

Investigating the timing of tone and phonation in Santiago Laxopa Zapotec¹

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1 Introduction

Most of the work on the interaction of tone and phonation has been based on descriptions of southeast and far east Asian languages, which lead to strong claims being made about what is possible for the interaction between tone and phonation (**masicaDefiningLinguisticArea1976**, **thurgoodVietnameseTonogenesisRevising2002**, **yipTone2002**, **enfieldArealLinguisticsMainland2005**, **michaudComplexTonesEast2012**, **brunelleTonePhonationSoutheast2016**). The main claim from many of these authors is that tone and phonation are codependent (i.e., certain tones only appear with certain phonations).

An example for this type of co-occurrence between tone and phonation is Mandarin's Tone 3 which is frequently associated with creaky voice (**hockettPeipingPhonology1947**).

2 The Laryngeal Complexity Hypothesis

The LARYNGEAL COMPLEXITY HYPOTHESIS (LCH) has its origins in the work from **silvermanLaryngealComplexity1990**, **blankenshipTimeCourseBreathiness1997**, **blankenshipTimingNonmodalPhonation2002**.

The basic premise of the LCH is that in languages that have both tone and phonation there needs to be an ordering between the 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. **laedefogedPreliminariesLinguisticPhonetics2000**, **gordonPhonationTypesCrosslinguistic2001** treated phonation as a by-product of how open or closed the glottis is during vocal fold vibration. This is schematized by Figure ???. The more

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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 [?].

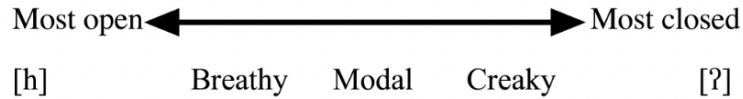


Figure 1: Simplified one-dimensional model for phonation. Based on **ladefogedPreliminariesLinguisticPhonetics1971, gordonPhonationTypesCrosslinguistic2001**

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 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 ??.

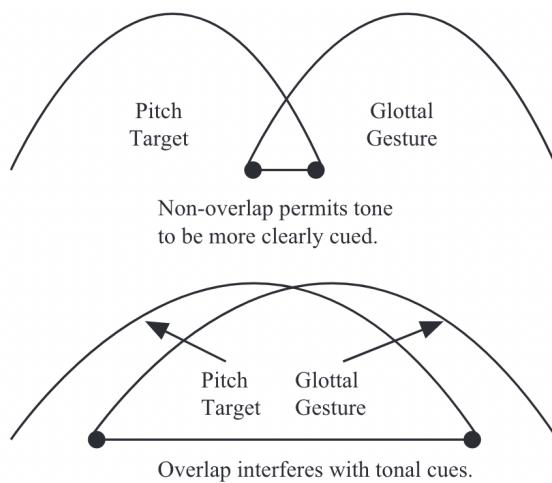


Figure 2: Representation taken from **dicanioCoarticulationToneGlottal2012**.

Some work has been done into investigating this in other languages, most notably **dicanioCoarticulationToneGlottal2012**. An investigation into glottals in Itunyoso Trique. **dicanioCoarticulationToneGlottal2012** 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, **dicanioCoarticulationToneGlottal2012** found that there was a statistically significant amount of perturbation throughout the vowel.

Another study on Jalapa Mazatec (**garellekAcousticConsequencesPhonation2011**) also investigated the interaction of tone and phonation. Jalapa Mazatec is a language with both contrastive tone and phonation and **garellekAcousticConsequencesPhonation2011** 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 ?? 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 **espositoVariationContrastivePhonation2010**, **garellekAcousticConsequencesPhonation2011**, **dicanioCoarticulationToneGlottal2012** in Section ??.

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 (**adlerAcousticsPhonationTypes2016**, **adlerDerivationVerbInitiality2018**, **foleyForbiddenCriticClusters2018**, **foleyExtendingPersonCaseConstraint2020**). It is closely related to San Bartolomé Zoogocho Zapotec (**longDiccionarioZapotecoSan2005**, **sonnenscheinDescriptiveC** and is mutually intelligible with this variety according to native speakers. As is common among Zapotecan languages, SLZ distinguishes between lenis and fortis consonants (**nellisFortisLenisCajonos1980**, **jaegerFortisLenisQuestion1983**, **uchiharaFortisLenisGlides2016**) and has a fairly standard five-vowel inventory. These contrasts and inventories can be seen in Table ?? and Table ??.

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 ?? followed by the tonal phonation in Section ??.

