

Laryngealization in Upper Necaxa Totonac

by

Rebekka Puderbaugh

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Department of Linguistics
University of Alberta

Examining committee:

Dr. Anja Arnhold, Supervisor
Dr. David Beck, Supervisor
Dr. Benjamin V. Tucker, Examiner
Dr. Stephanie Archer, Examiner
Dr. Ryan Shosted, External examiner

© Rebekka Puderbaugh, 2019

Abstract

This dissertation examines two laryngealization contrasts, one in vowels, the other in fricatives, in Upper Necaxa Totonac (UNT), a Totonacan language spoken in the Mexican state of Puebla. The laryngealization contrast in vowels has been identified in many other Totonacan languages and is presumed to be realized as a form of non-modal phonation in UNT. In fricatives, the contrast is posited between pulmonic and ejective fricatives, which are unusual in that they appear in a system that otherwise has no use for the glottalic airstream. The goal of this dissertation is to provide evidence that will help to determine whether laryngealization contrasts are the best description of the synchronic sound system in UNT, or if alternative descriptions might provide more satisfactory accounts for these contrasts. I hypothesize that many instances of laryngealized vowels are in fact the result of coarticulation with following glottal stops, while the ejective fricatives are better described phonetically as a sequence of fricatives followed by glottal stops.

In order to investigate the hypotheses above, phonemic laryngealization was first examined via a corpus analysis in Chapter 3. The analysis revealed highly frequent co-occurrence of laryngealized vowels and following glottal stops. No relationship was found between vowel laryngealization and ejective fricatives. The relationship between vowel and consonant laryngealization was further investigated in Chapter 4 through a statistical analysis of the difference in amplitude between the first and second harmonics (H1-H2) in laryngealized and non-laryngealized vowels. H1-H2 is an acoustic spectral measure that has been commonly shown to be associated with non-modal phonation in many languages. The analysis showed that H1-H2 values were not influenced by vowel laryngealization categories, but were influenced by the presence of a glottal

stop following the vowel. This finding suggests that the laryngealization categories of vowels need to be reconsidered in light of the context in which they occur.

In order to consider the potentially glottalic nature of ejective fricatives in UNT, Chapter 5 examined duration of sub-phonemic phonetic events that occur during fricative production, including oral closure (indicated by silent intervals) and frication (indicated by sustained noise). Contrary to expectations, ejective fricatives were longer than pulmonic fricatives in overall duration due to longer silent intervals between the end of frication and the onset of vowel phonation. The length of the silent interval suggested the possibility that the ejective fricatives were in fact clusters of fricative + glottal stop sequences. The silent intervals of ejective fricatives were compared to those of fricative + stop clusters, revealing a cross-linguistically common pattern of decreasing closure durations at places of articulation near the back of the vocal tract, and longer closures at places further front. The closure intervals of the ejective fricatives fit nicely into this duration continuum, suggesting that ejective fricatives may be better described as phonetic clusters.

Preface

This thesis is an original work by Rebekka Puderbaugh. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Phonetic documentation of Upper Necaxa Totonac", No. Pro00032296, 2 July 2012, and Project Name "Acoustic and Articulatory Documentation of Totonac-Tepehua", No. Pro00043940, 13 November 2013.

Portions of this thesis have been previously published. Part of the analysis in Chapter 5 appears in Puderbaugh (2015). Parts of the analyses in Chapters 3 and 4 will appear in Puderbaugh (2019).

Table of Contents

1	Introduction	1
1.1	Phonology of Upper Necaxa Totonac	2
1.1.1	Consonants	3
1.1.2	Vowels	4
1.1.3	Syllables and prosody	4
1.1.4	Phonotactics	5
1.2	Ejective fricatives	6
1.3	Laryngealized vowels	9
1.4	Summary and Research Questions	11
2	Materials	14
2.1	Segmental corpus analysis	14
2.2	Acoustic analysis	14
2.2.1	Data collection	15
2.2.2	Annotation	16
3	Laryngealization in adjacent segments	25
3.1	Introduction	25
3.2	Methods	26
3.3	Results	27
3.3.1	Segmental collocates	28
3.3.2	Laryngealization collocates	34
3.4	Discussion	38
4	Phonetics of laryngealized vowels in context	42
4.1	Background and hypotheses	42
4.2	Methods	43
4.3	Results	44
4.3.1	CV condition	47
4.3.2	VC condition	50
4.3.3	Summary	54
4.4	Discussion	55
5	Acoustic duration of ejective and pulmonic fricatives	57
5.1	Background	57
5.2	Hypotheses	62
5.3	Methods	65
5.4	Results	67
5.4.1	Spectrographic analysis of fricatives and affricates	67
5.4.2	Duration of acoustic events in frication production	71
5.4.3	Statistics	75

5.5	Discussion	98
5.5.1	Review of hypotheses with current findings	99
5.5.2	Conclusion	102
6	Discussion and Conclusions	104
6.1	Fricatives in Upper Necaxa Totonac	104
6.2	Vowels in Upper Necaxa Totonac	108
6.3	Contributions of the thesis	111
	References	112
	Appendix A Supplement to Chapter 2	118
	Appendix B Supplement to Chapter 3	126
	Appendix C Supplement to Chapter 4	132

List of Tables

1.1	UNT consonant inventory	3
1.2	UNT vowel inventory	4
1.3	Phonotactic environments of ? and ejective fricatives	6
1.4	Syllabification of fricative + stop clusters and ejective fricatives	8
3.1	Phoneme distributions before stops	29
3.2	Summary of highly frequent prefixes	29
3.3	Phoneme distributions after stops	30
3.4	Pre-fricative phoneme distributions	31
3.5	Post-fricative phoneme distributions	32
3.6	Pre-vocalic phoneme distributions	33
3.7	Post-vocalic phoneme distributions	34
3.8	Chi-squared residuals (all phonemes and preceding context)	35
3.9	Chi-squared residuals (all phonemes and following contexts)	36
3.10	Chi-squared residuals (stops, fricatives, and preceding vowels)	36
3.11	Chi-squared residuals (stops, fricatives, and following vowels)	37
4.1	Model summary, CV condition, Time 1	47
4.2	Model summary, CV condition, Time 3.	48
4.3	Model summary, VC condition, Time 1	52
4.4	Model summary, VC condition, Time 3	53
4.5	Summary of fixed effects, all analyses	54
5.1	Summary of findings from Maddieson et al. (2001)	59
5.2	Summary of findings from Beck (2006)	61
5.3	Sample lexical items by condition	66
5.4	Duration data from sample spectrograms	68
5.5	Acoustic events in frication production	75
5.6	Total duration in four phone types	77
5.7	Model summary of total duration	79
5.8	Frication duration in four phone types	83
5.9	Model summary of frication duration	85
5.10	Summary of lag durations across conditions	90
5.11	Summary of 4-condition lag model	91
5.12	Summary of lag durations across place of lag closure	95
5.13	Summary of 2-condition lag model	97
5.14	Comparative summary	99
A.1	UNT wordlist	118

B.1	Segment ID grid for collocation analysis	126
B.2	Chi-squared tests of preceding laryngealization	129
B.3	Chi-squared tests of following laryngealization	130
B.4	Chi-squared tests of VC sequences	131
B.5	Chi-squared tests CV sequences	131
C.1	H1-H2 analysis including three-way interaction (CV)	133
C.2	H1-H2 analysis including three-way interaction (VC)	134

List of Figures

2.1	Annotated spectrogram of pre-frication closure	19
2.2	Annotated spectrogram of a post-alveolar affricate	20
2.3	Annotated spectrogram of an ejective alveolar fricative	20
2.4	Glottal stop variants	22
2.5	Post-alveolar fricative followed by glottal stop	23
2.6	Lateral fricative followed by glottal stop	24
4.1	H1-H2 values for all vowels	45
4.2	CV condition	47
4.3	Plot of H1-H2, CV condition, T=3	49
4.4	Plot of H1-H2, CV condition, T=3	49
4.5	VC condition	51
4.6	Plot of H1-H2, VC condition, T=1	52
4.7	Plot of H1-H2, VC condition, T=3	53
5.1	Spectrograms of pulmonic and ejective fricatives	70
5.2	Spectrograms of fricative + stop clusters	72
5.3	Affricates produced by speaker HFM	73
5.4	Duration of acoustic events during fricative production	74
5.5	Summary of total duration distributions by frication condition.	77
5.6	Interaction effects from model of total duration	82
5.7	Summary of frication duration distributions by frication condition.	84
5.8	Interaction effects from model of frication duration	88
5.9	Summary of lag duration distributions by frication condition.	89
5.10	Lag model interaction effects	93
5.11	Lag durations in clusters and ejective fricatives only	95
5.12	Interaction effects from lag duration model summarized in Table 5.13.	98

Chapter 1

Introduction

In this thesis, acoustic and statistical methods are used to describe two sets of contrasts in Upper Necaxa Totonac (UNT) (ISO [tku]). These contrasts, between ejective and pulmonic fricatives on the one hand, and laryngealized and modal vowels on the other, have not yet been described with instrumental phonetic methods. While contrastive phonation in vowels is widely attested in many languages of Mesoamerica, including Mixtec (Gerfen & Baker, 2005), Zapotec (Pickett et al., 2010; Silverman et al., 1995; Esposito, 2010a), Trique (DiCanio, 2010, 2011), and Cora (Kim & Valdovinos, 2014), as well as in the Totonacan family (Trechsel & Faber, 1992; Levy, 1987; MacKay, 1994; Mackay & Trechsel, 2015; Brown et al., 2011), ejective fricatives have never been known to occur in any system that does not otherwise make use of the glottalic airstream mechanism, as is reported in UNT (Beck, 2006).

