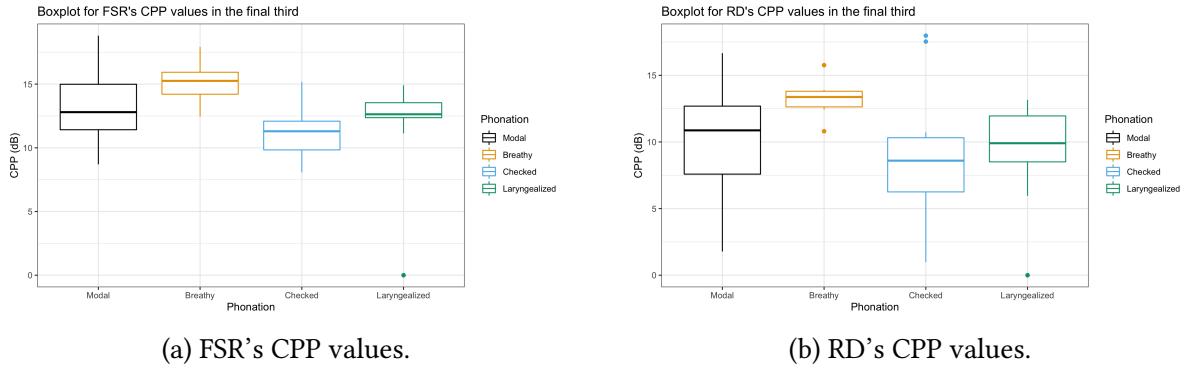


Figure 18: CPP values for FSR (a) and RD (b) for the final third of the vowel.

with a Satterthwaite's method for t-test analysis used to derive the p-values. Each of different measurements were treated as the dependent variable with word and speaker treated as random. In presenting the results of the statistical analysis, I will first present the results of the H1-H2 analysis, followed by H1-A3 and CPP.

The first statistical analysis took H1-H2 as the fixed effect with speaker and word as random. This analysis was repeated three times for each third of the vowels. The analysis for the first third of the vowels, results for which are presented in Table 8. This shows that there is no effect for the different phonation types.

Table 8: Results of the mixed-effects linear regression analysis on the first third of the vowel for H1-H2.

	Estimate	Std. Error	df	t value	p-value
Breathy	-0.3049	0.5795	116.4255	-0.526	0.600
Checked	-0.4731	0.4029	145.6184	-1.174	0.242
Laryngealized	-0.2938	0.4675	101.9977	-0.629	0.531

As can be recalled from Section 5.2.1, both FSR and RD show a lower value for H1-H2 for

breathy vowels in the last two-thirds of the vowels when compared to the model vowel's H1-H2 values. The results of the statistical analysis for the last two-thirds of the vowel, presented in Table 9 and Table 10, show that this behavior is significant.

At no point do the other phonation types reach significance with respect to H1-H2.

Table 9: Results of the mixed-effects linear regression analysis on the second third of the vowel for H1-H2.

	Estimate	Std. Error	df	t value	p-value
Breathy	-3.4158	1.3400	126.9590	-2.549	0.0120
Checked	-1.7466	0.9197	146.9995	-1.899	0.0595
Laryngealized	-0.7405	1.0852	117.0669	-0.682	0.4963

Table 10: Results of the mixed-effects linear regression analysis on the final third of the vowel for H1-H2.

	Estimate	Std. Error	df	t value	p-value
Breathy	-2.2131	1.0291	125.2092	-2.151	0.0334
Checked	-1.3487	0.6952	146.2461	-1.940	0.0543
Laryngealized	-0.8676	0.8202	116.8963	-1.058	0.2923

The second statistical analysis for the H1-A3 measurement shows some very clear behavior for breathy voice. As can be recalled from Section 5.2.2, we observe that breathy voice is clearly identified in all portions of the vowel with an elevated H1-A3 value when compared to the model vowels' values. We see that at all portions of the vowel, as seen in Tables 11, 12, 13 show significance.

Table 11: Results of the mixed-effects linear regression analysis on the first third of the vowel for H1-A3.

