The acoustics of phonation in Santiago Laxopa Zapotec[1]

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1 Introduction

- Phonation is a process where the larynx is used to alter the way different sounds are produced.
- This use of the larynx produces sounds which vary from being more breathy or creaky.
  - Other types of phonation also exist (see Esling et al. 2019 for a detailed discussion on the different phonation types that exist and how the larynx produces them).
- In some languages these alterations are described as being pathological, with some speakers just being more breathy or creaky than others (e.g., Klatt & Klatt 1990).
- In other languages these phonation types are used phonemically like in Gujarati, where vowels can be breathy or modal (Fischer-Jørgensen 1968).
- This phonemic use of phonation is particularly common in the Otomanguean language family from southern Mexico (e.g., Suárez 1983, Campbell, Kaufman & Smith-Stark 1986, Silverman 1997, Campbell 2017a,b).
- One of the common problems facing linguists who study phonation is determining what the acoustic correlates are for these different phonation types.
- This paper is a preliminary investigation into the acoustic correlates of the different phonation types in Santiago Laxopa Zapotec, an Otomanguean language spoken by approximately 1200 people.
- I show that that H1-H2 is not a very good indicator of phonation in Santiago Laxopa Zapotec, but like other Zapotecs H1-A3 is a good indicator of phonation.
- Additionally, Cepstral Peak Prominence is shown to be useful in distinguishing checked and laryngealized vowels apart for one of the speakers.

[1] I 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 of 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.

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2 Background

- It is commonly assumed that the vocal folds, which account for differences in pitch and voicing, are also responsible for differences in phonation.
- Ladefoged (1971) and Gordon & Ladefoged (2001) argued that phonation exists on a single dimension ranging from opened vocal folds to closed vocal folds.
- The variation in how open or closed the vocal folds are correspond to whether or not the sound produced is breathy or creaky.
- Ladefoged (1971) and Gordon & Ladefoged (2001) summarized this assumption in the diagram found in Figure 18.

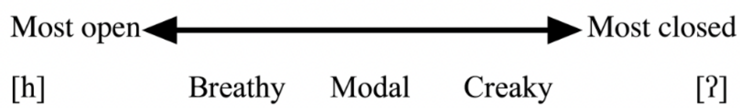

Figure 1: Simplified one-deminsional model for phonation. Based on Ladefoged (1971) and Gordon & Ladefoged (2001)

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- In addition to this degree of openness, linguists have found that there are other acoustic measurements that correlate to different types of phonation.
- Commonly, these acoustic measurements are spectral-tilt measurements.
- Spectral-tilt measurements are when you take the relative amplitude of different harmonics and subtract them from each other.
- Fischer-Jørgensen 1968 showed that the difference between the amplitude of the first harmonic and second harmonic can account for the differences between breathy and modal vowels.

3 Santiago Laxopa Zapotec

- Santiago Laxopa Zapotec (SLZ), endonym *Dille'xhunh Laxup*, is a a Northern Zapotec language spoken by approximately 1000 people in the municipality of Santiago Laxopa, Ixtlán, Oaxaca, Mexico and in diaspora communities in Mexico and the United States (Adler & Morimoto 2016, Adler et al. 2018, Foley, Kalivoda & Toosarvandani 2018, Foley & Toosarvandani 2020).
- Closely related to San Bartolomé Zoogocho Zapotec (Long & Cruz 2005, Sonnenschein 2005) and shares a high level of mutual intelligibility with it.