Currently, the differences between pulmonic and ejective fricatives and laryngealized and non-laryngealized vowels in UNT are framed as indicating phonological contrasts between plain and modified segments. Pulmonic fricatives and modal vowels are produced without any modifications from the typical articulatory configurations and may therefore be characterized as simple; laryngealized vowels and ejective fricatives, on the other hand, are complex in that they are produced with the articulatory configurations of the simple segments with the addition of laryngeal tension or glottal closure. Each of these contrasts may alternatively be considered sequences of vowels or fricatives followed by glottal stops, which are highly frequent in UNT. The auditory differences between the plain and modified segments would then be the result of allophonic variation. The data presented in this thesis will be used to argue that the

ejective fricatives are phonetic clusters of fricatives and glottal stops, and that at least some laryngealized vowels are the result of coarticulation with glottal stops. The thesis also touches upon the role of phonetics in documentary field linguistics, with particular emphasis on the interplay between phonetic descriptions and phonemic analysis.

The remainder of this chapter first summarizes the sound system of UNT as typically described in the literature in Section 1.1, including information on consonants, vowels, syllables and prosody, then provides some background on ejective fricatives in Section 1.2 and laryngealized vowels cross-linguistically in Section 1.3. Details pertaining to UNT are presented at the end of each.

1.1 Phonology of Upper Necaxa Totonac

Upper Necaxa Totonac is a Totonacan language spoken in the villages of Patla, Chicontla, San Pedro Tlalontongo, and Cacahuatlan, which are situated along the banks of the Upper Necaxa River in the Sierra Norte of the Mexican state of Puebla. Approximately 3400 people speak Upper Necaxa Totonac, a number that is fairly typical of Totonacan language communities, with most consisting of a few thousand speakers or fewer (McGraw, 2009; Lam, 2012). Most speakers of UNT are in their 40s or older, and few members of younger generations are learning the language at home.

Like other Totonacan languages (McQuown, 1990; Kung, 2007; McFarland, 2009), UNT is polysynthetic with nominative-accusative alignment. Constituent order is flexible and may be determined by information structure, but is usually verb initial (Levy & Beck, 2012). In contrast to its morphosyntactic complexity, UNT segmental phonology appears to be relatively straightforward with a typologically common inventory of consonants and vowels (with the exception of ejective fricatives), limited consonant clusters, and simple syllable structure. Further details on the segmental inventory, syllable structure and prosody are presented in Sections 1.1.1-1.1.3. Unless otherwise noted, descriptions of UNT phonology are drawn from Beck (2004).

Table 1.1: UNT consonant inventory in IPA notation, borrowed/marginal phones in parentheses

	Bilabial	Alveolar	Post- alveolar	Lateral	Palatal	Velar	Glottal
Plosive	p	t				k	ʔ
Trill/Tap		(r,r)					
Nasal	m	n				ŋ	
Affricate		ts	tʃ				
Fricative		s s'	ʃ ʃ'	ɬ ɬ'		x	(h)
Approx- imant	w			l	j		

1.1.1 Consonants

The consonant inventory of UNT as reported by Beck (2004) is shown in Table 1.1. Apart from the anomalous ejective fricatives, the consonant inventory of UNT resembles not only other Totonacan languages, but also the most common consonant inventories of the 317 languages surveyed in Maddieson (1984). Oral and nasal stops appear at bilabial, alveolar, and velar places of articulation, fricatives at alveolar, post-alveolar, and lateral places, and affricates at alveolar and post-alveolar places.¹ Voicing is not contrastive; all oral stops and fricative segments are phonologically voiceless. UNT differs from other Totonacan languages in the occurrence of ejective fricatives in parallel to the pulmonic fricatives. Alveolar trills and taps occur mainly in Spanish loanwords and are therefore considered marginal as contrastive segments. The velar fricative /x/ is often realized as a glottal fricative [h], with no apparent conditioning environment causing the variation. Glottal stop is considered to be part of the stop series, and a reflex of the Proto-Totonacan segment /*q/. As such, it retains some phonological properties of /q/ present in other varieties of Totonac, such as lowering preceding vowels, and triggering place assimilation in preceding nasals (Beck, 2004).

Table 1.2: UNT vowel inventory

	Front	Central	Back
High	i i: ɨ ɨ:		u u: ʉ ʉ:
Mid	e e: ɛ ɛ:		o o: ɔ ɔ:
Low		a a: ʌ ʌ:	

1.1.2 Vowels

The vowel inventory of UNT consists of a symmetrical 5-vowel system including the vowel qualities /a, e, i, o, u/ (Beck, 2004), shown in Table 1.2. The system likely began as a three-vowel system in Proto-Totonacan, where high vowels /i/ and /u/ were allophonically lowered to [e] and [o] in environments adjacent to /q,w,j,l,x/ (MacKay, 1994; Brown et al., 2011). Subsequent loss of some of the conditioning environments above resulted in the current five-vowel system. Each of the five vowel qualities may be contrastively short or long, laryngealized or non-laryngealized (also known as ‘plain’) (Beck, 2004). The quantity distinction does not appear to be the result of any phonological processes and is believed to have been present in Proto-Totonacan (Brown et al., 2011). No limitations on combinations of vowel length, laryngealization, and stress have been noted.

1.1.3 Syllables and prosody

Syllables in UNT, like other Totonacan languages, e.g. Huehuetla Tepehua (Kung, 2007), Filomeno Mata Totonac (McFarland, 2009), Tlachichilco Tepehua (Watters, 1980), and Misantla Totonac (MacKay, 1994), include obligatory onsets and optional codas. In vowel-initial roots and prefixes, the obligatory onset condition is satisfied through the insertion of a glottal stop word initially. Onsets may consist of a single consonant, including affricates and ejective fricatives, or clusters of up to two elements. Onset clusters may consist of a fricative followed by a stop, nasal, or approximant, or a stop

¹All other Totonac varieties also have the lateral affricate /tʎ/, a distinction that has merged with /t/ in UNT.

followed by an approximant (Kirchner & Varelas, 2002).² Optional syllable codas may also contain clusters of up to two elements. Coda clusters may be made up of a stop or a nasal followed by a fricative.³ Complex segments such as affricates and ejectives may not appear as elements of tautosyllabic clusters, regardless of syllable position. Ejective fricatives and fricative + stop clusters may not appear in syllable codas (Beck, 2004).

Phonemic stress often distinguishes nouns from verbs (Beck, 2004, 2008). In nouns, stress falls on the penultimate syllable, unless the word ends in a long vowel or a closed syllable, in which case the heavy weight draws stress to the final syllable. Verbs are always stress final, except suffixed verbs, which follow the same stress rules as nouns. While cues to stress in UNT are only sparsely documented, Beck (2008) indicates that stressed syllables are longer and louder, and have a “marked pitch contour” when the vowel is long (Beck, 2004, p. 15). In addition to its effect on the pitch, stress also interacts with vowel length, with long stressed vowels having the longest duration of any vowels in UNT (Garcia-Vega, 2014). Further details on phonetic cues to stress have not yet been described, but will be cursorily addressed at various points throughout this dissertation.

Little is known about prosody and intonational contours in UNT. However, vowel laryngealization may be used as an indicator of phonological phrase boundaries, as is the case in other varieties of Totonac and Tepehua, such as Coatepec Totonac (Levy, 2015; McQuown, 1940, 1990), Filomeno Mata Totonac (McFarland, 2009), and Tlachichilco Tepehua (Watters, 2010). In many cases, word final vowels are devoiced, laryngealized, or dropped entirely. The presence of both phonemic and prosodic laryngealization could result in potentially complex interactions requiring extensive exploration and description to untangle.