	Estimate	Std. Error	df	t value	p-value
Breathy	4.29036	1.31288	137.12067	3.268	0.00137
Checked	0.15001	0.84476	134.62215	0.178	0.85932
Laryngealized	-0.05694	1.07130	137.16596	-0.053	0.95769

However, the other phonations failed to reach significance when evaluated against H1-A3.

It is important to realize that at this point that H1-H2 and H1-A3 both have failed to account for checked and laryngealized phonations. This is also born out by the observations in Sections 5.2.1 and 5.2.2 which did not show any remarkable differences from the model. When we consider

Table 12: Results of the mixed-effects linear regression analysis on the second third of the vowel for H1-A3.

	Estimate	Std. Error	df	t value	p-value
Breathy	4.398	2.027	147.003	2.169	0.0317
Checked	1.195	1.426	147.000	0.838	0.4033
Laryngealized	-2.694	1.627	147.001	-1.656	0.0998

Table 13: Results of the mixed-effects linear regression analysis on the final third of the vowel for H1-A3.

	Estimate	Std. Error	df	t value	p-value
Breathy	5.2928	1.7966	127.0400	2.946	0.00383
Checked	-0.7825	1.2487	147.1011	-0.627	0.53189
Laryngealized	0.2669	1.4224	117.4917	0.188	0.85151

CPP we see both checked and laryngealized vowels clearly differentiated. This is born out in the statistical analysis. This analysis took CPP as fixed and speaker and word as random. This analysis showed that the first third of the vowel, Table 14 both breathy and checked voice were identifiable with CPP.

Table 14: Results of the mixed-effects linear regression analysis on the first third of the vowel for CPP.

	Estimate	Std. Error	df	t value	p-value
Breathy	3.4470	1.1743	145.9760	2.935	0.00387
Checked	-1.4190	0.7088	120.5020	-2.002	0.04754
Laryngealized	0.8240	0.9530	147.0083	0.865	0.38868

When considering the second-third of the vowel, Table 15, laryngealized vowels become clearly identifiable by CPP which is born out by the significance of laryngealized phonation and the lack of significance with breathy and checked. This is consistent with the observation that somewhere in the middle of the vowel there is either a full glottal stop or a period of creakiness in the two speakers that were evaluated for this study. This observation also bears witness to observations made by Avelino (2010) about the how each of the different manners that laryngealized vowels are produced in Yalálag Zapotec each have a period of model phonation followed by a aperiodicity or a glottal constriction beginning in the middle of the vowel.

In considering the final portion of the vowel, Table 16, the statistical analysis shows that only checked vowels can be reliably determined using CPP. This observations is consistent with the

Table 15: Results of the mixed-effects linear regression analysis on the second third of the vowel for CPP.

	Estimate	Std. Error	df	t value	p-value
Breathy	1.5044	1.4073	128.0083	1.069	0.287094
Checked	-0.5804	0.9789	146.0792	-0.593	0.554154
Laryngealized	-2.2898	1.1354	117.6213	-2.017	0.046006

facts that checked phonation consists of a period of creakiness or full glottal closure at the end of the vowel. The other phonation types fail to reach significance.

Table 16: Results of the mixed-effects linear regression analysis on the final third of the vowel for CPP.

	Estimate	Std. Error	df	t value	p-value
Breathy	1.6391	1.0173	139.8563	1.611	0.10939
Checked	-2.1386	0.6449	129.1392	-3.316	0.00119
Laryngealized	-1.1158	0.8142	140.5570	-1.370	0.17274

6 Discussion of the results

Based on the results of the spectral-tilt measurements, there is some agreement and disagreement in what measures capture the different phonations best. In agreement with Esposito (2010), the male SLZ speaker’s production of the different phonation types was best captured by H1-A3.