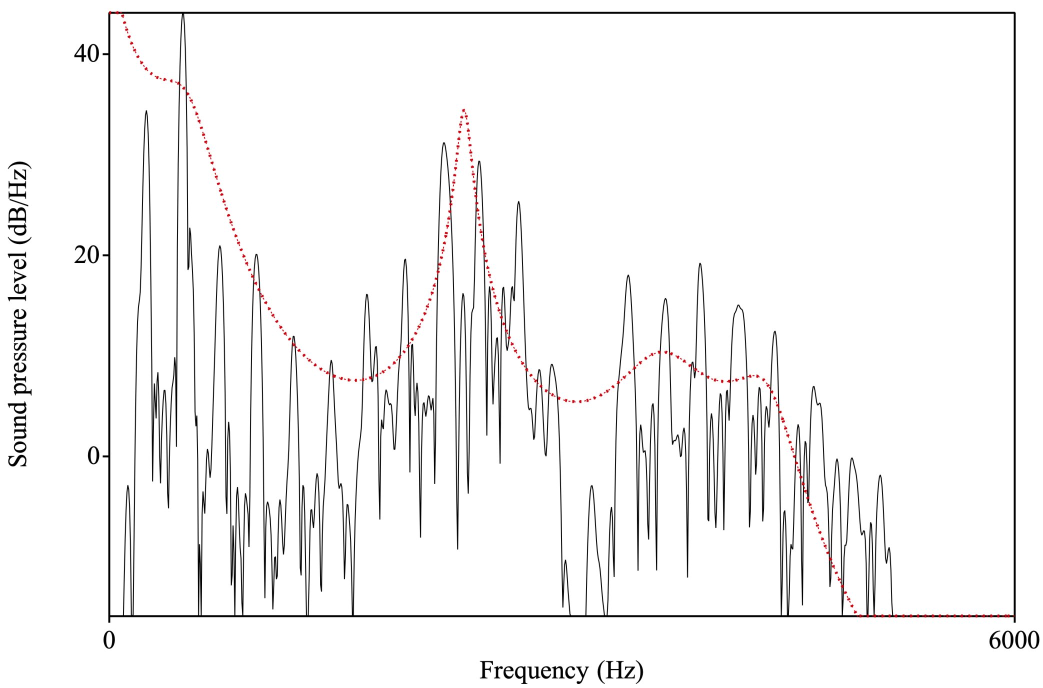


Figure 2: Spectral slice with LPC smoothed line overlaid for the vowel [e]. The harmonics in the spectral slice are represented by each of the dark peaks. The leftmost black solid line peak is the first harmonic (H1) and each subsequent peak represents the next highest harmonic (H2 through H*n*). The 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*.

Table 1: Consonant inventory for Santiago Laxopa Zapotec

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

- SLZ is similar to other Zapotecan languages in distinguishing lenis and fortis consonants (e.g., Nellis & Hollenbach 1980, Jaeger 1983, Uchihara & Pérez Báez 2016).

- SLZ has a standard five vowel inventory.

Table 2: Vowel qualities in Santiago Laxopa Zapotec.

	front	central	back
high	i		u
mid	e		o
low		a	

- These five vowels, additionally, appear with one of four different phonation types which will be discussed in greater detail in Section 3.2.

3.1 Tone in Santiago Laxopa Zapotec

- Similar to other Otomanguean languages, SLZ is tonal (Suárez 1983, Campbell, Kaufman & Smith-Stark 1986, Silverman 1997, Campbell 2017a,b).

- SLZ has five distinct tonal patterns that appear on the syllables of nouns, see Table 3.

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

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

- These five tonal patterns are illustrated in Figures 3 and 4 for two different SLZ speakers.

- Figures 3 and 4 shows the five tonal contrasts averaged for each tonal contrast from the onset to ending of the vowel.

- The first 20-25% of Figures 3 and 4 can be ignored due to the influence of consonantal transitions.

- Evidence from Brinkerhoff, Duff & M. C. Wax Cavallaro (2021) and Brinkerhoff, Duff & M. Wax Cavallaro (2022), however, suggests that the five tonal patterns are epiphenomenal in SLZ.
  - Similar to what McPherson (2022) found for Poko (Skou, PNG).

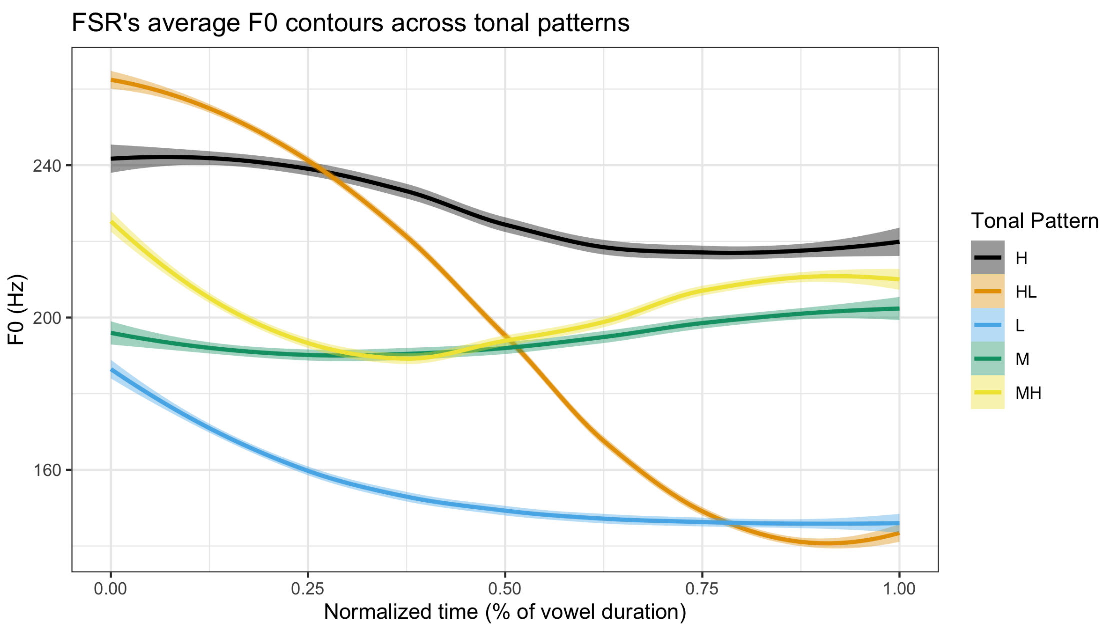


Figure 3: Tonal contrasts for FSR averaged and time normalized. Each line in this graph represents the average of approximately 10 syllables for each tonal pattern.