3.1 Tone in SLZ

As is common among Oto-Manguean languages, SLZ is a tonal language (**suarezMesoamericanIndianLanguage1980**, **campbellMesoAmericaLinguisticArea1986**, **silvermanLaryngealComplexityOtomanguean1997**,

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	z̪̫	ʒ	ç			χ̪̫
	fortis		s	ʂ	ʃ				
affricate	lenis		dz̪̫						
	fortis		ts̪̫		ʈʃ̪̫				
lateral	lenis		l̪̫						
	fortis		l̪̫						
trill			r						
approximate					j			w	

Table 2: Vowels inventory in Santiago Laxopa Zapotec.

	front	central	back
high	i		u
mid	e		o
low		a	

campbellOtomangueanHistoricalLinguistics2017a, campbellOtomangueanHistoricalLinguistics2017b

In SLZ there are five surface tones which appear on a syllable. Following other papers on SLZ, I am representing the tone using Pike's numbers (**sichelFeaturalLifeNominals2020**). Pike's numbers are commonly used in describing Mesoamerican tone systems and has its origins in **pikeToneLanguagesTechnique1948** work with Mixtec. A good summary of this system and its comparisons to other tone marking systems is given in **weePhonologicalTone2019**. Pike's numbers represent the highest tone with the number 1 and then each subsequent tonal level is represented with the next number until all levels have been assigned. In the case of a language with three distinct levels the number 1 represents the highest tone, the number 2 represents the mid tone, and finally the number 3 represents the lowest tone. Additionally, these different numbers can be combined to represent the different contour tones that exist in the language, for example 21 representing a tone that starts at the mid level and then increases its pitch to high.

Following discussion from **brinkerhoffTonalPatternsTheir2022** 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

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

High	a ¹	xha	[za ¹]	'clothing.POSS'
Mid	a ²	lhill	[ri ²]	'house.POSS'
Low	a ³	yu'	[ju ³]	'earth'
Rising	a ²¹	yu'u	[ju'u ²¹]	'quicklime (Sp. cal)'
Falling	a ¹³	yu'u	[ju'u ¹³]	'house'

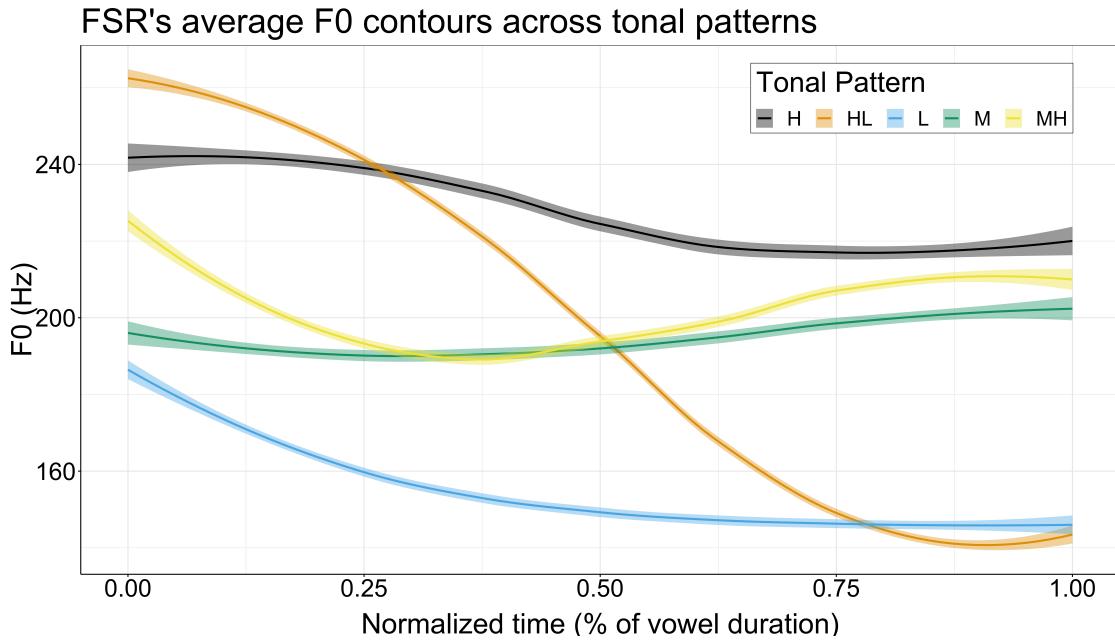


Figure 3: Tonal contrasts for FSR averaged and time normalized. Each line in this graph represents the average of approximately 10 syllables for each tonal pattern.

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.

