Investigating the timing of tone and phonation in Santiago Laxopa Zapotec[1]

Mykel Loren Brinkerhoff

1 Introduction

Most work on the interaction of tone and phonation has been based on descriptions of south-east and far east Asian languages. This lead to strong claims on the interaction between tone and phonation (Masica 1976, Thurgood 2002, Yip 2002, Enfield 2005, Michaud 2012, Brunelle & Kirby 2016). Main claim from these authors is that tone and phonation are codependent. This is often referred to as a register system. Meaning that we only observe certain tones with certain phonations. Mandarin Tone 3 is always associated with creaky voice (Duanmu 2007). 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). This is often born out with research into register systems. Also found in pathological voice quality (Klatt & Klatt 1990, Titze 2000, 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. Tone and phonation freely co-occur or exhibit a much freer distribution than what is found in register languages. San Lucas Quiaviní Zapotec is one such example.

- This paper adds to this debate by:
  - Providing another description of a language that uses tone and phonation
  - Evaluates the claims of Silverman (1997)

2 The Laryngeal Complexity Hypothesis

The Laryngeal Complexity Hypothesis (LCH) has it 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 a strict ordering between the laryngeal gestures for tone and phonation. This premise comes from the understanding that the same mechanism that is responsible for tone is also responsible for the production of phonation. The mechanism that is assumed to be responsible is the vocal folds and glottis. The rate that vocal folds vibrate is

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responsible for changing the frequency that the sound is produced at. This is often perceived as pitch and when pitch is lexicalized it becomes tone. The faster the vocal folds vibrate the higher the pitch and the slower the vocal folds vibrate the lower the pitch.

The notion that the vocal folds and glottis are responsible for phonation comes from work by Ladefoged (1971) and Gordon & Ladefoged (2001) which 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 [ʔ].

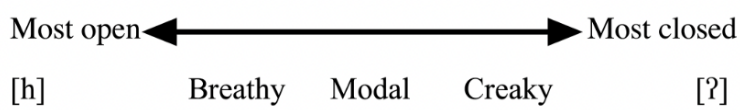

Figure 1: Simplified one-deminsional model for phonation. Based on Ladefoged (1971) and Gordon & Ladefoged (2001)

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The LCH assumes that phonation and tone are both produced at the vocal folds anf 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 does assume that there is a close link between production and perception. Primarily, this means that it is burden of the speaker to produce both the tone and phonation gestures in a way that is the most perceptually salient. The assumptions of the LCH is schematized in Figure 2.

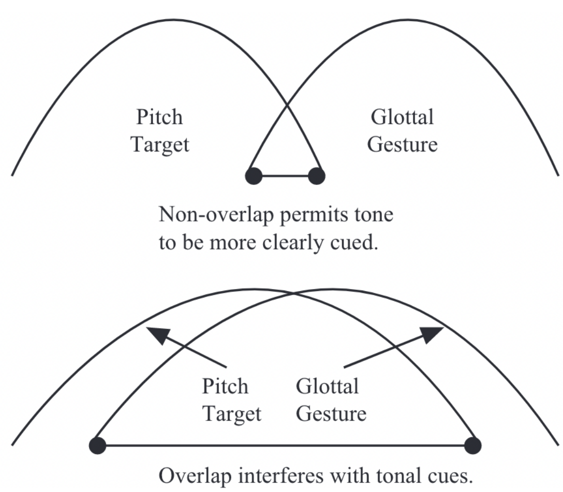

Figure 2: Representation taken from DiCanio (2012).

Some work has been done into investigating this in other languages, most notably DiCanio's (2012) investigation into glottals in Itunyoso Trique. DiCanio found that when there is a large degree of overlap in the signal then the acoustic signal for F0 had perturbation. If, however, the degree of overlap was minor then the acoustic signal had no perturbation. In Itunyoso Trique, DiCanio found that there was a statistically significant amount of perturbation throughout the vowel. 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 investigates the interaction of tone and phonation in the Northern Zapotec language of 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. Following this discussion on Santiago Laxopa Zapotec, this paper discusses an acoustic analysis of phonation modelled on Esposito (2010), Garellek & Keating (2011), and DiCanio (2012) in Section 5.

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. These contrasts and inventories can be seen in Table 1 and Table 2.

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

3.1 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-Peón 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).