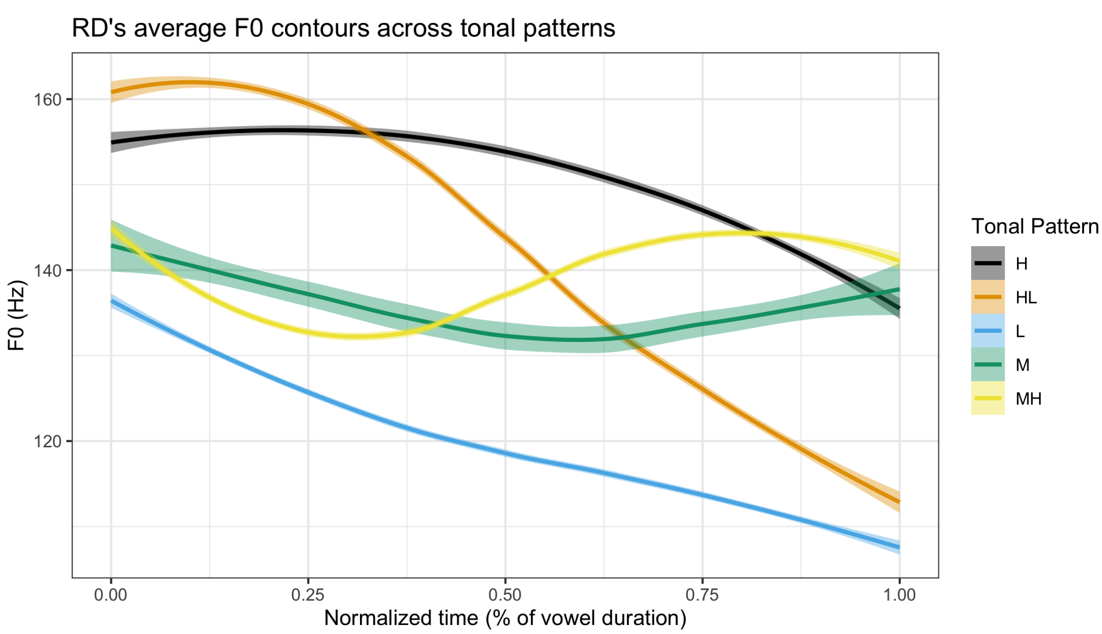


Figure 4: Tonal contrasts for RD averaged and time normalized. Each line in this graph represents the average of approximately 10 syllables for each tonal pattern.

3.2 Phonation in Santiago Laxopa Zapotec

- Zapotecan languages commonly make use of contrastive phonation on vowels (e.g., Avelino 2004, Long & Cruz 2005, Avelino 2010, López Nicolás 2016, Chávez-Peón 2010, Ariza-García 2018).

- SLZ has four contrastive phonation types: modal /a/, breathy /a̤/, checked /aˀ/, and laryngealized /aˀa/.

(1) Four-way near minimal phonation contrast
  a. *yag* [çag^{L}] ‘tree; wood; almúd (unit of measurement approximately 4kg)’
  b. *yah* [ça̤^{L}] ‘metal; rifle; bell’
  c. *yu’* [çu^{ˀL}] ‘earth’
  d. *ya’a* [çaˀa^{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.

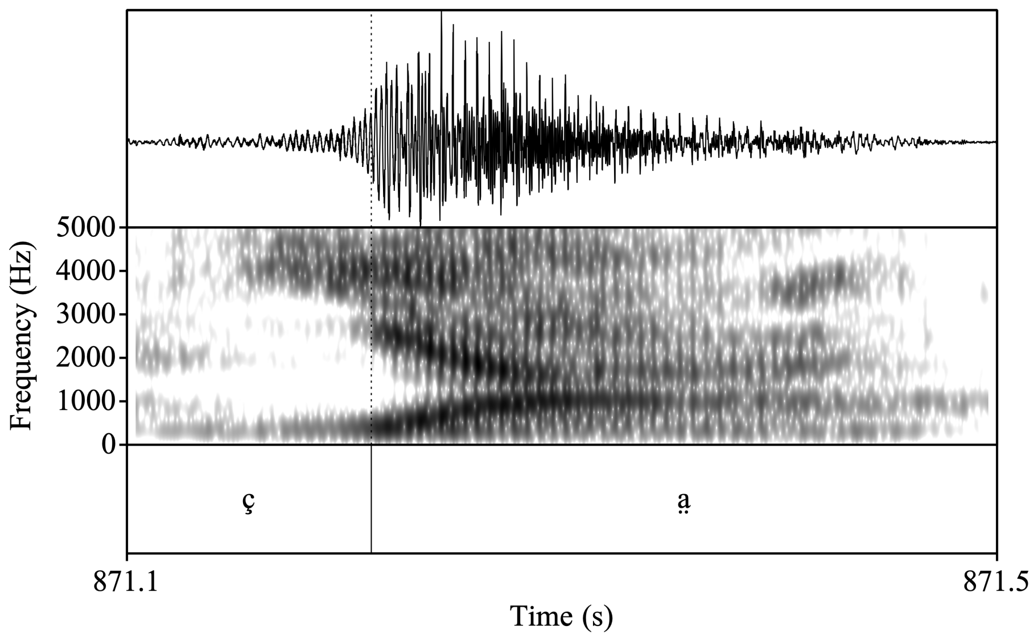


Figure 5: FSR’s breathy vowel in the word *yah* ‘metal; rifle’

- 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.