3.2 Phonation in SLZ

Among Zapotecan languages it is quite common for languages to make use of contrastive phonation (avelinobecerraTopicsYalalagZapotec2004, longDiccionarioZapotecoSan2005, avelinoAcousticElelopeznicolasEstudiosFonologiaGramatica2016, chavez-peonInteractionMetricalStructure2010). 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 (??). In representing the checked and laryngealized vowels, I follow the same procedure as other authors (e.g., avelinoAcousticElectroglossographicAnalyses2010, uchiharaToneRegistrogen in representing the 'glottal stop' element as a superscripted glottal stop in the IPA transcription

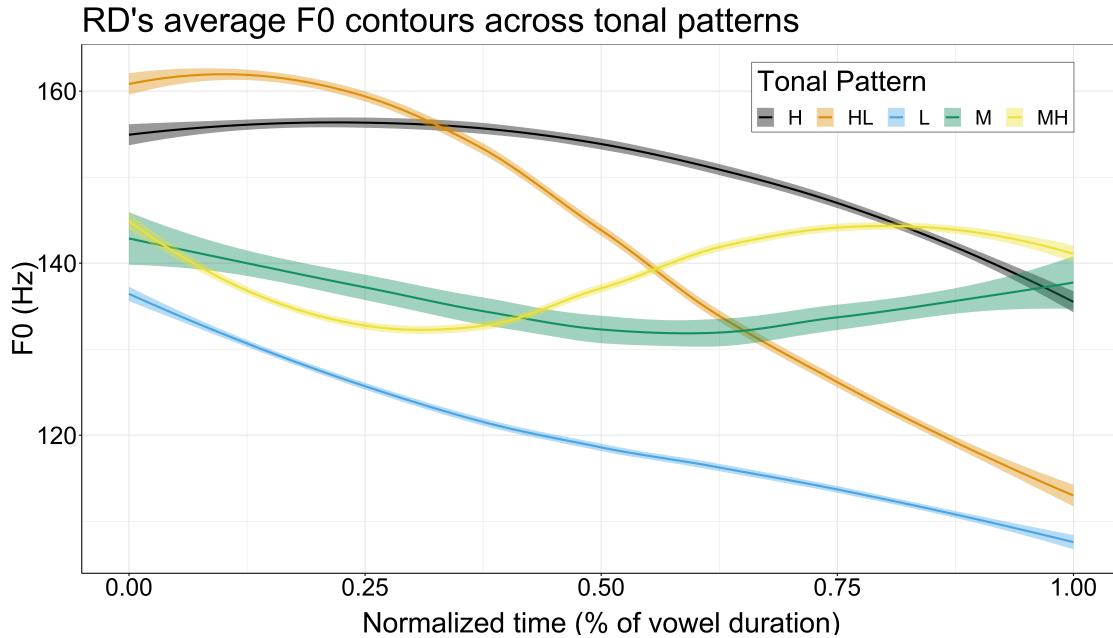


Figure 4: Tonal contrasts for RD averaged and time normalized. Each line in this graph represents the average of approximately 10 syllables for each tonal pattern.

(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., [aq]).

- (1) Four-way minimal phonation contrast
 - a. *ya* [ja³] ‘bell’
 - b. *yah* [jɑ³] ‘metal/rifle’
 - c. *ya'* [ja'⁹] ‘pound’
 - d. *ya'a* [ja'a³] ‘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 ??.

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 ??.

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 ([longDiccionarioZapotecoSan2005](#), [avelinobecerraTopicsYalalagZapotec2004](#), [avelinoAcousticElectroglossographicAnalyses2010](#), [sonnenscheinDescriptiveGrammarSan2005](#), [adlerAcousticsPhonationTypes2016](#)). In order to avoid confusion, I will use the term laryn-

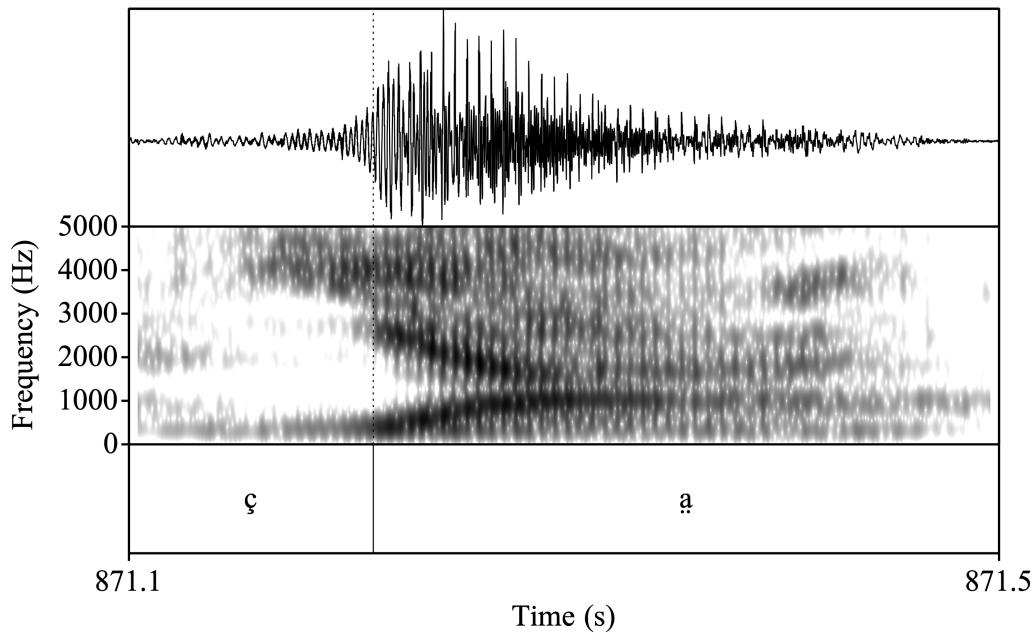


Figure 5: Breathy vowel in the word *yah* ‘metal/rifle’