(1) Four-way minimal phonation contrast
  a. *ya* [ja$^{\text{L}}$] 'bell'
  b. *yah* [ja̤$^{\text{L}}$] 'metal/rifle'
  c. *ya'* [jaˀ$^{\text{L}}$] 'pound'
  d. *ya'a* [jaˀa$^{\text{L}}$] 'market'

Table 1: Consonant inventory for Santiago Laxopa Zapotec

		bilabial	alveolar	retroflex	alveo-palatal	palatal	velar	labio-velar	uvular
nasal	lenis		n						
	fortis	mː	nː						
stop	lenis	b	d				g	gʷ	
	fortis	p	t				k	kʷ	
fricative	lenis		z	ʐ̥~ɽ	ʒ	ç			ʁ~χ
	fortis		s	ʂ	ʃ				
affricate	lenis		d͡z						
	fortis		t͡s		t͡ʃ				
lateral	lenis		l~ɾ						
	fortis		lː						
trill			r						
approximate						j		w	

Table 2: Vowels inventory in Santiago Laxopa Zapotec.

	front	central	back
high	i		u
mid	e		o
low		a	

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 3.

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 4.

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 realted Yalálag Zapotec that among his consultants there were at least four different pronunciations as seen in Table 3 In SLZ, each of the consulted 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* [ʂa̰ːg] 'topil'[2], see Figure 5 for a comparison between this consultant's pronunciation of

[2]A topil is a type of government office in traditional Oaxacan communities somewhat akin to a sherif.

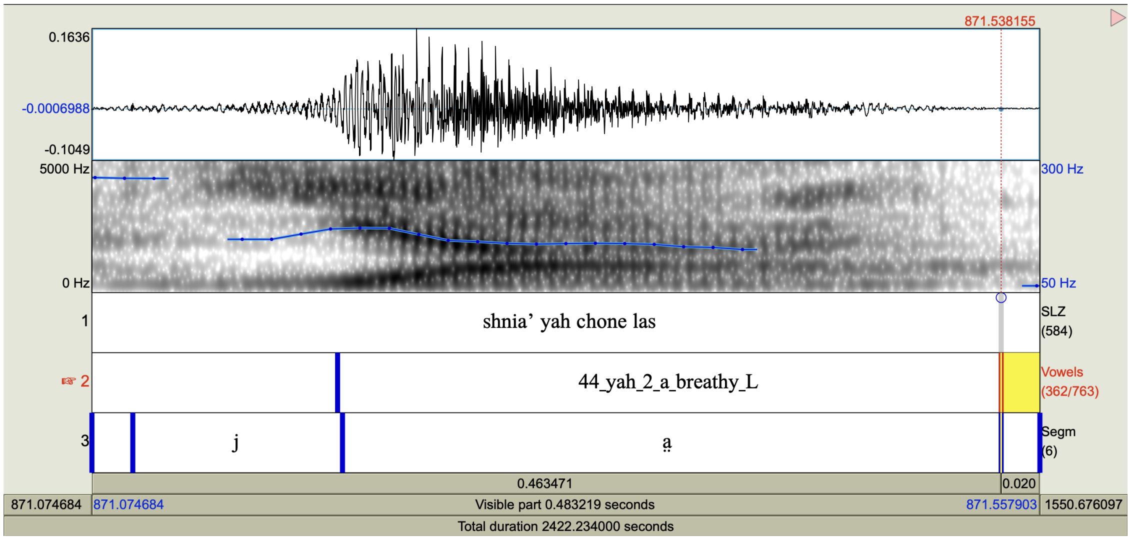

Figure 3: Breathy vowel in the word *yah* ‘metal/rifle’

[INSERT YA’ SPECTROGRAM AND WAVEFORM]

Figure 4: Breathy vowel in the word *ya’* ‘pound’

Table 3: Layngealized Vowels in Yalálag Zapotec

/V’V/	[VʔV]
	[VV̰V]
	[VV̰:V̆]
	[VV̰V̰]

the laryngealized vowels.

[INSERT SIDE BY SIDE SPECTROGRAMS]

Figure 5: Comparison of FSR’s laryngealized vowels in *ya’a* ‘mountain’ 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 sanity check that these were in fact the same vowels and both consultants reliably identified the words and would produce the laryngealized vowel according to their own idiosyncrasies. However, a more detailed perception study is beyond the scope of this paper.