1.1.4 Phonotactics

Descriptions of phonotactic patterns in UNT have focused primarily on consonant sequences and clusters. Table 1.3 summarizes the environments in which stops, fricatives

²In practice, only the velar and alveolar stops have been found in stop + approximant clusters. /k/ appears in /kl/, /kw/, and /kɾ/ clusters, while the only such cluster /t/ appears in is /tw/. Note that Kirchner & Varelas (2002) considers the alveolar tap to be a phonological approximant.

³Although this structure resembles the production sequence of affricates, the phonemic affricate segments /ts/ and /tʃ/ are notably absent from syllable codas, except in cases of ideophonic sound symbolism.

Table 1.3: Phonotactic environments of ʔ and ejective fricatives. ✓ indicates that the segment occurs in the given environment. 'R' indicates that the occurrence is restricted in some way. *Sources differ about whether ejective fricatives occur in these environments; the dictionary data confirms that they do occur, but perhaps only across morpheme or syllable boundaries.

Context	Oral stops (P)	ʔ	Pulm fricatives (F)	Ej fricatives	Fric + Stop clusters
#_V	✓	✓	✓	✓	✓
V_#	✓	✓	✓	-	-
V_V	✓	✓	✓	✓	✓
F_	✓	✓R	✓R	✓*	✓
_F	✓	✓	✓	-	-
N_V	✓	✓	✓	✓	✓
P_	✓	✓R	✓	✓	✓
_P	✓	✓R	✓	-	-

and clusters have been reported to occur (Beck, 2006; Kirchner & Varelas, 2002). The table demonstrates the similarity between the distributions of stops and fricatives, generally. In comparison to pulmonic fricatives and stops, ejective fricatives occur in more restricted environments. They do not occur word finally, before pulmonic fricatives, or before stops. However, ejective fricatives occur in precisely the same phonotactic environments as fricative + stop clusters. A major difference between ejective fricatives and clusters is that clusters may resyllabify into sequences that cross syllable boundaries⁴, while ejective fricatives occur only at syllable onset (Beck, 2006). In situations where a fricative-final prefix attaches to a glottal initial stem, the sequence is maintained rather than fusing into a phonetic ejective fricative, as in *killhó'x'a'* /kiɫ.ʔó'.ʃ'a/ 'one's lips' where the prefix *killh-* attaches to the stem *hó'x'a'*. In fact, the only cases of reported fricative + glottal stop clusters cross both syllable and morpheme boundaries (Beck, 2006) (c.f. section 1.1.3).

1.2 Ejective fricatives

Ejective fricatives are cross-linguistically rare, presumably due to the complex nature of their articulation and the difficulty in generating the airflow necessary for frication

⁴Bauer (2015) differentiates between clusters and sequences in precisely this scenario, where the main difference between them is that a cluster occurs within a syllable, while a sequence occurs across the syllable boundary.

from the glottalic airstream mechanism (Maddieson et al., 2001; Shosted & Rose, 2011). They account for only a small proportion (1.52%) of segments reported in the UCLA Phonological Segment Inventory Database (UPSID) and appear in only ten languages, or 2.22%, in comparison to ejective stops in 15.08% of languages and ejective affricates in 13.08% (Maddieson & Precoda, 1990). Shosted & Rose (2011) report an additional eight languages with ejective fricatives, including Upper Necaxa Totonac, and a further 13 languages with /s'/ appear in PHOIBLE Online (Moran et al., 2014). Other than UNT, none of these languages has ejective fricatives as the only glottalic segments.

Ejective speech is produced by means of the glottalic airstream; airflow is initiated not by the lungs, but by the manipulation of pressure in the air trapped above the glottis (Catford, 2010; Henton et al., 1992; Maddieson, 2013). In stops, the compression necessary to increase air pressure and allow for egressive airflow is achieved via simultaneous closures at the glottis and an oral place of articulation. While these closures are maintained, the larynx moves upward, increasing air pressure in the newly sealed chamber. After compression, the oral closure is released, followed by release of the glottal closure. Ejective fricatives are complicated by the need for sustained outward airflow in order to produce friction. As a result of these articulatory pressures, ejective fricatives are often preceded by silent intervals indicating glottal closure, as in Kabardian (Gordon & Applebaum, 2006) and Amharic (Demolin, 2002), or flanked by them as in Mehri (Ridouane et al., 2015). Ejective fricatives may also be affricated, as in Tigrinya (Shosted & Rose, 2011) where friction is preceded by an oral closure. Ejective fricatives have been differentiated from pulmonic fricatives by their shorter friction periods in Tlingit (Maddieson et al., 2001), Amharic (Demolin, 2015) and Kabardian (Gordon & Applebaum, 2006), presumably as a result of the limited air supply available for their production. Unlike ejective fricatives in other languages, friction in the ejective fricatives of UNT appeared to be longer than that of pulmonic fricatives in pre-vocalic environments, as well as in fricative + stop clusters (Beck, 2006). Friction in ejective fricatives was followed by a short silent interval; no appreciable preceding closures were noted.

The phonology of ejective fricatives also plays a role in their identification in UNT. The synchronic distribution of ejective fricatives in UNT resembles those of fricative +

Table 1.4: Syllabification of fricative + stop clusters and ejective fricatives. Examples are presented in practical UNT orthography (in italics) and phonemic notation using IPA symbols. Morpheme boundaries are indicated by ‘-’, syllable boundaries by ‘.’. Fricative + stop clusters at syllable boundaries syllabify into coda and onset regardless of morphology, but ejective fricatives do not (Beck, 2006). Data were taken from (Beck, 2006, 2011a)

Clusters		Ejectives	
Morphology	Syllabification	Morphology	Syllabification
<i>místu'</i> /'mistu/	/'mis.tu/	<i>hó'x'a'</i> /'ʔoʃ'a/	/'ʔo.ʃ'a/
'cat'		'skin'	
<i>pálhka</i> /'pałka/	/'pał.ka/	<i>pa:lh'á:</i> /pa:ɬ'a:/	/pa:.'ɬ'a:/
'griddle'		'cut open sth's belly'	
<i>taxtú</i> /ta-ʃtu:/	/ta.ʃ.'tu:/	<i>a'hs'awini'</i> /aʔ-s'awi-'ni/	/aʔ.s'a.wi.'ni/
INCHOATIVE-out 'leave'		head-defeat-AGT 'trickster, deceiver'	
<i>kihó'x'a'</i> /kiɬ-ʔoʃ'a/	/kiɬ.'ʔo.ʃ'a/	<i>ma:x'a'he:nín</i> /ma:-'ʃ'aʔa-e:-nin/	/ma:.'ʃ'a.ʔe:.'nin/
mouth-skin 'one's lips'		CLS-shine-CLS-DTRN 'be illuminated'	

stop clusters, which occur only in syllable onset position (Beck, 2006; Kirchner & Varelas, 2002). Clusters may also cross syllable boundaries such that the fricative appears in the coda of the preceding syllable, and the stop appears in the onset of the following syllable. In contrast, the ejective fricatives do not resyllabify as fricative + glottal stop clusters, remaining instead in the onset of the following syllable according to Beck (2006). Table 1.4 illustrates this syllabification scheme in both mono-morphemic and morphologically complex polysyllabic stems with fricative + consonant clusters and ejective fricatives at word internal syllable boundaries.

Ejective fricatives are believed to have their origins in historical fricative + /q/ clusters. In UNT, all instances of /q/ have shifted to become /ʔ/. Beck (2006) notes that a historical origin of ejective fricatives in fricative + ʔ sequences would predict a parallel distribution between ejective fricatives and clusters, precluding the appearance of phonological evidence to differentiate between them. A very few instances of fricative

+ /ʔ/ are reported to arise in glottal-initial words preceded by a fricative-final prefix. All of the reported fricative + /ʔ/ clusters are produced by the addition of one of three fricative-final prefixes to stems beginning with /ʔ/: *ix-* /iS-/ 'his/her', *helh-* /ʔeɬ-/ 'mouth (interior)', and *killh-* /kiɬ-/ 'mouth (exterior)'.

1.3 Laryngealized vowels

Laryngealization contrasts fall along a continuum of phonation from voiceless, produced with a widely spread glottis, through varying degrees of glottal constriction to complete glottal closure (Ladefoged, 1971; Gordon & Ladefoged, 2001; Blankenship, 2002). Vowel phonation contrasts are somewhat rare, occurring in less than 3% of languages in UPSID (Maddieson & Precoda, 1990). Laryngealized vowel contrasts occur in only 4 languages (0.89%) in UPSID. An additional 5 languages contrast breathy and modal vowels (1.11%), and a further 3 languages contrast voiced and voiceless vowels (0.67%). The PHOIBLE Online database includes 18 additional languages with /a/ in their vowel inventories (Moran et al., 2014).