[INSERT YA’ SPECTROGRAM AND WAVEFORM]

Figure 6: Breathy vowel in the word *ya'* ‘pound’

gealized following **avelinoAcousticElectroglossographicAnalyses2010**. In addition to a wide number of different names these vowels also exhibit a wide range of allophones.

avelinoAcousticElectroglossographicAnalyses2010 found in the closely related Yalálag Zapotec that among his consultants there were at least four different pronunciations as seen in Table ???. In SLZ, each of the consulted language experts would produce this vowel differently. One

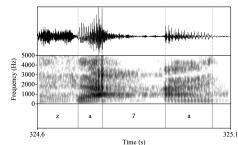
Table 4: Layngealized Vowels in Yalálag Zapotec

/V'V/	[V?V]
	[VVV]
	[V̄V̄:V̄]
	[V̄V̄V̄]

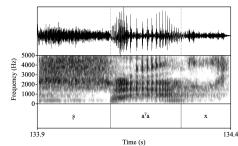
consultant would do rearticulation, where there is a full glottal stop in the middle of the vowel, or creaky voice. This alternation seemed to be in free variation but there was a greater tendency to creak in low toned words, such as *xa'ag* [ʂə:g] ‘topil’², see Figure ?? for a comparison between

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

this consultant's pronunciation of the laryngealized vowels.



(a) *za'a* 'corncob'



(b) *xa'ag* 'topil'

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.

[INSERT SIDE BY SIDE SPECTROGRAMS]

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

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 (**masicaDefiningLinguisticArea1976**, **thurgoodVietnameseTonogenesisRevising2002**, **yipTone2002**, **enfieldAreallLinguisticsMainland2005**, **michaudComplexTonesEast2012**, **brunelleToneP**). What has been found in these descriptions is that certain tones and phonations are codependent (i.e., only occur with each other). For example **smalleyProblemsConsonantsTone1976** and **ratliffMeaningfulToneStudy1992** 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 (**hockettPeipingPhonology1947**). **brunelleTonePerceptionNorthern2009** 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 amodal phonation (Boehm p.c.).

However, there has been some observations—especially in Mesoamerican—that tone and phonation can co-vary (**silvermanLaryngealComplexityOtomanguean1997, garellekAcousticConsequencesPL**). This means that tone can independently occur with any phonation type. This has also been extensively described in multiple Zapotecan languages (**avelinobecerraTopicsYalalagZapotec2004, avelinoAcousticElectroglossographicAnalyses2010, chavez-peonInteractionMetricalStructure2010, campbellZenZontepecChatinoAspect2011, villardPhonologyMorphologyZacatepec2015, lopeznicolasEstudiosFonologiaGramatica2016**)

chavez-peonInteractionMetricalStructure2010 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 ???. 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 (**chavez-peonInteractionMetricalStructure2010**).

	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 (**avelinobecerraTopicsYalalagZapotec2004**). The distribution of SLZ tonal and phonation interactions are given in Table ??.

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 (**eslingVoiceQualityLaryngeal2011**). 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, **uchihiaraToneRegistrogenesisQuiavini2016**

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 (**huffmanMeasuresPhonationTyp andruskiPhonationTypesProduction2000**) and Jalapa Mazatec (**silvermanPhoneticStructuresJalapa1995 blankenshipTimeCourseBreathiness1997**). 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 ??.