[INSERT SIDE BY SIDE SPECTROGRAMS]

Figure 6: Comparison of RD’s laryngealized vowels in *ya’a* ‘mountain’ and *xa’ag* ‘topil’

3.2 Tone in SLZ

As is common among Oto-Manguean languages, SLZ is a tonal languages (Suárez 1983, Campbell, Kaufman & Smith-Stark 1986, Silverman 1997, E. W. Campbell 2017a,b). In SLZ there are five surface tones which appear on a syllable.

Table 4: SLZ tones

High	a^{H}	*xha*	[ʐa^{H}]	'clothing.POSS'
Mid	a^{M}	*lhill*	[ɾiʒ^{M}]	'house.POSS'
Low	a^{L}	*yu'*	[juˀ^{L}]	'earth'
Rising	a^{MH}	*yu'u*	[juˀu^{MH}]	'quicklime (Sp. cal)'
Falling	a^{HL}	*yu'u*	[juˀu^{HL}]	'house'

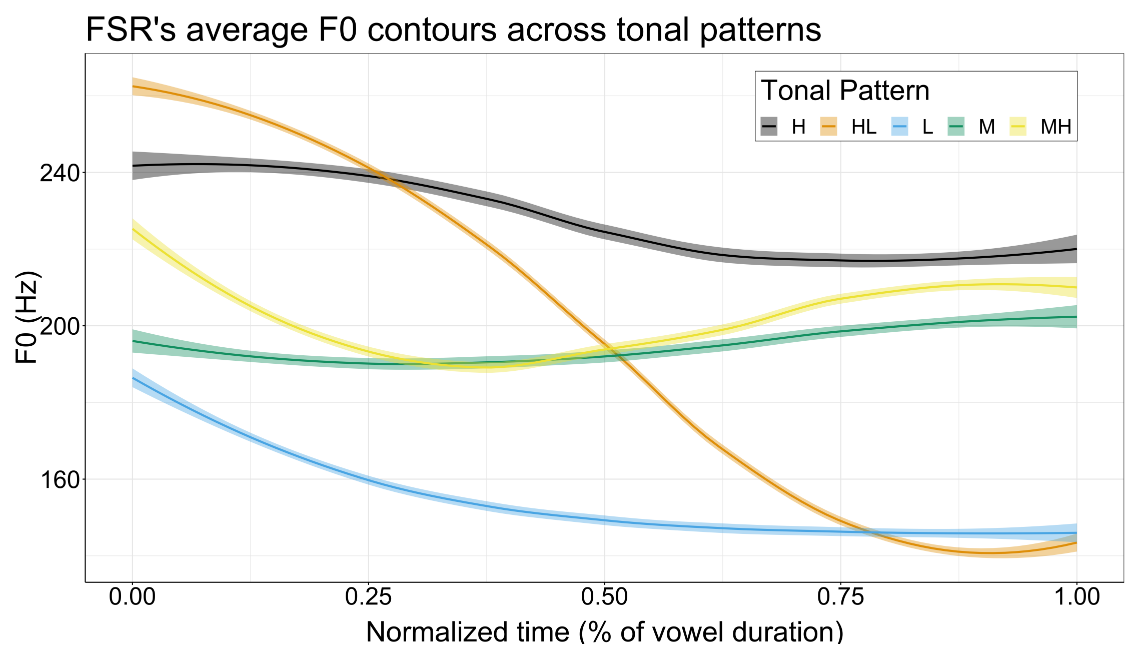

Figure 7: Tonal contrasts for FSR averaged and time normalized.

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. This has the appearance of being a prototypical "word tone" language following Pike's (1948) categorization. However, recent work from Shih & Inkelas (2019) and McPherson (In press) has argued that the "word tone" description is epiphenomenal and can be derived via surface constraints on tone. Which is what Brinkerhoff, Duff & Wax Cavallaro (2022) argues.