Phonation types have highly variable acoustic profiles, with differences depending in part on whether the phonation is contrastive or allophonic, breathy, creaky, or otherwise modified. Spectral and acoustic measures have been found to differentiate between modal and non-modal phonation types in several languages including English, Korean, and Hmong (Garellek, 2010), Mazatec, Mpi, and Chong (Blankenship, 2002), Zapotec (Esposito, 2010b), and Gujarati (Esposito, 2006; Keating & Esposito, 2006), among others. The difference in amplitude between the first and second harmonics, often reported as H1-H2, or H1*-H2* to indicate adjustment for values of the first formant, appears to be the most reliable measure for differentiating phonation types across languages (Keating et al., 2011; Slifka, 2006), though unadjusted H1-H2 may also be used (Keating & Esposito, 2007). Other measures, such as the difference in amplitude between the first harmonic and the first or higher formant (H1-A1, H1-A2, H1-A3, etc.), cepstral peak prominence, and others have also been used to measure voice quality differences (Keating & Esposito, 2007; Keating et al., 2011).

In addition to spectral differences, the timing of vowel phonation is affected by contrastiveness. Non-modal phonation lasts longer and is more highly differentiated from modal phonation when the phonation differences are contrastive than when they are non-contrastive (Blankenship, 2002; Garellek, 2010). In Hupa, laryngealization spreads from following consonants onto a portion of preceding vowels, but never laryngealizes the entire length of the vowel (Gordon, 2001).

Laryngealization has long been of particular interest to linguists working with Totonacan languages. Laryngealized vowels are prevalent in several languages of the family including Zapotitlán de Mendez (Aschmann, 1946), Papantla (Levy, 1987), Misantla (MacKay, 1994), and Filomeno Mata (McFarland, 2009), in addition to Upper Necaxa Totonac (Beck, 2011b). The related Tepehua languages reflect this contrast in glottalized consonants that correspond to laryngealized vowels in languages of the Totonac lineage (Watters, 1980, 1988, 2010; Kung, 2007; MacKay & Trechsel, 2013). Historical reconstructions variably support the reconstruction of laryngealized vowels (Brown et al., 2011) or glottalized consonants (Mackay & Trechsel, 2018; MacKay & Trechsel, 2011) in Proto Totonacan based on these correspondences. The Tepehua and Totonac branches of the Totonacan family tree are differentiated in part based on the temporal location of laryngealization in the syllable: Tepehua languages manifest laryngealization in syllable onsets, and Totonac languages realize laryngealization in the syllable nucleus.

Across the Totonacan family, descriptions of vowel laryngealization are somewhat varied. Aschmann (1946) described three types of laryngealized vowels in Zapotitlán de Mendez Totonac, ranging from a modal vowel followed by a glottal stop to a “completely laryngealized” vowel flanked by glottal stops on either side. In a phonetic sketch of the Totonac of Papantla, Herrera Zendejas (2014) described non-modal vowels as occurring in three forms: creaky voice (characterized by irregular glottal pulses) throughout the entirety of vowel duration, creaky voice in only a portion of the vowel duration (typically the beginning), or “stiff voice”, indicating a more subtle degree of laryngealization throughout vowel duration. Tokens with stiff voice were reportedly difficult to identify either by ear or qualitative spectrographic analysis; in these cases the contrast was most clearly associated with the spread of voicing onto the preceding

consonant. The resultant voiced stops had shorter closure duration than typical voiceless stops preceding modal vowels, and a progressive decrease in amplitude throughout the stop closure. Non-modal vowels were also found to have overall lower intensity than modal vowels. In UNT, some speakers seem to laryngealize more clearly and reliably than others (Beck, personal communication).

Glottal stops are notoriously variable in their production across languages (Bao, 2009; Esling et al., 2005; Garellek, 2013; Quick, 2003; Whalen, 2016; Elías-Ulloa, 2016), often appearing as periods of non-modal phonation in vowels rather than a period of complete closure. Their variability likely contributes to the difficulty in identifying and classifying glottal stops according to traditional phonological categories. There is clearly a relationship between laryngealized vowels and glottal stops, which feature prominently in the phonological descriptions of many Totonacan languages, though their phonemic status is not always clear. McQuown (1940) analyzed the glottal stop as an independent phoneme in Coatepec Totonac, distinct from the vowels adjacent to it. Aschmann (1946) concluded to the contrary that glottal stops were rightfully interpreted as integrated with the vocalic nucleus rather than distinct and separate phonemic category in the Totonac of Zapotitlán de Mendez. Arana Osnaya (1953) subsequently pointed out in her reconstruction of Proto-Totonacan, the “special problem” of vowels in Totonacan, referring to inconsistencies in vowel quality, length, and laryngealization that led to difficulties in reconstruction by the comparative method.

In languages of the Tepehua branch, glottalized stops often induce laryngealization on following vowels (MacKay & Trechsel, 2013). The difficulty in accounting for laryngealization in both synchronic and diachronic Totonacan systems continues today (Trechsel & Faber, 1992; Watters, 2010; Garcia-Vega, 2014; Herrera Zendejas, 2014).

1.4 Summary and Research Questions

UNT has been reported to maintain contrasts between two series of fricative and vowel phonemes. These contrasts both involve an altered laryngeal configuration, leading to ejective fricatives contrastive with pulmonic fricative on the one hand and laryngealized vowels contrasting with modal vowels on the other. In addition to these contrasts,

glottal stops are posited as independent phonemes belonging to the stop series. The laryngeal contrasts and glottal stops all share similar articulatory mechanisms in that they involve some degree of glottal constriction or closure, likely leading to similarities in acoustic output. Phonological patterns of co-occurrence between fricatives, vowels and glottal stops also play a role in the identification of the reported contrasts, often with appeals to diachronic origins.

There are two main questions to be addressed in this dissertation. The first is whether the ejective fricatives might be better interpreted as clusters of fricatives + glottal stops. The second is whether laryngealized vowels might be allophonically laryngealized as a result of proximity to glottal stops rather than phonemically laryngealized. These questions are addressed first through a corpus study of the *Upper Necaxa Totonac Dictionary*, which reveals patterns of co-occurrence across lexical forms, and then through analyses of certain acoustic aspects of each class of sound. The findings support the analysis of ejective fricatives as clusters and suggest that at least some laryngealized vowels may be the result of coarticulation with glottal stops. The thesis concludes with some general discussion about the usefulness of phonetic research to documentary linguistics generally and especially the establishment of reproducible phonological analyses.

The remainder of this thesis consists of distributional and acoustic descriptions of speech segments in UNT. Chapter 2 summarizes the methods of data collection and annotation that are used in this thesis, along with illustrative spectrograms of target segments. Further details of the methods are presented in each chapter as relevant. Chapter 3 examines patterns of segmental distributions throughout the *Upper Necaxa Totonac Dictionary* (Beck, 2011b), paying particular attention to the patterns of co-occurrence of glottal stops and ejective fricatives with laryngealized and non-laryngealized vowels. Chi-squared tests are used to determine the independence (or lack thereof) between laryngeal features of adjacent segments. Chapter 4 analyzes two acoustic measures known to be associated with vowel phonation cross-linguistically, the difference in amplitude between the first two spectral harmonics, and fundamental frequency. Each analysis is performed separately for two contexts, one where vowels are preceded by consonants, and the other where vowels are followed by consonants. Qualitative predictors reflecting laryngeal category of consonants and vowels, consonant manner, and

syllable stress, as well as interactions between such factors are included in the models. Chapter 5 analyzes segmental and subsegmental duration of ejective and pulmonic fricatives in a variety of phonetic environments. Comparisons are made between fricatives in clusters and before vowels. Additional contextual factors such as word position, stress, and adjacent vowel laryngealization are also addressed. Chapter 6 summarizes the findings of the previous three chapters and provides some critical commentary and directions for future research.

Chapter 2

Materials

The majority of the analyses presented in this thesis are based on a collection of acoustic data obtained over the course of two field trips to Patla and Chicontla in September 2012 and January 2014. The present chapter describes how audio data were recorded and subsequently annotated for acoustic analysis based on the phonemic transcriptions available in the *Upper Necaxa Totonac Dictionary* (Beck, 2011b). Sample spectrograms are presented to illustrate the annotation conventions. Further background and methods particular to each chapter will be introduced in situ.

2.1 Segmental corpus analysis

Chapter 3 analyzes segmental collocates of laryngealization in both consonants and vowels. The analysis is based on words and affixes available in the *Upper Necaxa Totonac Dictionary* (Beck, 2011b). All entries were included in the analysis, after conversion to a phonemic transcription. Further details of the data extraction process are presented in Chapter 3.

2.2 Acoustic analysis

This section provides information about word list materials, the speakers who provided the audio data for the current studies, and the method of data collection.