- 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, Ariza-García 2018).

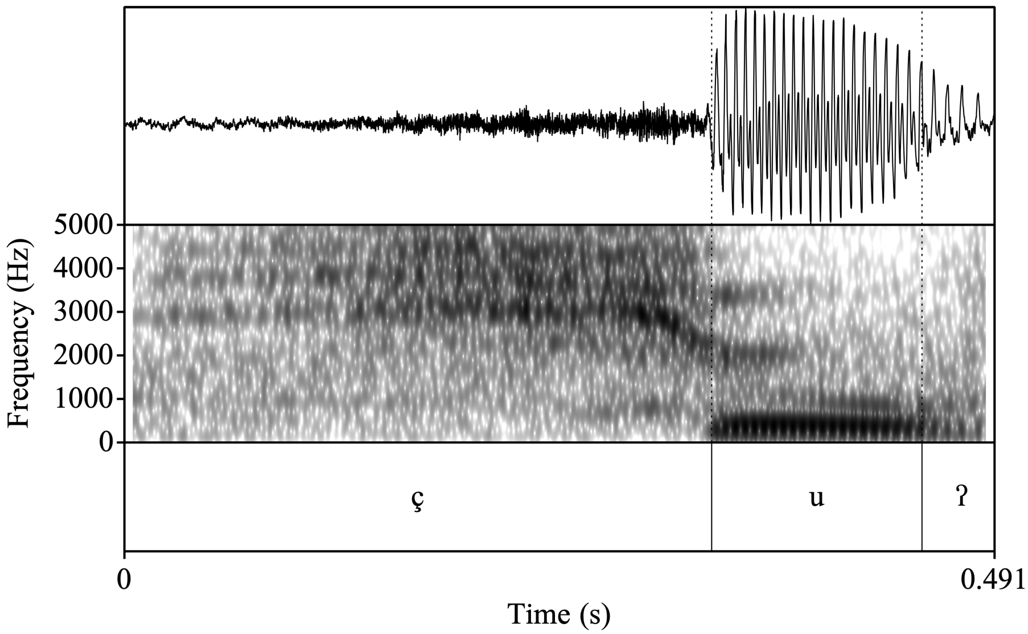


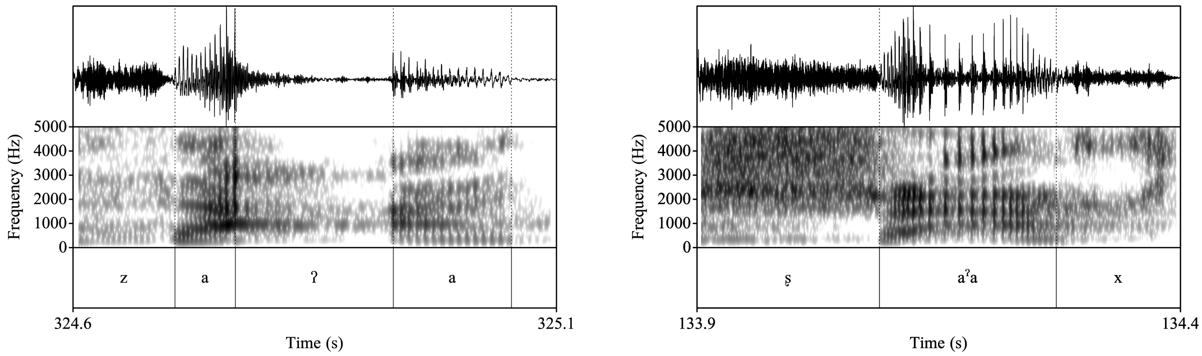
Figure 6: RD's checked vowel in the word *yu'* 'earth'

- 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 4.

Table 4: Layngealized Vowels in Yalálag Zapotec

/V'V/	[VʔV]
	[VV̰V]
	[VV̰:V̌]
	[VV̰V̰]

- In SLZ, this vowel is also highly variable.
- One consultant does 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 words with a L tone, such as *xa'ag* [s̢a̰ːx] 'topil'[2], see Figure 7 for a comparison between this consultant's pronunciation of the laryngealized vowels.