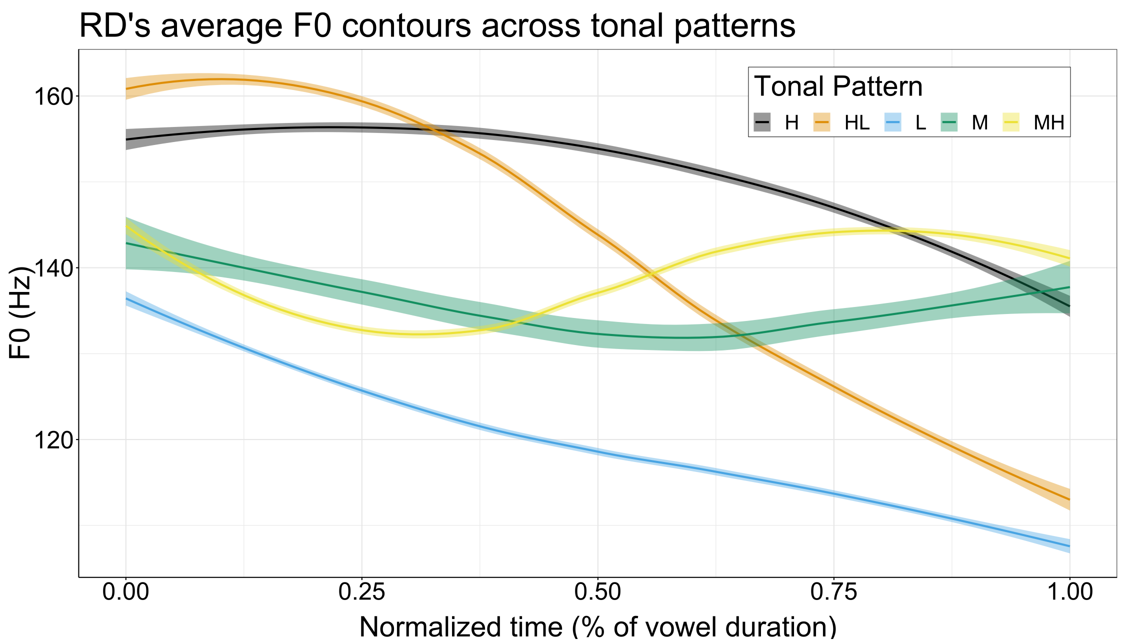

Figure 8: Tonal contrasts for RD averaged and time normalized.

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 (i.e., only occur with each other). 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 phonaiton 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 amodal phonation (Boehm p.c.).

However, there has been some observations–especially in Mesoamerican–that tone and phonation can co-vary (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-Peón 2010, E. Campbell 2011, Villard 2015, López Nicolás 2016)

Chávez-Peón (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.

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 varities (e.g., Avelino 2004). The distribution of SLZ tonal and phonation interactions are given in Table 6.

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

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

Table 6: Distribution of tone and phonation in SLZ

	Modal	**Breathy**	**Checked**	**Laryngealized**
High	✓	–	✓	✓
Mid	✓	✓	✓	✓
Low	✓	✓	✓	✓
High-Low	✓	✓	✓	✓
Mid-High	✓	✓	–	✓

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 phoantion 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 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.

5 Acoustic investigation into the phonation

One of the primary ways to measure and investigate phonation is using spectral measures. This has 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). Most studies that are using spectral measures are 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 5.

When conducting spectral 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 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.