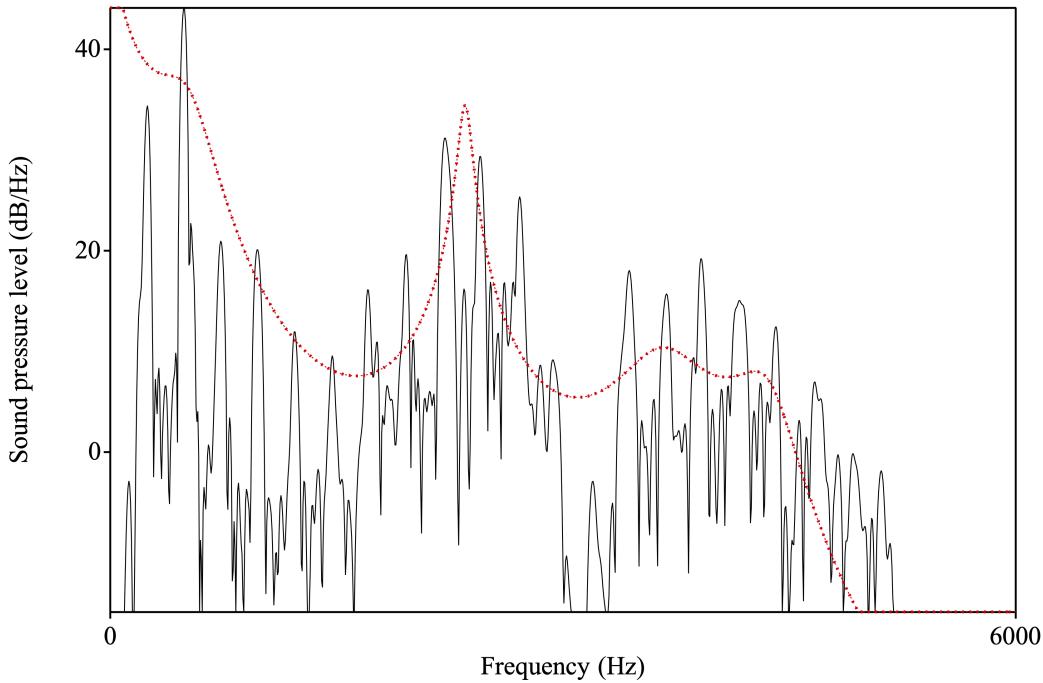


Figure 9: Spectral slice with LPC smoothed line overlaid for the vowel [e]. The harmonics in the spectral slice are represented by each of the dark peaks. The leftmost black solid line peak is the first harmonic (H1) and each subsequent peak represents the next highest harmonic (H2 through Hn). The red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

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 (**garellekPhoneticsVoice2019** 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 (**espositoVariationContrastivePhonation2010**). 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 (**shueVOICESAUCEProgramVoice2009**) and PraatSauce (**kirbyPraatSauce2022**) produces both corrected and uncorrected values.

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 **garellekPhoneticsVoice2019** 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 Zencastr³, a professional podcasting website, 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.

After the elicitation were completed the audio was uploaded into ELAN (**wittenburgELANProfessionalFrame**) for initial segmentation into sentences. This was then followed by segmenting of the vowel portion in Praat (**boersmaPraatDoingPhonetics2021**). These segments were then inputted to VoiceSauce (**shueVOICESAUCEProgramVoice2009**) where each vowel was resampled at 16kHz for acoustic measurement. The acoustic measurements of VoiceSauce were then analyzed in R (**rcoreteamLanguageEnvironmentStatistical2021**). In order to investigate the differences in

³<https://zencastr.com/>

timing, each vowel was normalized for time.

5.2 Spectral-tilt results

The results of the spectral-tilt measurements were for the most part accurate. As noted by **espositoVariationContrastivePhonation2010** 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 **espositoVariationContrastivePhonation2010**, 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 measured similarly to the other non-modal vowels. This is not too unsurprising considering the fact that the female speaker would more often produce a full glottal fricative in these environments than a breathy vowel. This can be seen in Figure ?? where the modal vowel is represented by the solid black line. All other lines which represent breathy, checked, and laryngealized are all lower than that of the modal.

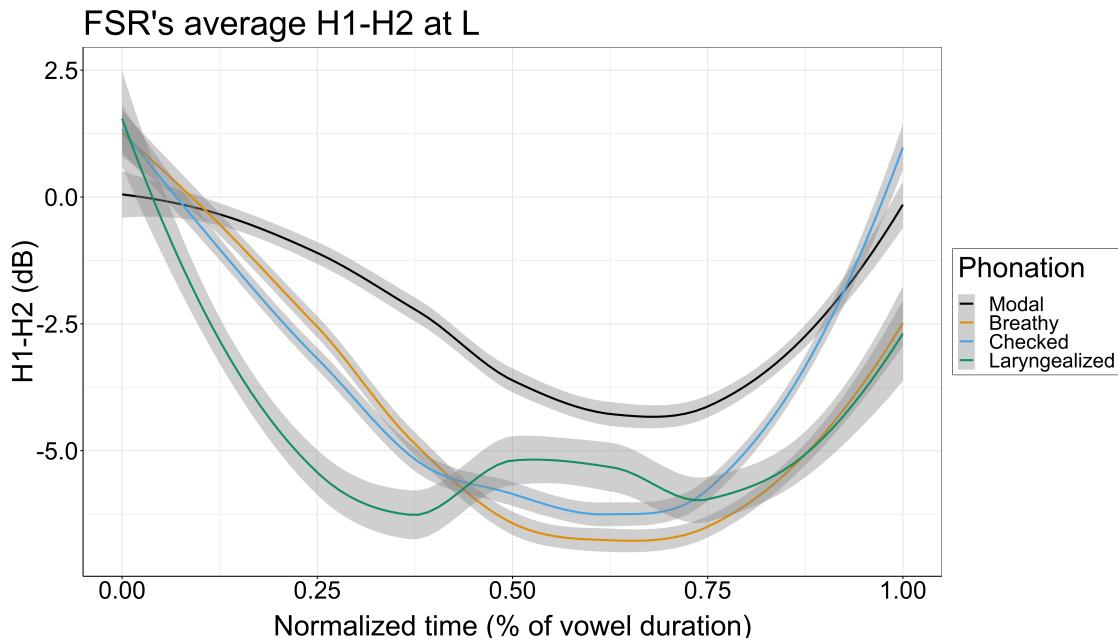


Figure 10: FSR's H1-h2 values.