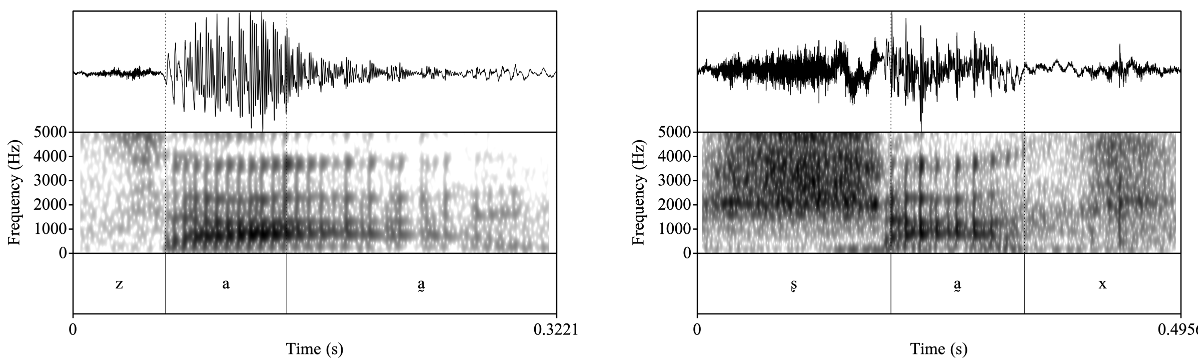


(a) *za'a* 'corncob'

(b) *xa'ag* 'topil'

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

- Another consultant only ever produces creaky voice for these vowels regardless of the tone with the word.



(a) *za'a* 'corncob'

(b) *xa'ag* 'topil'

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

3.3 Interaction of tone and phonation in Santiago Laxopa Zapotec

4 Methodology

- Two native language speakers of SLZ who live in Santa Cruz, CA took part in this study (one male).
- Because of the COVID-19 pandemic data collection was conducted remotely using Zencastr[3], 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).

[2] A topil is a type of government office in traditional Oaxacan communities somewhat akin to a sheriff.
[3] https://zencastr.com/

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

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

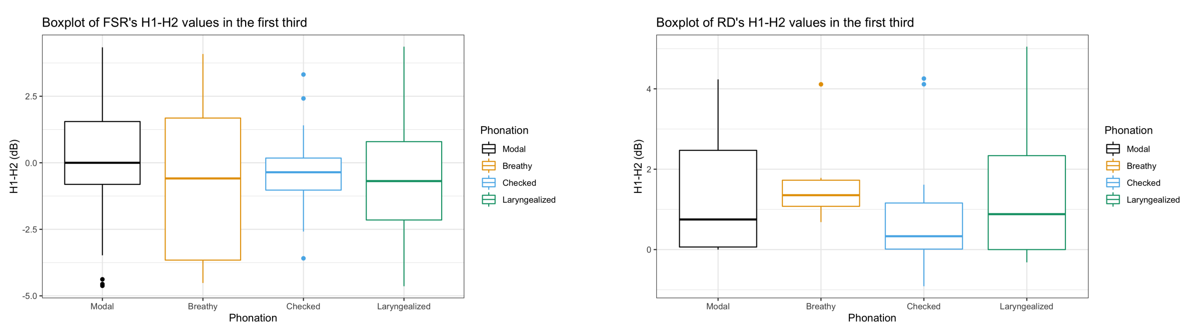
Table 6: Number of unique syllables for each interaction of tone and phonation in the data.

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

- The

5 Results

5.1 H1-H2 spectral-tilt



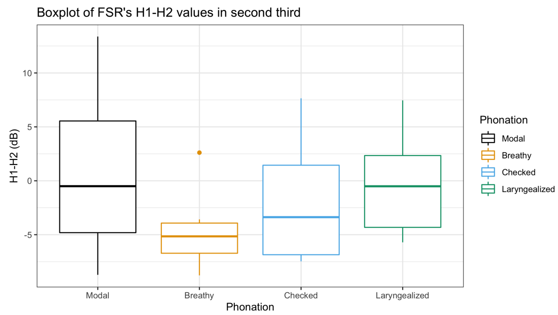
(a) FSR's H1-H2 values.

(b) RD's H1-H2 values.

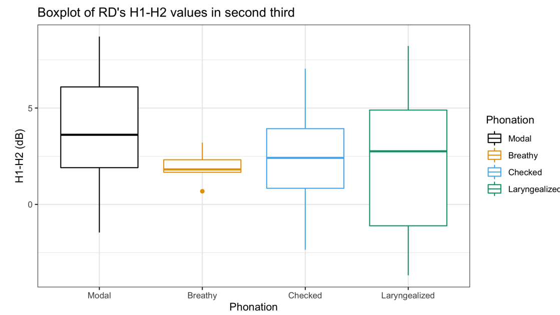
Figure 9: Mean H1-H2 values for the first third of the vowel according to each phonation type.

5.2 H1-A3 spectral-tilt

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 12.

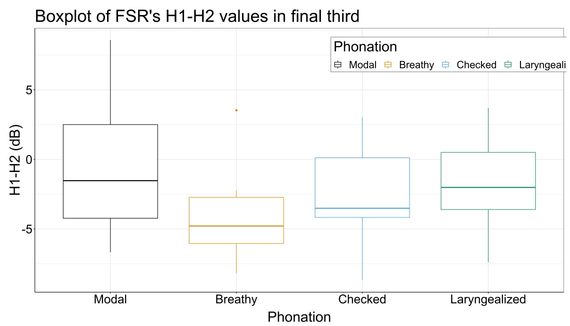


(a) FSR's H1-H2 values.