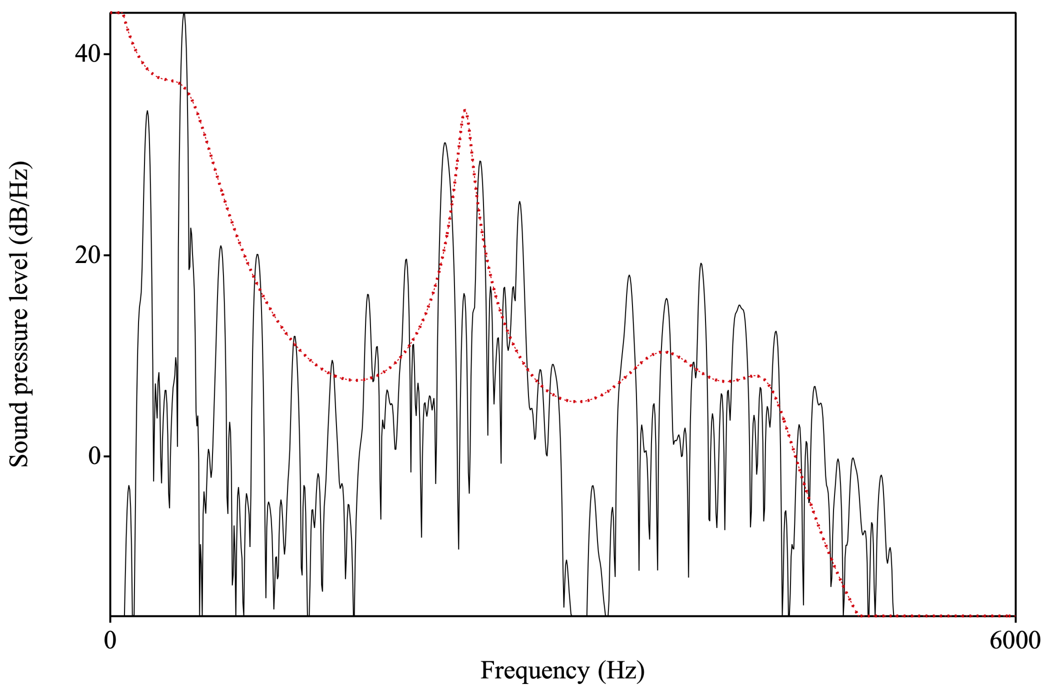

Figure 9: Spectral slice with LPC smoothed line overlaid for the vowel [e]. The harmonics in the spectral slice are represented by each of the dark peaks. The leftmost black solid line peak is the first harmonic (H1) and each subsequent peak represents the next highest harmonic (H2 through H*n*). The 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 A1 through A*n*.

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 Zencastr[3], a professional podcasting website, or

[3]https://zencastr.com/

in-person outside in a well ventilated location, using a Zoom H4n handheld recorder (44.1kHz, 16-bit). Participates 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.

After the elicitation 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 inputted to VoiceSauce (Shue, Keating & Vicenik 2009) were 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.

5.2 Results

The results of the spectral-tilt measurements were for the most part accurate. As noted by Esposito (2010) for a Central Valley Zapotec, there is a difference in which acoustic measurements were most informative for the speakers based on their sex. Similar to Esposito, the female speaker was best characterized with the H1-H2 measurements and the male speaker was best characterized with H1-A3. For the female speaker this was true for all phonation types except for breathy voice which c

As mentioned previously, one of our speakers would regularly produce the laryngealized vowels with rearticulation, meaning that they produced the vowel with glottalization, with either creakiness or a full glottal closure, in the middle of the vowel. This is in contrast with the checked vowels which have a short period of creakiness or a full glottal closure at the end of the vowel. This means that our spectral-tilt measurements should reflect a difference in time with creaky voice appearing earlier in the laryngealized vowels than checked vowels. When we compare the spectral-tilt measurements for this speaker, see Figure 10.