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. In Figure ??,

the spectral-tilt values for laryngealized and checked vowels are plotted along a time normalized scale. The important thing to be aware of is the difference in where the lowest part of the plot is located. For checked vowels, represented by the solid lines, the lowest part of the spectral-tilt measurement is located in the last quarter of the vowel. This dip, however, occurs earlier in the vowel for the laryngealized vowels closer halfway to 75% of the vowel.

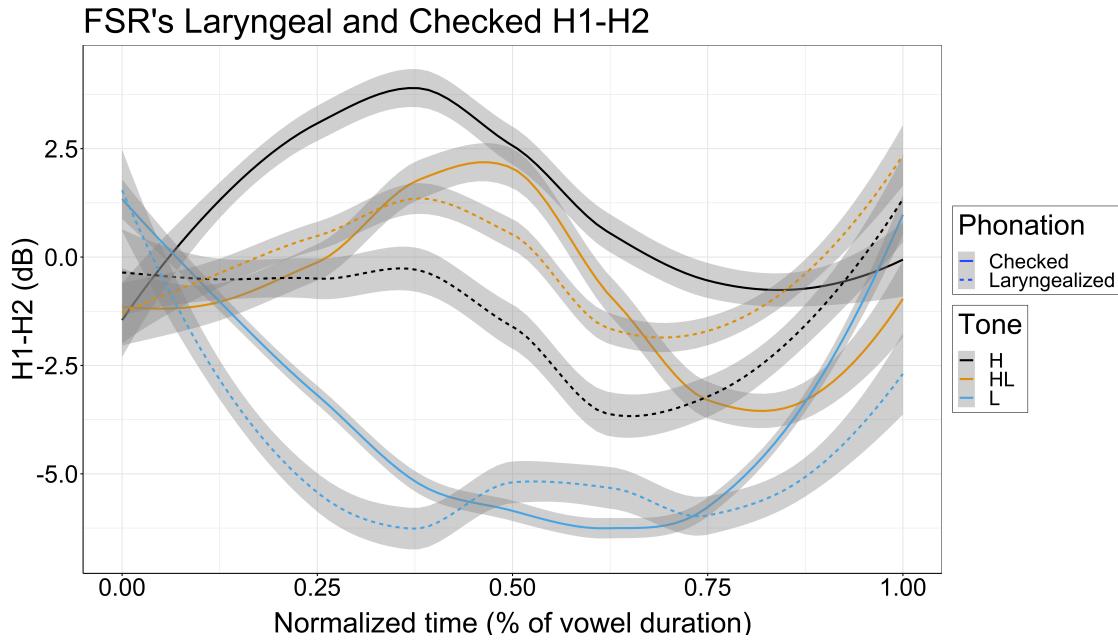


Figure 11: FSR's H1-h2 values for checked and laryngealized.

As mentioned mentioned previously, the results of the spectral analysis for the male SLZ speaker were inconclusive in terms of H1-H2. As seen in Figure ?? all of the different phonation types are essentially identical with less than 1 dB difference between the different phonation types. The H1-A3 spectral measures, however, show the expect patterns, as seen in Figure ??.

5.3 Statistical results

In order to determine whether or not the gestures for pitch and phonation are overlapping a mixed-effects linear regression analysis was performed with a Satterthwaite's method for t-test analysis used to derive the p-values. Following **garellekAcousticConsequencesPhonation2011**, the results for both speaker were combined together and then divided into thirds based on the normalized times. This allows for analysis of each third of the vowel to determine if the phonation and pitch gestures are overlapping. To this effect, the F0 measurements where treated as the dependent variable with speaker treated as random. The results of the analysis showed that the phonation categories, spectral-tilt measurements, and CPP all had an effect on F0 in different portions of the vowel. Specifically the portions of the analysis showed that did not show any