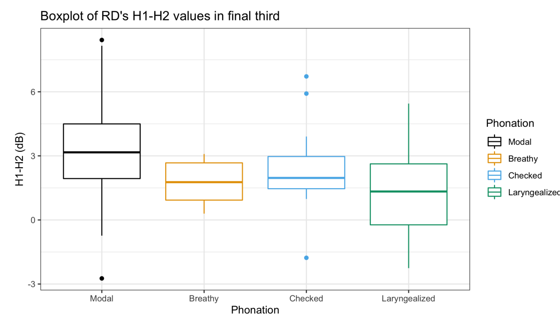


(b) RD's H1-H2 values.

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

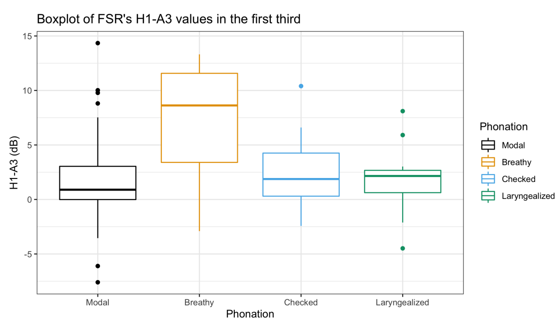


(a) FSR's H1-H2 values.

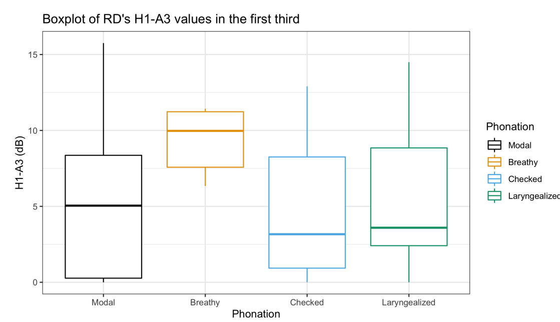


(b) RD's H1-H2 values.

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



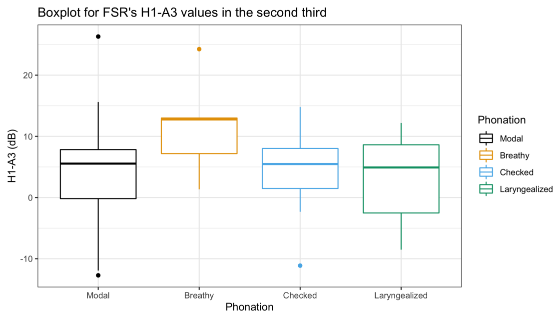
(a) FSR's H1-A3 values.



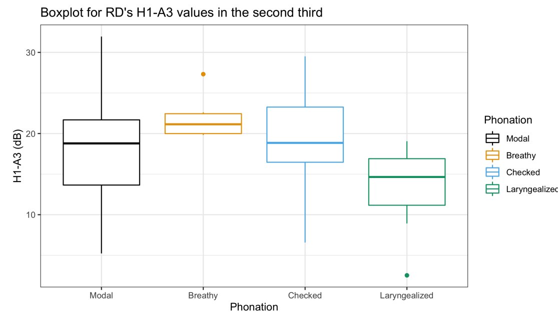
(b) RD's H1-A3 values.

Figure 12: H1-A3 values for FSR (a) and RD (b) for the first third of the vowel.

In the second third of the vowel, Figure 13, 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 continues throughout the rest of the vowel for laryngealized vowels, see Figure 14b. 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



(a) FSR's H1-A3 values.

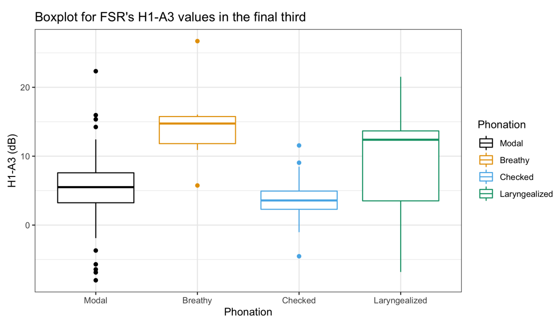


(b) RD's H1-A3' values.

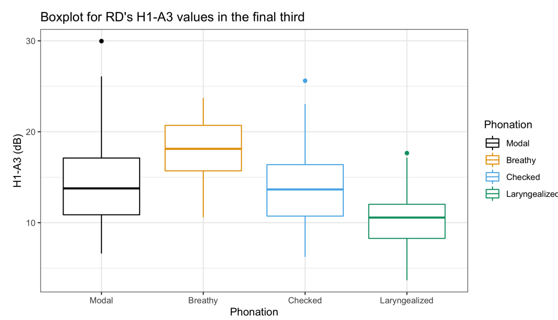
Figure 13: H1-A3 values for FSR (a) and RD (b) for the second third of the vowel.

modal vowel.

In looking at the final portion of the vowels, Figure 14, 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.



(a) FSR's H1-A3 values.



(b) RD's H1-A3 values.