2.2.1 Data collection

Four speakers of Upper Necaxa Totonac (two women, two men) provided the audio data included in the acoustic analyses. Speakers ranged in age from early 30s to about 60 years old. The speakers were all native to Patla and were bilingual in Spanish. All speakers had grown up speaking UNT, with younger speakers being exposed to more Spanish earlier in life. All of the speakers still speak UNT in the community on a daily basis, though Spanish is also very frequently used. Interactions with the author were undertaken in Spanish.

The word list for this study was initially compiled from orthographic forms found in the *Nuevo diccionario del idioma totonaco del Río Necaxa* (*New dictionary of the Upper Necaxa Totonac language*, Beck 2011a), a practical bilingual dictionary compiled for the use of speakers of UNT and derived from the more comprehensive *Upper Necaxa Totonac Dictionary* (Beck, 2011b). The original list of 66 words, collected in the field in 2012, was designed to capture potential variability of the three ejective fricative segments /s', f', ɸ/, including words where ejective fricatives appeared before vowels word initially, and between vowels word medially. In its initial form, the word list was balanced for laryngealization of the following vowel and syllable stress as much as possible. Other characteristics of vowels, such as quality and length were not included in the word list design due to the added complexity including such factors would entail. On a subsequent field trip in 2014, a supplemental list was collected that included words containing pulmonic fricatives in parallel environments to those of the ejective fricatives, in addition to affricates and pulmonic fricatives in fricative + stop clusters to allow for a comparison between these segment types and ejectives. The final word list consisted of 130 word forms, though some forms were not produced by all speakers. The complete wordlist from both field trips appears in Appendix A.

Recordings were made in speakers' homes using a Marantz portable digital audio recorder (PMD 660) and a head-mounted ear set microphone.¹ By using a head-mounted setup, the distance from the speaker's mouth to the microphone was kept fairly constant throughout the recording session and across speakers, ensuring reasonably consistency

¹The microphone differed from one field trip to the next, but both microphones were high quality and produced audio that was not judged by the author to be substantially different from each other.

in the audio recordings. All recordings were made at a sample rate of 44.1 kHz with the exception of one, which was made at 96 kHz and subsequently down-sampled to 44 kHz in order to remain consistent with the other recordings.

The word list was not intentionally arranged in any particular order, and all speakers were presented with words in the same list order. The procedure for recording the word list was explained to speakers prior to beginning the recording. Speakers were asked to repeat each word three times within the frame sentence in *ixla wanli' ... chuwa* [ʃla wanli ... tʃuwa] 'he said ... now'. During recording, speakers had visual access to the orthographic form of list items in UNT and written translations in Spanish, both of which were presented on the author's laptop screen. In addition to these written prompts, speakers were also orally prompted with a Spanish translation. No restrictions were imposed on speech rate or speed of moving through the word list. Speakers were encouraged to identify problems or points of confusion with any and all word list items and often took the opportunity to discuss each item as it was recorded. In several cases, alternative words were suggested by the speaker when the item on the word list was unfamiliar to them. Often, the suggested forms were related forms to the originally proposed item with a different morphology. Alternate word forms were accepted at the time of recording, but phonologically unrelated lexical forms were later excluded from the analysis.

Each elicitation session resulted in a single audio file in WAV (.wav) format. The recordings were allowed to run throughout the session without stopping unless the speaker requested that the recorder be turned off. This practice ensures minimal disruption during the recording sessions, making the speakers more likely to be at ease, as well as capturing any incidental discussion between the researcher, the speaker, and other consultants, where present (Bower, 2008). Preserving the recording session from start to finish was also found to work as a memory aid for the author, as listening to the recordings provided a re-immersion in the surrounding environment of the recording.

2.2.2 Annotation

Audio files were annotated in their full, unedited forms. First, each file was segmented at the word level using the segmentation mode in ELAN (Wittenburg et al., 2006).

Segments were annotated with the orthographic form of each target word using ELAN's Transcription mode. This process of segmenting and transcribing allowed the original recording session to be maintained intact, while allowing for future avoidance of long gaps in the recording, whether they were full of conversation, background noise, or other material not relevant to the present analyses. The annotations were then exported in the Praat TextGrid format, which served as the basis for annotations of individual phonemic segments.

After the initial word-level segmentation in ELAN, audio data were further segmented and measured using Praat (Boersma & Weenink, 2018). Words were annotated from start to finish, allowing for the contribution of more than one relevant segment per word token to some analyses. In keeping with traditional analyses and to avoid the imposition of unnecessarily subjective judgments about the identity of segments, the audio files were annotated in accordance with the phonemic forms of words as transcribed in the dictionary (Beck, 2011b), rather than the audible impression of each segment. For example, many instances of laryngealized vowels were produced without audible non-modal phonation; nevertheless, all vowels that are orthographically transcribed as laryngealized were also labeled as laryngealized in the TextGrid. Phonemes were labeled with standard IPA notation, based on conventional orthographic transcriptions of UNT. Conversion from orthography to phonemic representation was straightforward as a result of the one-to-one relationship between orthographic and phonemic segments. Further details of the annotation conventions are presented in the subsections below.

The following sections provide descriptions of annotation conventions along with illustrations for each segment type by way of sample spectrograms. All figures in this section represent frequency on the x -axis and time on the y -axis. The frequency range is shown from 0-10000 Hz in order to show differences in the centers of spectral energy during release periods. Higher amplitudes of spectral energy are represented by darker shading in the spectrograms. All of the spectrograms were created from the recording of speaker GMM's speech unless otherwise noted.

Fricatives, oral stops, and affricates Oral stops, affricates, and all fricatives were annotated with a single set of conventions in order to reflect similarities in their pro-

duction. Each of these segment types involve oral constriction, sometimes resulting in complete closure, and release of that constriction allowing air to flow. In some instances the release was then followed by a further interval of silence or near silence. Thus, fricatives, oral stops and affricates were annotated according to three possible events: closure, release, and lag. *Closure* and *lag* both refer to an interval of silence, where *closure* was defined as silent intervals preceding release, and *lag* was used to refer to silence following release. *Release* indicates the interval where air is flowing and noise is generated.

Stops and affricates typically involved a period of closure, followed by a release. The release of closure was often visible as a brief spike in amplitude in the acoustic waveform, corresponding with broad spectrum energy (a dark vertical line) in the spectrogram. In affricates the release burst was closely followed by a period of turbulent friction noise with no intervening silent period between them. Fricatives were most commonly produced without any preceding closure, though some instances of pre-frication lag were observed in both ejective and non-ejective fricatives. Onset of the fricative release interval typically did not involve a burst, beginning instead with the abrupt onset of sustained turbulent noise at a steady amplitude. After the release, fricatives and affricates were sometimes observed with a lag interval before the onset of vowel phonation.

Closure Figure 2.1 illustrates annotation of pre-release closure in one token of the lateral fricative /ɬ/. Closure intervals were defined as beginning at the end of the second formant in the preceding vowel or sonorant, or the abrupt end of friction noise where applicable, and ending with the onset of broad spectrum energy in the release (burst or friction), or the onset of vowel phonation in cases where the release burst was not apparent. Closure intervals were labeled separately from the release and encoded with the segment label followed by a 'c' for closure (e.g. 'tc' indicates the closure of an alveolar stop).

Release Figure 2.2 shows the closure and release intervals of one token of the post-alveolar affricate /tʃ/. Release periods began with a burst, if present, or the onset

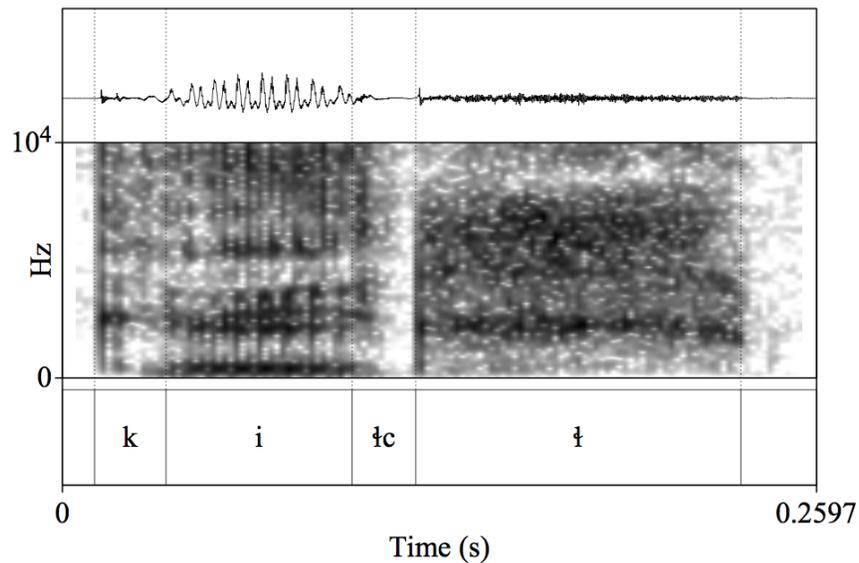


Figure 2.1: Pre-release silence in one token of /k/ from speaker HFM. Detail taken from **kilhpɑ'nlhúlu'** /kiłpɑn'ɰulu/ 'jowly, with swollen cheeks'.

of frication noise, and ended with the end of noise. Release intervals were labeled according to the segmental category, with no further modifications (e.g. 't' indicates the release burst of a voiceless alveolar stop). The release portion of affricates and some fricatives was made up of a burst followed by frication. Both the burst and any following frication were considered to be part of the release. As a result, the release was substantially longer in fricatives and affricates than in stops.