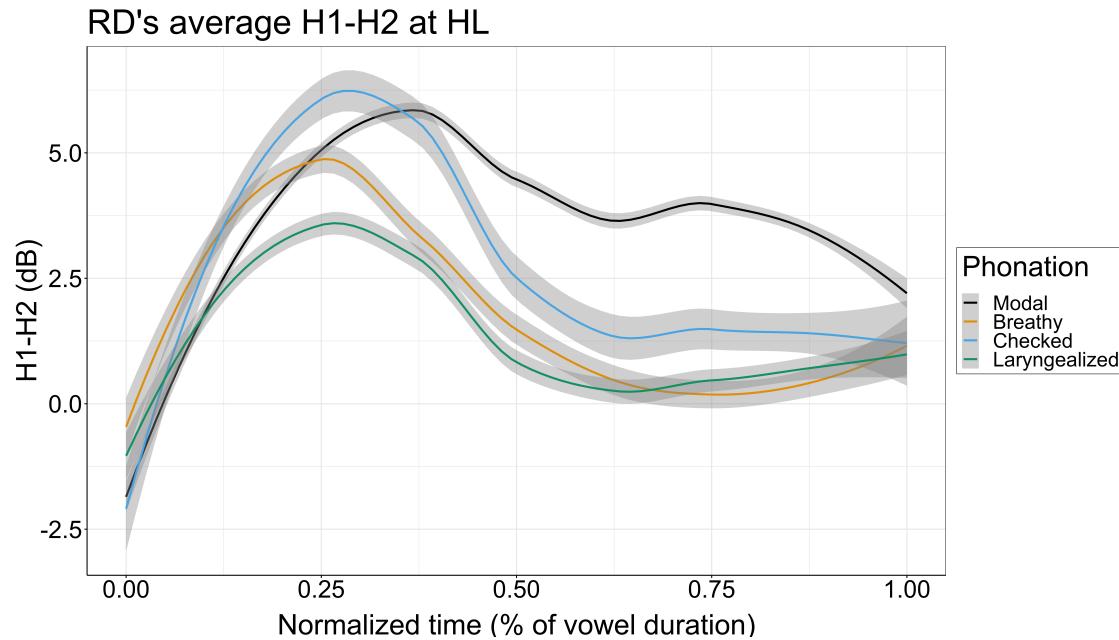


Figure 12: RD's H1-H2 values in HL toned syllables.

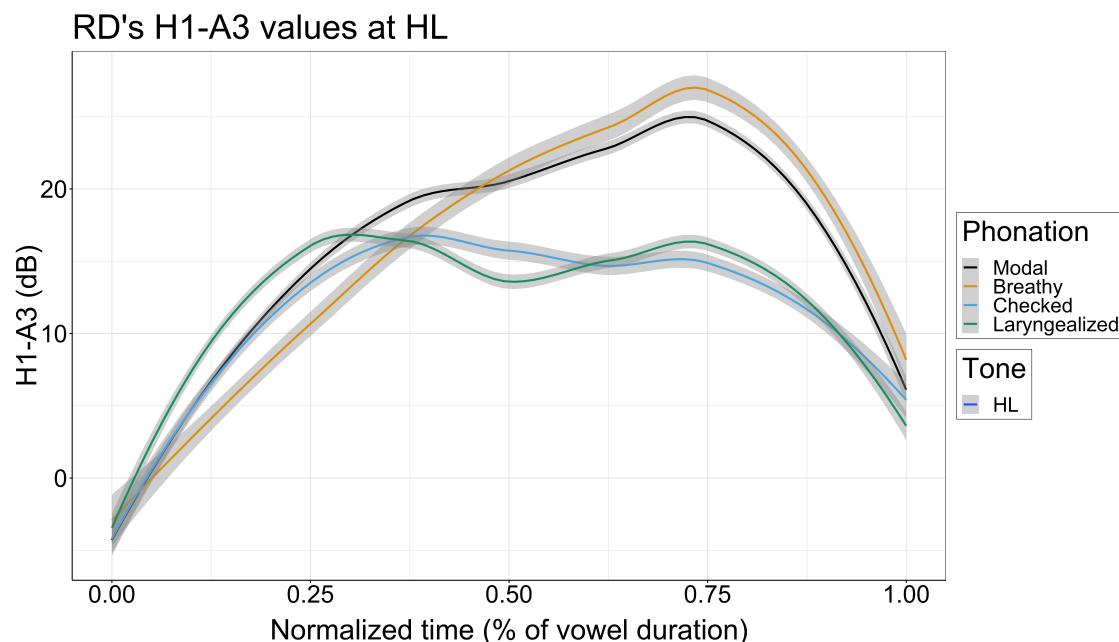


Figure 13: RD's total H1-A3 values in HL toned syllables.

effects where the first third of the vowel for CPP and the last third for the laryngealized category. The spectral-tilt measurements of H1-H2 and H1-A3 had an effect on F0 in all portions of the vowel.

Table 7: Results of the mixed-effects linear regression analysis on the first third of the vowel.

	Estimate	Std. Error	df	t value	p-value
Breathy	-23.41	0.8128	23710	-28.799	<0.001
Checked	-9.123	0.6933	23710	-13.159	<0.001
Laryngealized	9.712	0.6733	23710	14.424	<0.001
H1-H2	2.163	0.06640	23710	32.572	<0.001
H1-A3	-0.6678	0.03436	23710	-19.434	<0.001
CPP	0.04144	0.03289	23710	1.260	0.208

Table 8: Results of the mixed-effects linear regression analysis on the second third of the vowel.