Contrary to Esposito (2010), however, H1-H2 was not the best measurement for phonation in all instances for the female SLZ speaker. FSR’s breathy vowels were best measured using H1-A3. This fact suggests several things. The first thing that we can surmise is that H1-H2 is not always the best measurement to use for phonation. It also suggests that Esposito’s (2010) observation, that H1-H2 is best for female speakers of Zapotec and H1-A3 for males, might be not be applicable to all varieties of Zapotec. However, there still remains a large amount of work to collaborate the results of this study. Primarily, this work was based on the results of only two speakers. Now that the COVID-19 pandemic has decreased in severity and most of the population in Santiago Laxopa has been vaccinated, more speakers can be consulted. This is especially important because it will allow us the opportunity to understand how laryngealized vowels are produced and what cues help differentiate these vowels.

This fact concerning laryngealized vowels is especially true given FSR’s spectral-tilt measurements for laryngealized vowels were nearly identical to the spectral-tilt measurements for

modal vowels. However, one thing that is important is that we still got a lower CPP vowel in the second-third of the vowel in these laryngealized vowels. This position is exactly where one would expect to find some acoustic cue. Additionally, we do see in the spectrograms for these laryngealized vowels a decrease in amplitude for a period of time. This decrease in amplitude is important because Gerfen & Baker (2005) found that even a small decrease of amplitude was enough for people to identify a glottal stop. When one considers RD's measurements for laryngealized vowels which are consistently produced with creaky voice, one finds that they show a consistently lower spectral-tilt measurement which matches what one would expect to see. This behavior suggests that breathy voice is articulated differently than those breathy vowels that are measured with H1-H2 (Esposito 2010).

Recent work, summarized in Esling et al. (2019), actually shows that the whole larynx is involved with the production of the different phonation types. Based on Moisik & Esling (2014) and other work, Esling et al. (2019) proposes a new model for accounting for the complex interactions in the larynx. This model termed the LARYNGEAL ARTICULATOR MODEL assumes that instead of a one-dimensional model you instead have a network of nodes that act in synergistic and anti-synergistic manners to each other. In a sense these nodes either work in a cooperative way strengthening or supplementing the workings of each other or the nodes are antagonistic and do not work together. These different nodes and their abbreviations are given in Table 17.

Table 17: A list of the different nodes and their abbreviations in the Laryngeal Articulator Model.

States/Nodes	Physiological description
vfo	vocal folds open (abducted)
vfc	vocal folds closed (adducted/prephonation)
epc	epilaryngeal constriction
epv	epilaryngeal vibration
tfr	tongue fronting
tre	tongue retraction
tra	tongue raising
tdb	tongue double bunching
↑lx	raised larynx
↓lx	lowered larynx
Hf0	increased vocal fold tension, less vibrating mass (high f0)
Lf0	decreased vocal fold tension, more vibrating mass (lower f0)

These twelve nodes not only represent the interactions of the larynx but also represents actual physiological representations. This means that any given node represents what is occurring with a given part of the larynx. For example, the node 'epc' represents any epilaryngeal constriction when activated. Now these nodes are not just independent entities but interact in complex ways

with other nodes. These interactions are best captured as a network or web of nodes as seen in Figure 19.