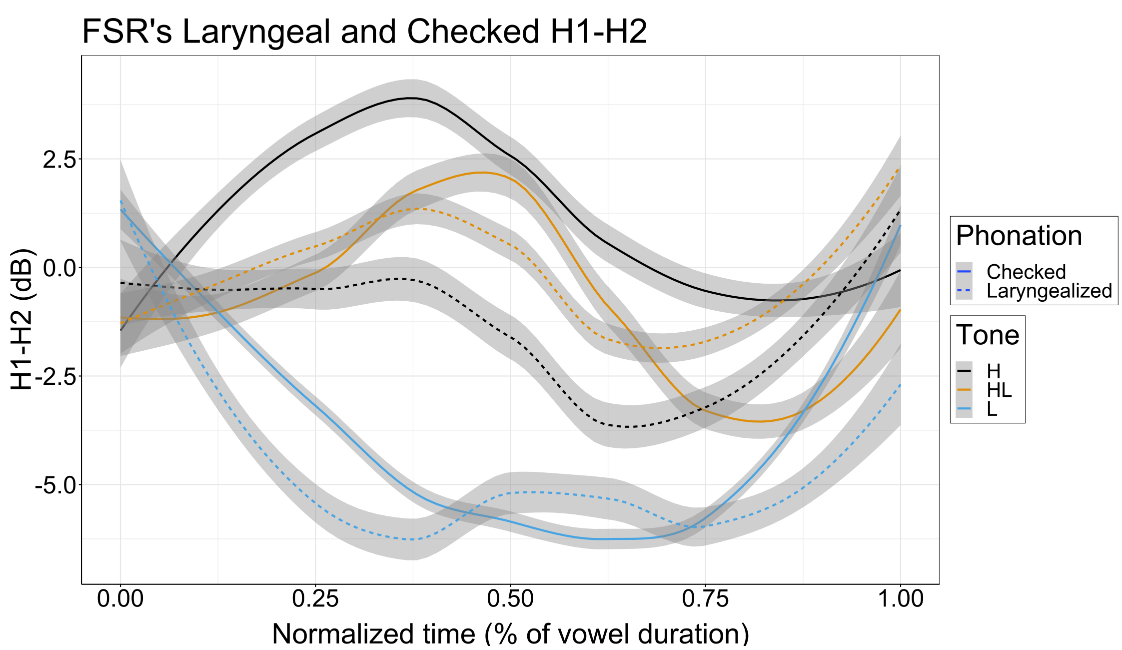

Figure 10: FSR's H1-h2 values for checked and laryngealized.

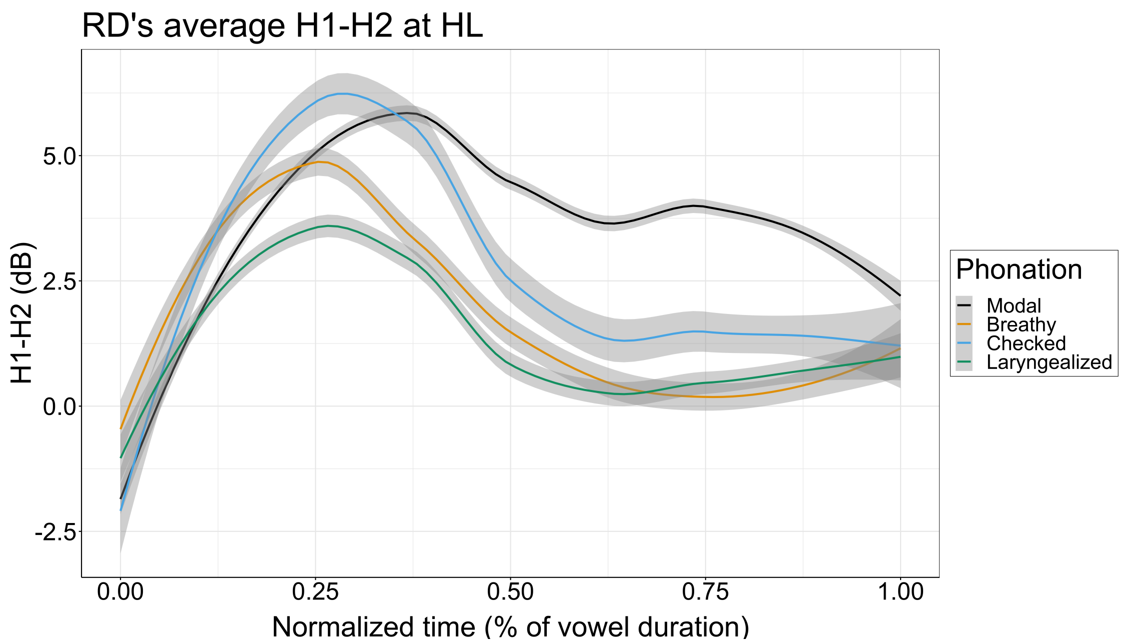

Figure 11: RD's H1-H2 values in HL toned syllables.