Lag Figure 2.3 illustrates an interval of post-release lag in one token of /tʃ/ including non-modal phonation in the following vowel. In many tokens of fricatives and affricates, the release period was followed by a period of silence before the onset of vowel phonation. These lag periods began at the end of frication and continued until the resumption of modal phonation in the following vowel. Lag intervals were often silent, but at times also included low amplitude noise, intermittent bursts of broad spectrum noise, or periods of non-modal phonation. This is addressed further in Section 2.2.2 which describes the annotation of glottal stops and relates them to the lag intervals described here. Lags were labeled with the symbol indicating the consonant phoneme followed by a '-'.

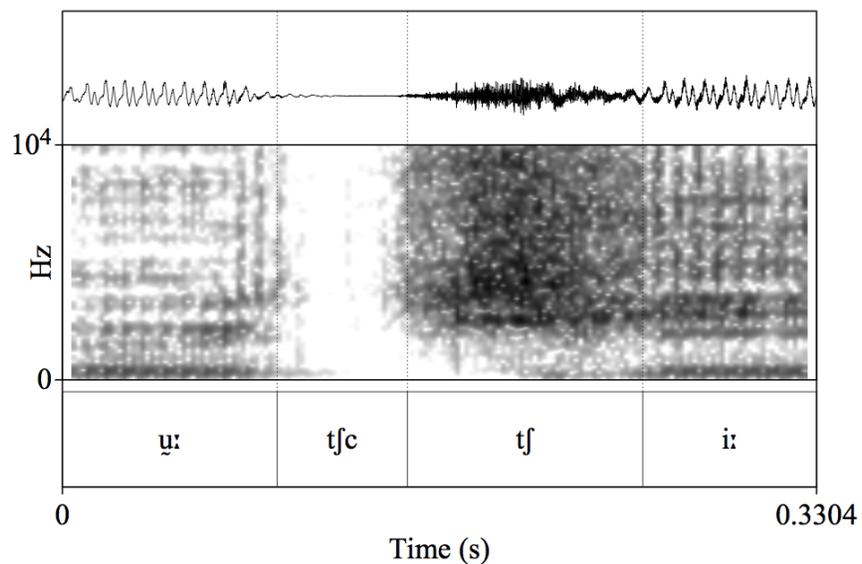


Figure 2.2: /tʃ/ segment produced by speaker HFM. Detail from $a:'tu:'chi:yé:klh$ / $a:tu:tʃi:'jɛ:kɬ$ / 'mint'.

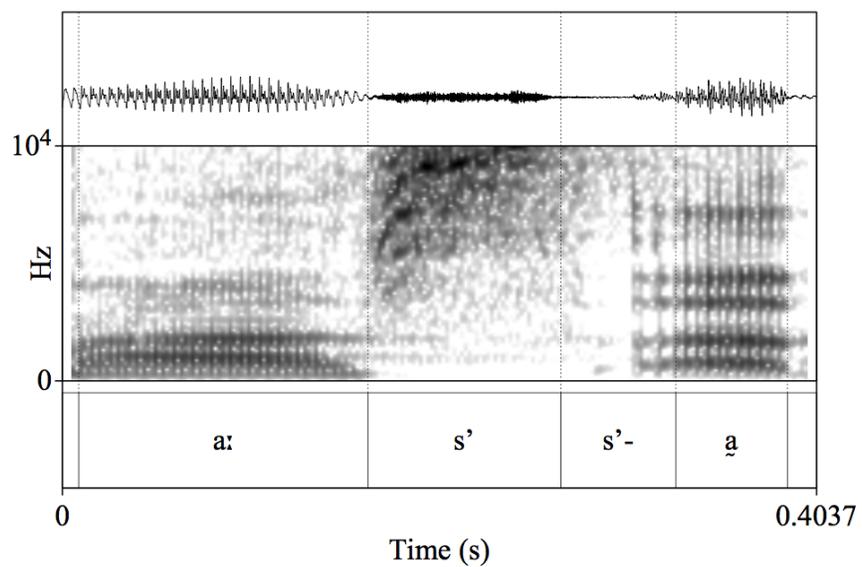


Figure 2.3: Post-frication lag in the production of an /s'/ produced by speaker GMM. Detail taken from $ma:s'a'ta:nán$ / $ma:s'a:ta:'nan$ / 'raise children'.

Glottal stops Glottal stops are highly variable in their production (see Section 1.3), and therefore do not present a predictable acoustic profile that lends itself easily to a single set of annotation conventions. In the present data, glottal stops were produced in several forms, a selection of which are presented here. There was no obvious pattern in the data that predicted which form a glottal stop would take. Segments were labeled as glottal stops only if they were represented in the orthography by the character <h>. In addition to orthographic glottal stops, the data include several cases of phonetic segments acoustically reminiscent of glottal stops that were not identified in transcriptions. Such segments have not been included in the present analysis.

Figure 2.4 presents some of the possible acoustic realizations of glottal stops between vowels and sonorants. While these examples are not necessarily exhaustive, they represent some of the most frequent productions and illustrate the complicated nature of such highly variable segments. Figure 2.4a shows an example of a glottal stop produced as non-modal phonation that persists throughout the duration of surrounding vowels without any visible boundaries between them. Figure 2.4b shows an example of a glottal stop realized as a period of non-modal phonation with decreased amplitude relative to surrounding vowels of higher amplitude. Figure 2.4c shows a glottal stop produced as a silent period interrupted by a brief glottal pulse with little or no notable changes in phonation of surrounding vowels. Figure 2.4d shows a brief period of non-modal phonation at the end of the preceding vowel, followed by a period of relative silence and little or no non-modal phonation in the following vowel. Figure 2.4e shows a glottal stop produced as a silent period punctuated by multiple glottal bursts and both preceded and followed by non-modal phonation in surrounding sonorants. Figure 2.4f shows a period of relative silence with continuous low amplitude energy reminiscent of a voice bar corresponding to the transcribed location of a glottal stop.

Glottal stops sometimes also appear adjacent to fricatives across syllable and morpheme boundaries, as illustrated in Figures 2.5 and 2.6. Such instances of glottal stops were much more uniform in their appearance, always occurring with a substantial period of silence, and often being flanked at start and end with bursts representing the impact of glottal closure and the subsequent reopening of the glottis. Visual comparison

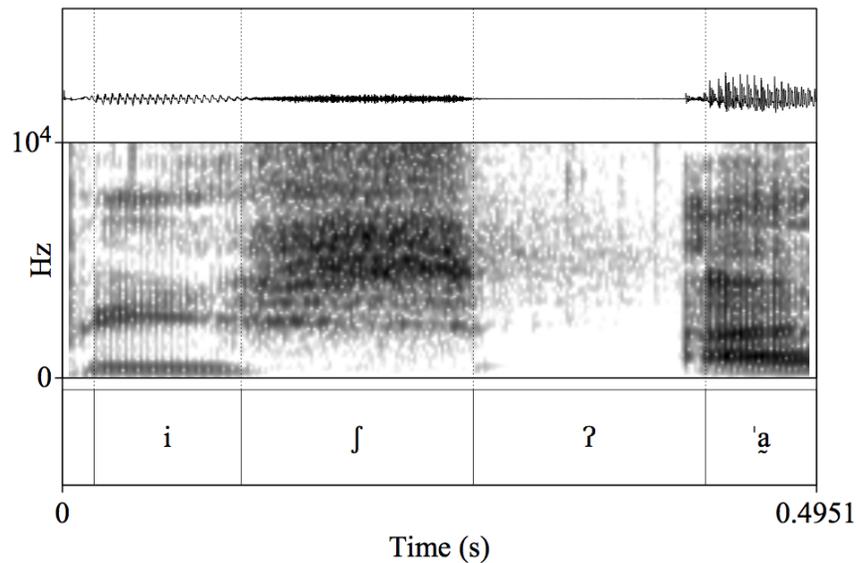


Figure 2.5: [fʔ] sequence across a morpheme boundary. Detail from *pixhá'lha'* [piʃ-ʔaʔa] 'large (bunch or bouquet)'

with the spectrograms of ejective fricatives, such as 2.3 reveals similarities between these heterosyllabic/heteromorphemic fricative + glottal stop clusters and ejective fricatives.