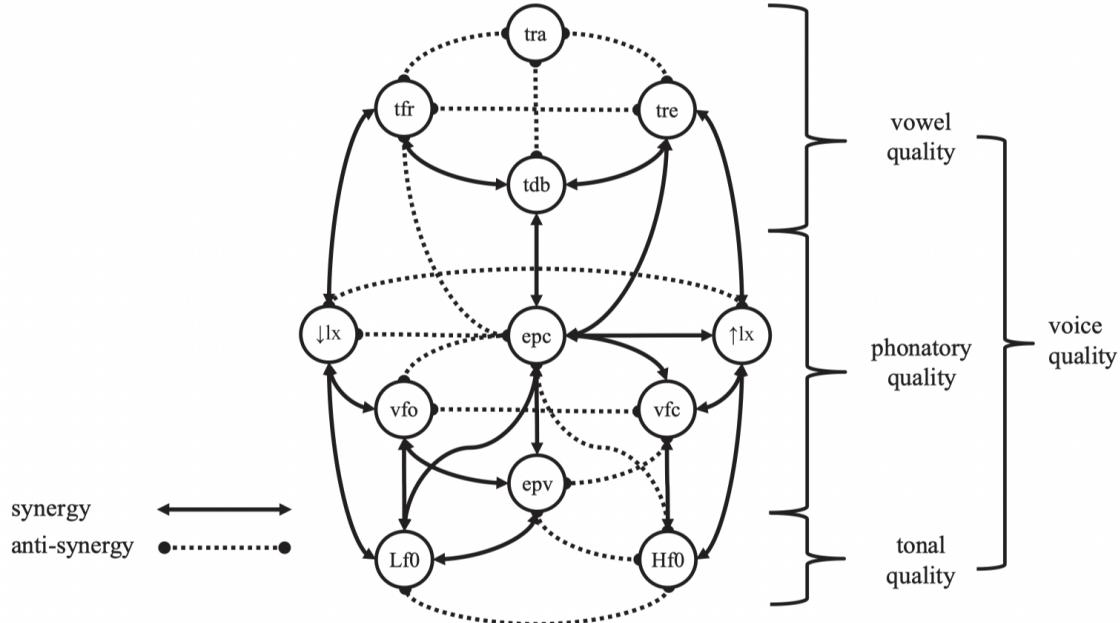


Figure 19: Network of synergistic and anti-synergistic nodes in the Laryngeal Articulator Model. Taken from Esling et al. (2019).

Figure 19, shows which nodes interact in synergistic and anti-synergistic ways. This network is divided into three parts that represent the nodes which are responsible for vowel quality, phonatory quality, and tonal quality. For example, the node ‘epc’ which is one of the nodes responsible for phonatory quality (i.e., responsible for producing phonation) has synergistic relationships with the nodes representing larynx raising ($\uparrow\text{lx}$), vocal fold closure (vfc), tongue bunching(tdb), tongue retraction (tre), and for decreasing the vocal fold mass leading to a lowering of f0 (Lf0). In contrast this same node has anti-synergistic relationships with tongue fronting (tfr), larynx lowering ($\downarrow\text{lx}$), vocal fold opening (vfo), and increasing vocal fold tension which leads to less vibrating mass and an increase to f0 (Hf0). This means that when there is epilaryngeal constriction there is an increased chance for the synergistic relationships to also co-occur. However, this does not mean that the synergistic nodes must co-occur when the node is activated.

While Esling et al.’s (2019) Laryngeal Articulator Model does make a compelling argument for the complexity of the larynx and allows for a detailed account of what the larynx is doing during phonation, it is not entirely clear if this added complexity is altogether warranted. From the results of the statistical analysis the simplified one-dimensional model of the larynx is fully capable of explaining the behavior we observe in SLZ and the other Oto-Manguean languages which form the backbone of the LCH. If, however, we were observe large degrees of overlap

between tone and phonation then it stands to reason that the LCH does not capture the nature of the laryngeal systems we are observing and a different model of the larynx, such as the Laryngeal Articulator Model, is needed to capture the more complex interactions of tone and phonation.

7 Conclusion

In conclusion, this paper has provided a brief introduction to the tonal and phonation systems of Santiago Laxopa Zapotec, an understudied variety of Sierra Norte Zapotec. This system is important for studying the interaction of tone and phonation because of the complex interactions between tone and phonation that are found in this language. This paper presented a preliminary analysis of the tone and phonation contrasts and their correspondents in the acoustic signal.

Contrary to acoustic work on other Zapotec varieties by Esposito (2010), which showed that female speakers' phonation contrasts were best characterized by H1-H2 and male speakers' contrasts by H1-A3, SLZ suggests that both male and female speakers' breathy voice is best characterized by H1-A3 and checked and laryngealized voice are characterized by a difference in the timing of CPP contrasts.

This ability of speakers to interpret the acoustic signals in conjunction with the acoustic signals for tone is of great interest and would benefit from a perception experiment to determine what it is that the speakers are using to differentiate the different phonation types. This is especially true for laryngealized vowels which have such a varied pronunciation.

This study will benefit from further analysis and data collection. Now that the world is in a safer state in regards to COVID-19 it is important to collect data from more speakers to corroborate the data and analysis from FSR and RD.

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