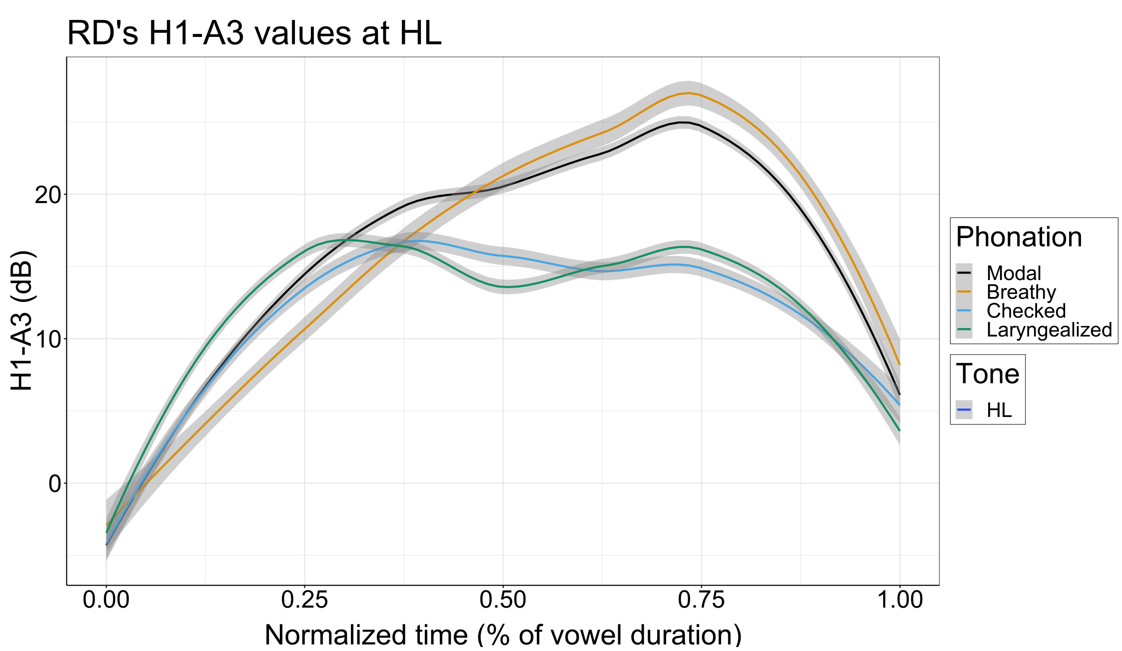

Figure 12: RD's total H1-A3 values in HL toned syllables.

- Might be useful to validate h1-h2 and h1-a3 measurements as useful diagnostics.
- What do the measurements show me?
  - FSR shows a timing difference between checked and rearticulated in h1-h2.
  - RD shows the differences we expect to see in h1-a3 but not

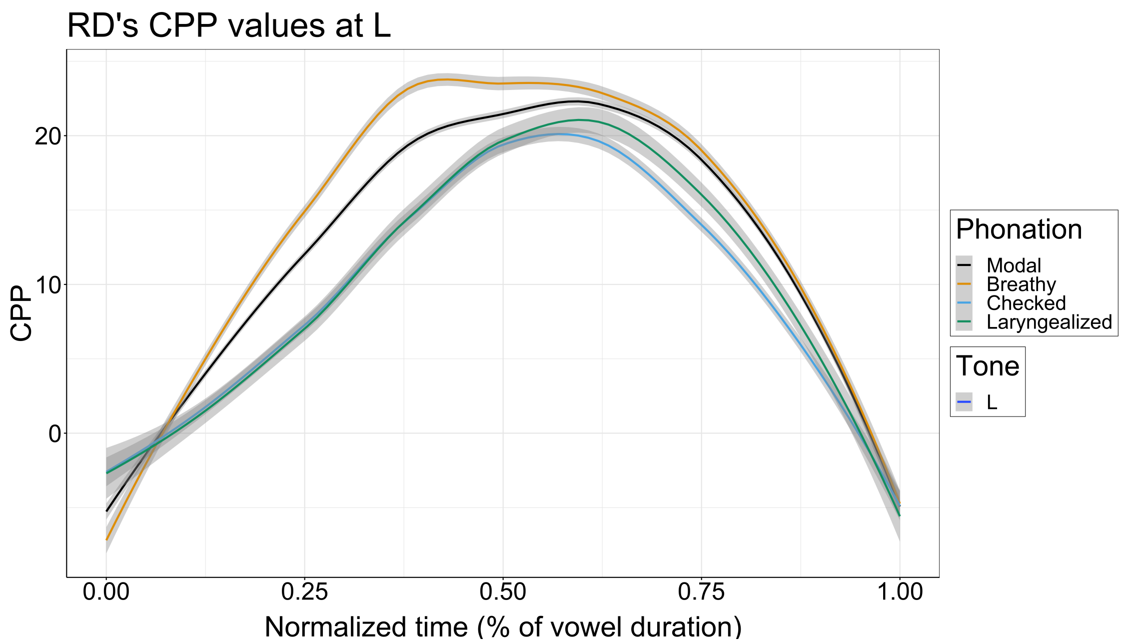

Figure 13: RD's CPP values.

5.3 Discussion of the results

6 Challenges to theories

- How does this support or detract from Silverman's (1997) claims?
    - Do we see the gestural timing that Silverman (1997) claims to exist?
- Issues with breathy not present with H.
- Additionally there is this question about why we are seeing laryngealized vowels in H tone
    - Could Esling et al.'s (2019) model of interactions be used to explain what we are seeing?