Vowels and other sonorants Vowel segmentation relied on the cues of surrounding consonants. Generally vowels were considered to be portions of speech with clear formant structure apparent in the spectrogram. Vowel boundaries were sometimes determined by the presence or absence of the second formant, especially in relation to the onset of stop closure (see 2.2.2). In the case of vowels adjacent to glottal stops, shown in Figure 2.4, the segmentation boundary was placed at the onset or offset of more-or-less modal phonation in the vowel. Amplitude of the waveform was also used as an indication of the transition between vowel and glottal stop, with a higher amplitude indicating vowels rather than glottal stops.

Sonorant consonants do not play a role in the analyses presented in this dissertation, but they were nevertheless segmented in words where they occurred. Boundaries between vowel-sonorant sequences were placed at approximately the midway point of the transition from one oral configuration to the next. Vowel-nasal sequences were

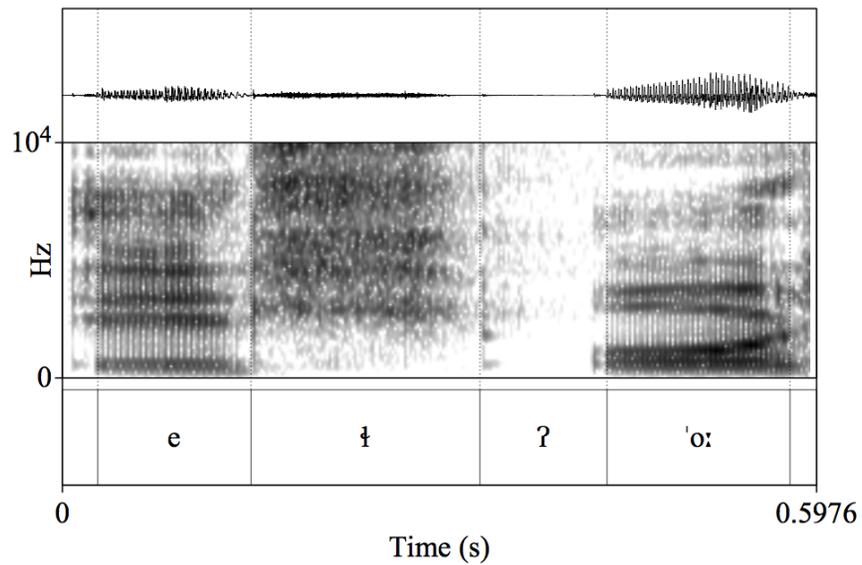


Figure 2.6: [ɬʔ] sequence across a morpheme boundary. Detail from helhhó:x'a' /ʔeɬ-ʔo:ʃ'a/ 'one's lips'

somewhat easier to segment due to the sharp transition into the period of damped energy and anti-formant structure of nasals when compared to surrounding vowels.

Chapter 3

Laryngealization in adjacent segments

The present chapter provides a quantitative description and analysis of the segmental contexts in which laryngealization occurs in *The Upper Necaxa Totonac Dictionary* (Beck, 2011b). The analysis tests the hypothesis that laryngealized segments are more likely to occur adjacent to other laryngealized segments. Findings reveal interdependence between segmental laryngealization and laryngealization of preceding and following contexts, particularly between vowels and following glottal stops. The regular co-occurrence of laryngealization in adjacent segments suggests a redundancy in the phonemic representation that could be resolved by retaining the laryngeal feature in only one of the segments in the sequence and deriving the laryngealization of the other segment through traditional allophonic rules.

3.1 Introduction

Laryngealization is considered to be a contrastive characteristic of the vowel system of UNT (Beck, 2004). Consonants have not been described as maintaining laryngealization contrasts, but if we consider that glottal stops and ejective fricatives are both produced with laryngeal tension, perhaps we can consider these segments to be laryngealized as well. If laryngealization is contrastive in both consonants and vowels, there ought not be a strong correspondence between vowel laryngealization and laryngealization of surrounding consonants. On the other hand, a high correspondence between laryngealized vowels and laryngealized consonants might indicate an allophonic alternation that has heretofore been overlooked.

The main aim of this chapter is to explore the general patterns that arise between consonants and vowels with respect to laryngealization. Collocational patterns of laryngealization in both laryngealized and non-laryngealized environments are explored using methods inspired by corpus linguistics. Basic descriptions of other collocational patterns in the data are also presented. The discussion relates the findings discovered here to the following two chapters investigating acoustic dimensions of laryngealization in vowels in laryngeal and non-laryngeal contexts.

3.2 Methods

The materials for the present analysis were extracted from the digital version of the *Upper Necaxa Totonac Dictionary* (Beck, 2011a). All forms were included in the analysis, including head words, inflected forms, and affixes that received their own entries. For a first foray into quantitative phonotactic study of laryngealization, the *Dictionary* is good source material because it broadly represents the language as it has been encountered to date and serves as a transparent resource for future researchers to refer to. While it is possible that certain sequences may be over-represented in a corpus built from dictionary forms, the subject matter and vocabulary in the *Dictionary* are broad and not limited by style or topics as a corpus of stories or conversations would be. Potentially over-represented sequences are discussed where relevant below. The resulting corpus is the largest and most comprehensive dataset available for studying the segmental collocation patterns in UNT.

The data required little pre-processing before inclusion in the analysis because the orthography of UNT is transparent at the phonemic level. Dictionary forms were copied into a plaintext file format, then transliterated into IPA using `grep` and `regex` (regular expressions) find-and-replace methods. Following a method similar to Bauer (2015), transcriptions were accepted as given in the published dictionary. Because some segments were encoded by complex character sequences (i.e. affricate digraphs, ejective fricatives, vowels with length, stress and laryngealization diacritics), phonemic symbols were delimited by inserted spaces on either side. Segment sequences such as clusters were therefore split into component segments by these spaces, while complex segments

such as /tʃ/ were retained as a unit without a space between the two characters of the digraph. Word boundary markers (#) were inserted at the end of each word to ensure that segments were not interpreted as adjacent across word boundaries. The resulting list of prepared word data was then converted into a single text string from which immediately preceding and following segments were identified for all segments using the `shift` function from the `data.table` package (Dowle & Srinivasan, 2017) in R (R Core Team, 2017).

A single data frame was constructed from this collocational data, which was further classified according to the segment and the context in which it occurred. Each segment and its collocates were classified according to twenty binary identifiers loosely analogous to phonological features. These binary features allowed segments and their contexts to be separated into subsets on the basis of one or more features. Features were defined for each segment by way of a grid (see Appendix B), which was then merged with the segmental data sets in R. Three classes of segments (stops, fricatives, and vowels) and their contexts are analyzed here. Each segment class was divided into a set with laryngeal constriction and one without laryngeal constriction. In this way, fricatives were divided into ejective and pulmonic categories; vowels were divided into laryngealized and non-laryngealized, and stops were divided into oral (p,t,k) and glottal (?). Cross-tabulations of these binary features resulted in the count data presented in the following section. Chi-squared tests were performed on these count data in order to determine whether laryngealization of context segments was related to laryngealization of target segments.

3.3 Results

This section presents the results of the analyses described above. First, distributions of preceding and following segmental collocates are described for stops, fricatives, and vowels. These distributions are then analyzed with chi-squared tests to determine whether there is a relationship between segmental and contextual laryngealization.

3.3.1 Segmental collocates

A general summary of the segmental collocates of stops, fricatives and vowels is reported here. Each segment class is further divided into member segments for illustrative purposes. Preceding and following contexts for all segments have been divided into the 6 categories: laryngealized vowels, non-laryngealized vowels, stops, fricatives, other consonants (including affricates, nasals, and other sonorants), and word boundaries. Laryngealization will be further addressed in the statistical analysis. The data are presented as raw counts as well as percentages of the total number of tokens per segment category.

Stops

A total of 15705 stop tokens occurred in the dictionary corpus. These tokens were distributed among the segment types as follows: /p/ segments 18%, /t/ segments 31.6%, /k/ segments 24.2%, and /ʔ/ segments 26.1%. Less than 0.04% of stops were represented by the marginal phonemic segments /b/ and /d/, which have been excluded due to their small numbers (6 tokens in total). The remaining 15699 tokens were included in the present analysis.