	Estimate	Std. Error	df	t value	p-value
Breathy	-9.634	0.7874	23540	-12.235	<0.001
Checked	-3.509	0.6564	23540	-5.346	<0.001
Laryngealized	-2.261	0.6437	23540	-3.513	<0.001
H1-H2	3.371	0.04283	23540	78.707	<0.001
H1-A3	-0.4599	0.02592	23540	-17.741	<0.001
CPP	-0.9082	0.04806	23540	-18.897	<0.001

Table 9: Results of the mixed-effects linear regression analysis on the last third of the vowel.

	Estimate	Std. Error	df	t value	p-value
Breathy	-5.247	0.8224	24490	-6.380	<0.001
Checked	-4.494	0.6898	24490	-6.514	<0.001
Laryngealized	1.013	0.6670	24490	1.519	0.129
H1-H2	3.079	0.04900	24490	62.845	<0.001
H1-A3	-0.6611	0.02372	24490	-27.867	<0.001
CPP	0.5377	0.02958	24490	18.176	0.208

6 Discussion of the results

Based on the results of the statistical analysis, SLZ appears to have a large degree of overlap in the tonal and phonation gestures in contrast to the strict ordering that is predicted to occur according to the LCH. The LCH predicts that languages that have contrastive tone and phonation should not have any overlap between tone and phonation. The rational for this comes from the one-dimensional nature of the larynx proposed by **laedefogedPreliminariesLinguisticPhonetics1971**. As previously mentioned, this model assumes that the vocal folds are the primary force in determining both tone and phonation. The assumption that tone and phonation are controlled by only the vocal folds is actually inaccurate. Recent work, summarized in **eslingVoiceQualityLaryngeal2019**,

actually shows that the whole larynx is involved with the production of the different phonation types. For example, based on laryngoscopy, creaky voice shows that in addition to the vocal folds, the thyroarytenoid muscle contract from the borders of the arytenoids to the front of the epilaryngeal tube. In addition, the ventricular folds are often also engaged in creaky voice which has the effect of increasing the vibrating mass in the larynx, adds damping, encourages irregular vibration, and perturbs the mucosal wave from crossing the vocal folds (**moisikModelingBiomechanicalInfluence**)

Based on this and other work **eslingVoiceQualityLaryngeal2019** 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 ??.

Table 10: 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 ??.

Figure ??, 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

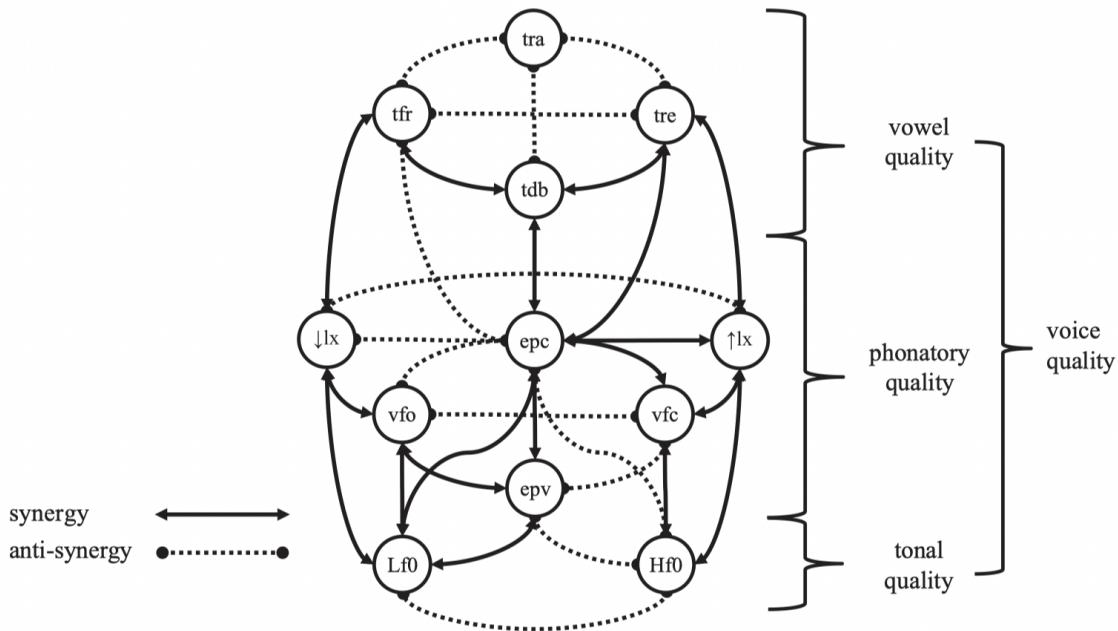


Figure 14: Network of synergistic and anti-synergistic nodes in the Laryngeal Articulator Model. Taken from [eslingVoiceQualityLaryngeal2019](#).

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.

7 Conclusion