7 Esposito 2010

- Esposito investigates variation in Santa Ana del Valle Zapotec for variation due to gender, F0 and prosodic position.
- Results were inconclusive as to whether or not gender was creakier or breathier though the acoustic measurements (H1-H2 and H1-A3) suggest that there is a difference in PRODUCTION.
- Strong effects of F0 were observed
- The phonation contrasts were present in all positions but were not always well-defined.

- There has been a wide number of studies that have observed phonation differences based on gender, F0, and position. For example females are often described as being breathier than males (though this was not true all the time) and prosodic position produced different phonations. Additionally, all of these cases involve allophonic or suprasegmental phonation (i.e., non-phonemic)
- Very little work has investigated languages with phonemic phonation contrasts
- Jalapa Mazatec and San Lucas Quiaviní Zapotec are some of the few that have seen some study.
- In those studies females were breathier than the male speaker.
- SADVZ is an ideal language to study the variation in phonation because it has relatively free word order and the contrastive phonation that exists.
- Spectral measurements have been found to be very useful measure of phonation in a wide number of different languages.
- Most of these have been focused on H1-H2, however, relationships with H1 compared to higher harmonics have also been found to be useful.
- Most previous studies have not used corrected or normalized measure but have been focused on a single vowel /a/ because it minimizes the effects of the F1
- Esposito focuses on H1-H2 (open quotient) and H1-A3 (speed of vocal fold closure) based on a pilot study she ran in 2003.
- Vowel measurements were made by splitting the vowel into four equal parts and h1-h2 and h1-h3 measurements were made in the last quarter of each vowel.
- H1-A3 and H1*-A3* were effective in distinguishing the different phonation types in males. The difference between corrected and uncorrected were not significant.
- H1-H2 was effective for females speakers.
- The fact that h1-h2 was effective for females and h1-a3 for males suggests that they are using different laryngeal settings. Female speakers are making more use of open-quotient whereas male speakers are using the speed of vocal fold closure to distinguish the different phonation types.
- When looking at whether or not there is an effect for prosodic position it was observed that F0 had more of an effect than position.
- What was found was that all three contrasts were maintained but differed in how clearly they are produced.

8 DiCanio 2012

- DiCanio is concerned with exploring the effects that tone and glottal consonants have on each other.
- Much of the earlier work on coarticulation claimed that the processes of the interaction of tone and phonation/glottal consonants revealed something universal or a set of constraints that applied to all languages.
- More recent work actually argues against this notion specifically that there aren't language-wide or universality but instead is based on language-specific patterns.
- One of these areas has to do with the phasing or co-articulation discussion.
- One area that has received substantially less discussion is on the realm of tone and phonation type contrasts.
- This study serves two main purposes: (i) expand the emperical basis for the analysis of tone-segment coarticulation and (ii) test how changes in relative timing of glottal consonants affect F0 on adjacent vowels.
- One main question I have is that these contrasts that DiCanio is describing seem to be almost more akin to phonation contrasts instead of segmental changes. However, he does seem to have a good amount of information from his dissertation which suggests that these are segmental instead of qualities of the vowel (DiCanio 2008).
- There is some discussion about Silverman (1997) where glottal consonants are abruptly phased relative to the vowels.
- According to Silverman there needs to be abrupt phasing so listeners can distinguish the tone and the glottal contrast.
- Trique does a wonderful job to at allowing us to test this claim that there is abrupt phasing. Specifically this paper investigates whether the amount of coarticulatory overlap between glottals and vowels effect the F0 perturbation.
- Trique has prominence and is reflected by a large distribution of contrasts in the final-syllables of words. But these contrasts are neutralized in non-final syllables. Phonetically realized by increased duration
- Spectral tilt was used to measure the magnitude of glottal tension or spreading. H1-H2 is a useful diagnostic for differentiating breathy, modal, and tense/creaky phonation. Additionally, H1-A3 is useful for breathy vs. non-breathy.
- Results were z-transformed and then a linear mixed effects model was run with speaker as random.
- Breathy phonation is described as higher h1-h2 values and lower H1-H2 values with lower F0. Lower F0 is associated with breathy voice.

9 Conclusion

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