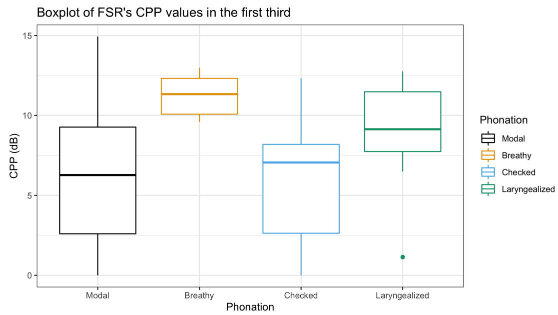
Figure 14: H1-A3 values for FSR (a) and RD (b) for the final third of the vowel.

5.3 Cepstral Peak Prominence

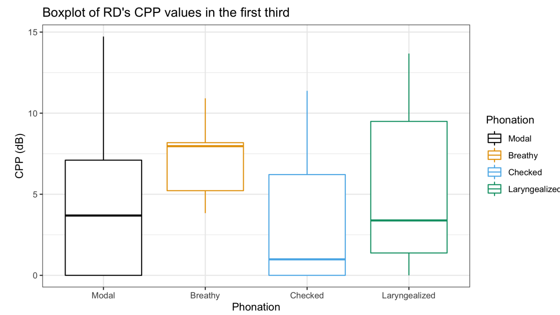
5.4 Statistical results

Table 7: 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

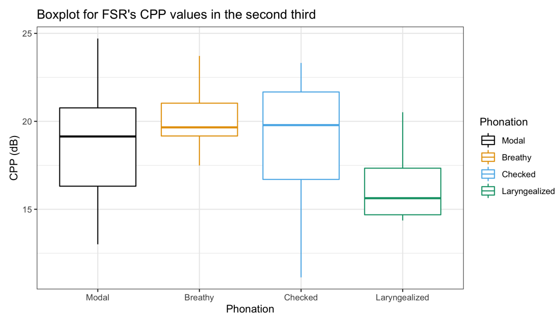


(a) FSR's CPP values.

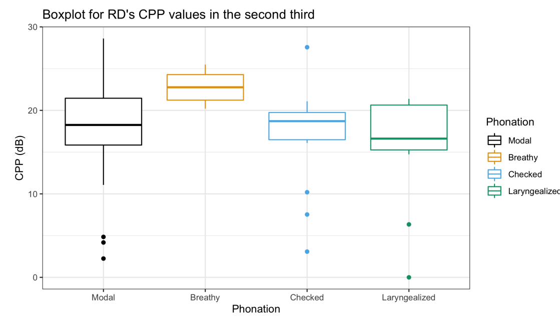


(b) RD's CPP values.

Figure 15: CPP values for FSR (a) and RD (b) for the first third of the vowel.

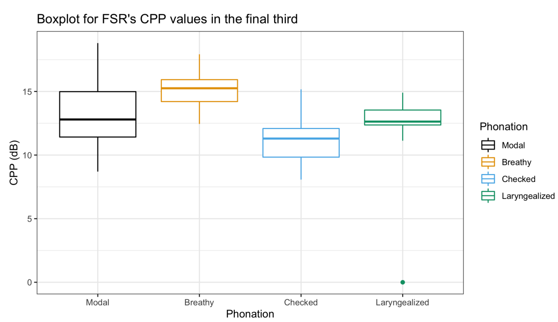


(a) FSR's CPP values.

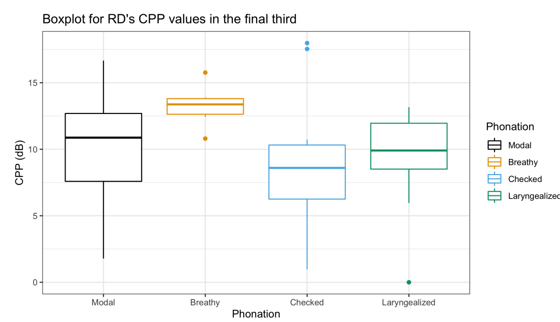


(b) RD's CPP values.

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



(a) FSR's CPP values.



(b) RD's CPP values.

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

As can be recalled from Section 5.1, 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 8 and Table 9, show that this behavior is significant.

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

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, 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

Table 8: 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 9: 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

vowels' values. We see that at all portions of the vowel, as seen in Tables 10, 11, 12 show significance.

Table 10: 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

Table 11: 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

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 5.1 and 5.2 which did not show any remarkable differences from the model. When we consider CPP we see both checked and laryngealized vowels clearly differentiated. This is born out in

Table 12: 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

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 13 both breathy and checked voice were identifiable with CPP.

Table 13: 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 14, 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.

Table 14: 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

In considering the final portion of the vowel, Table 15, the statistical analysis shows that only checked vowels can be reliably determined using CPP. This observations is consistent with the 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 15: 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

6.1 Laryngeal Complexity Hypothesis

- The Laryngeal Complexity Hypothesis (LCH) has its origin in work from Silverman (1997) and Blankenship (1997, 2002).
- The LCH claims that languages that have both tone and phonation need them to be phased/ordered with respect to each other.
- This is required because it is assumed that the same mechanism for tone is also responsible for phonation.
  - Tone is the rate of vocal fold vibration.
  - Ladefoged (1971) and Gordon & Ladefoged (2001) argued that phonation exists on a single dimension ranging from opened vocal folds to closed vocal folds.
- The variation in how open or closed the vocal folds are correspond to whether or not the sound produced is breathy or creaky.
- Ladefoged (1971) and Gordon & Ladefoged (2001) summarized this assumption in the diagram found in Figure 18.

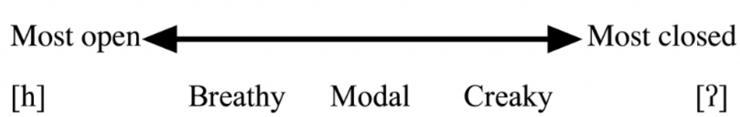


Figure 18: Simplified one-deminsional model for phonation. Based on Ladefoged (1971) and Gordon & Ladefoged (2001)

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- Because the same organ is responsible for these two different phenomena there is a mismatch in trying to produce both at the same time.
- The LCH assumes that there needs to be a strict ordering in the glottal gestures.
- 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.
- In Figure 19, 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.

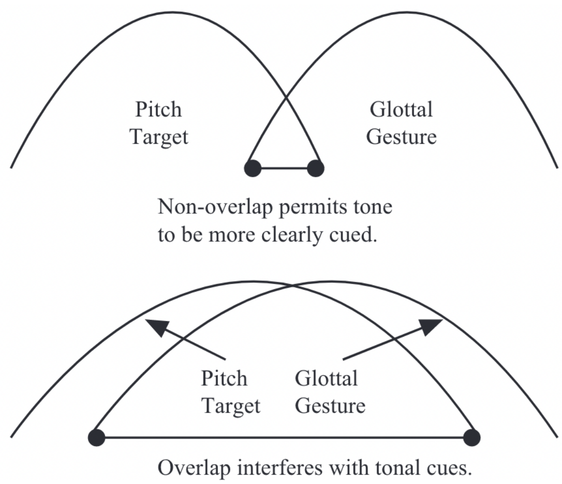

Figure 19: Representation taken from DiCanio (2012).

- DiCanio (2012) 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.
- 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.

6.2 Laryngeal Articulator Model

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 20.

Table 16: 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)

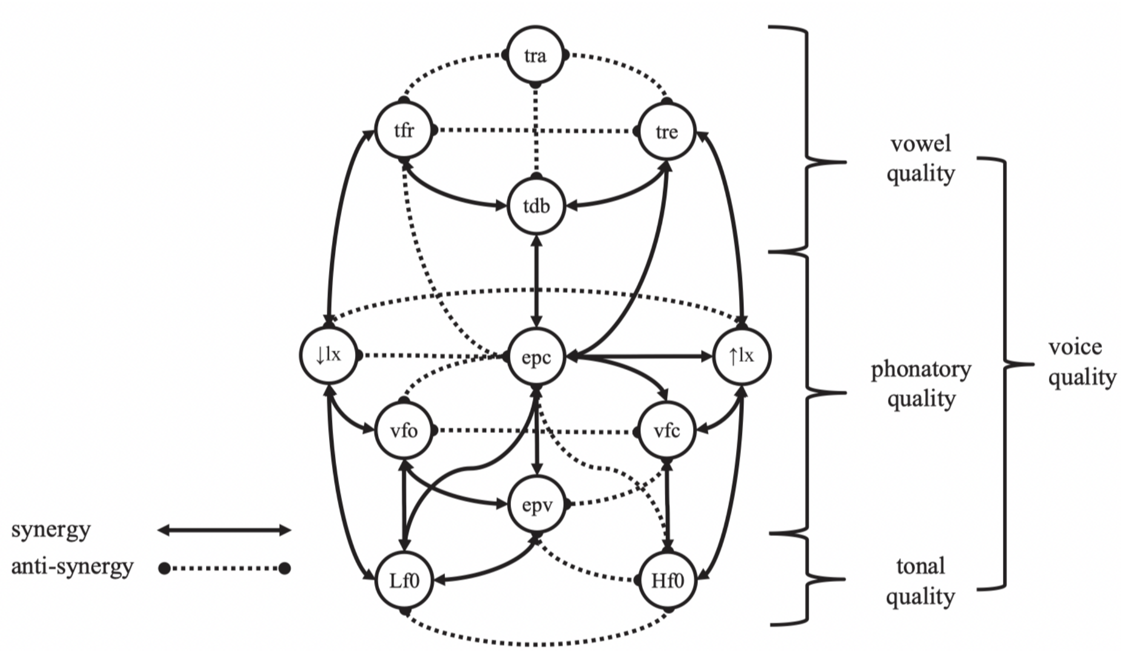

Figure 20: Network of synergistic and anti-synergistic nodes in the Laryngeal Articulator Model. Taken from Esling et al. (2019).

7 Conclusion

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