Table 3.1 presents a summary of stops and their preceding environments. The most striking finding here is that 72.94% of /ʔ/ tokens occur after laryngealized vowels. Closer inspection of glottal stop tokens revealed that some of these collocations were due to frequent meronymic prefixes made up of laryngealized vowels followed by glottal stops. Table 3.2 summarizes the count data for each of these prefixes in the dictionary. In total, these prefixes accounted for 1471, or 36% of instances of glottal stops after laryngealized vowels. In order to investigate whether these instances might bias the overall result, these 1471 items were removed, leaving 1523 instances of glottal stops preceded by laryngealized vowels out of 2634 instances of glottal stops in all environments, or approximately 58%. Removing the frequent prefix tokens to perform a more conservative analysis did not affect the overall results of the statistical tests in the present chapter. Therefore, the analyses presented below include all of the dictionary data.

Table 3.1: Counts of preceding environments of stop segments in Beck 2011b. 5 /b/ tokens and 1 /d/ token have been excluded. Percentages were calculated by segment (column).

Preceding context	p	t	k	ʔ	Total
v̄	268 (9.47%)	626 (12.61%)	715 (18.82%)	2994 (72.94%)	4603 (29.32%)
v	940 (33.22%)	1240 (24.97%)	1705 (44.88%)	406 (9.89%)	4291 (27.33%)
stops	226 (7.99%)	165 (3.32%)	46 (1.21%)	13 (0.32%)	450 (2.87%)
fricatives	327 (11.55%)	1326 (26.71%)	511 (13.45%)	12 (0.29%)	2176 (13.86%)
other consonants	131 (4.63%)	255 (5.14%)	228 (6%)	287 (6.99%)	901 (5.74%)
#_	938 (33.14%)	1353 (27.25%)	594 (15.64%)	393 (9.57%)	3278 (20.88%)
Total	2830	4965	3799	4105	15699

Table 3.2: Summary of highly frequent prefixes incorporating laryngealized vowels followed by glottal stops. (Note: ALN = alienative, STM = stimulus Beck 2011b.)

Orthography	IPA	Gloss	Count
a'h-	ᵛʔ-	'head'	493
a'ha-	ᵛʔa-	'ear'	714
la'ha-	lᵛʔa-	'face'	264
ma'h-	mᵛʔ-	'ALN'	184
ma'ha-	mᵛʔa-	'hand'/'STM'	112
Total			1471

Table 3.3 summarizes following contexts of stop tokens. Here, both /p/ and /t/ occur before non-laryngealized vowels in more than half of their tokens, with /k/ and /ʔ/ also occurring more often before non-laryngealized vowels than before any other segment. In most cases, the remaining tokens occur mainly before laryngealized vowels,

resulting in the vast majority of stops occurring before vowels, reflecting the preferred CV structure of syllables.

Table 3.3: Counts of following environments of stop segments in Beck (2011b). 5 /b/ tokens and 1 /d/ token have been excluded. Percentages were calculated by column.

Following context	p	t	k	ʔ	Total
v̆	810 (28.62%)	1235 (24.87%)	837 (22.03%)	543 (13.23%)	3425 (21.82%)
v	1931 (68.23%)	3068 (61.79%)	1795 (47.25%)	1876 (45.7%)	8670 (55.23%)
stops	1 (0.04%)	20 (0.4%)	156 (4.11%)	273 (6.65%)	450 (2.87%)
fricatives	51 (1.8%)	25 (0.5%)	546 (14.37%)	686 (16.71%)	1308 (8.33%)
other consonants	8 (0.28%)	130 (2.62%)	334 (8.79%)	489 (11.91%)	961 (6.12%)
_#	29 (1.02%)	487 (9.81%)	131 (3.45%)	238 (5.8%)	885 (5.64%)
Total	2830	4965	3799	4105	15699

Fricatives

Fricative segments occurred 6292 times in the *UNT Dictionary*, about 93% of which were pulmonic. Approximately 30.21% were /s/ tokens, 31.04% were /ʃ/, and 31.8% were /tʃ/. Ejective fricatives make up 6.93% of fricative tokens in the dictionary, with /sʰ/ accounting for nearly half of these (2.97%). The post-alveolar /ʃʰ/ made up 1.95% of fricative tokens, and /tʃʰ/ accounted for the remaining 2%.

Table 3.4 summarizes preceding contexts for each of the 6 fricative categories. Ejective fricatives occur word initially in higher proportions than pulmonic fricatives. This is likely due to the high percentage of ejectives occurring word initially. Except for alveolar segments, ejective fricatives occur after modal vowels with lower frequency

than pulmonic fricatives. Vowels are the most frequent preceding environment overall, though somewhat less frequent for ejective fricatives than pulmonic fricatives. A similar pattern is also apparent for laryngealized vowel contexts, with the exception of the post-alveolar segment. Ejective and pulmonic fricatives occur with similar frequencies after stops, with the exception of /ɬ/, which has a relatively low incidence of stops in its preceding environment. /ɬ/ also differs from other fricatives in occurring after modal vowels at a higher rate than any other fricative. It also has a reduced rate of occurrence word initially and following stops.

Table 3.4: Proportions of preceding environments for fricative segments in Beck (2011b). Percentages are calculated by segment (column).

Preceding Context	s	s'	ʃ	ʃ'	ɬ	ɬ'	Total
ṽ	166 (8.73%)	3 (1.6%)	222 (11.37%)	16 (13.01%)	231 (11.54%)	10 (7.94%)	648 (10.30%)
v	680 (35.77%)	73 (39.04%)	825 (42.24%)	32 (26.02%)	1057 (52.8%)	33 (26.19%)	2700 (42.91%)
stop	442 (23.25%)	43 (22.99%)	409 (20.94%)	30 (24.39%)	348 (17.38%)	36 (28.57%)	1308 (20.79%)
fricative	59 (3.1%)	10 (5.35%)	46 (2.36%)	2 (1.63%)	4 (0.2%)	0	121 (1.92%)
other Cs	75 (3.95%)	1 (0.53%)	87 (4.45%)	1 (0.81%)	92 (4.6%)	1 (0.79%)	257 (4.08%)
#_	479 (25.2%)	57 (30.48%)	364 (18.64%)	42 (34.15%)	270 (13.49%)	46 (36.51%)	1258 (19.99%)
Total	1901	187	1953	123	2002	126	6292

Table 3.5 summarizes following contexts of fricative segments. Because ejective fricatives do not occur at the ends of words or as the first element in consonant clusters, their following environments only include vowels (cf. 1.1.4). Their occurrences are rather evenly distributed across laryngeal categories in vowels, though higher proportions of

all three ejective fricatives (all over 50%) occur before non-laryngealized vowels, which are of course more frequent than laryngealized vowels. In comparison, a relatively small proportion of pulmonic fricatives occurs before vowels (approximately 26-27% across vowel laryngealization categories in all three pulmonic fricatives), due in part to the greater number of possible contexts. A fairly high proportion of pulmonic fricatives occur before stops (/s/ 40.77%, /ʃ/ 41.07%, /ɬ/ 29.92%).

Table 3.5: Proportions of following environments for fricative segments in Beck (2011b).

Following Context	s	s'	ʃ	ʃ'	ɬ	ɬ'	Total
ṽ	207 (10.89%)	85 (45.45%)	204 (10.45%)	55 (44.72%)	229 (11.44%)	53 (42.06%)	833 (13.24%)
v	311 (16.36%)	102 (54.55%)	342 (17.51%)	68 (55.28%)	310 (15.48%)	73 (57.94%)	1206 (19.17%)
stop	775 (40.77%)	0	802 (41.07%)	0	599 (29.92%)	0	2176 (34.58%)
fricative	0	0	5 (0.26%)	0	116 (5.79%)	0	121 (1.92%)
other consonants	442 (23.25%)	0	410 (20.99%)	0	383 (19.13%)	0	1235 (19.63%)
_#	166 (8.73%)	0	190 (9.73%)	0	365 (18.23%)	0	721 (11.46%)
Total	1901	187	1953	123	2002	126	6292

Vowels

28,966 vowel tokens were tallied in the *UNT Dictionary* corpus. Approximately 68% of these vowels were non-laryngealized, and 32% laryngealized. Table 3.6 summarizes the distributions of occurrences of laryngealized and non-laryngealized vowels across preceding contexts. Distributions of both laryngealized and non-laryngealized vowels

Table 3.6: Proportions of preceding environments for vocalic segments in Beck (2011b). Percentages are calculated by column.

Preceding context	v̥	v	Total
v̥	9 (0.1%)	6 (0.03%)	15 (0.5%)
v	210 (2.27%)	53 (0.27%)	263 (0.91%)
oral stop	2882 (31.14%)	6800 (34.50%)	9682 (33.43%)
glottal stop	543 (5.87%)	1876 (9.52%)	2419 (8.35%)
ejective fricative	193 (2.09%)	243 (1.23%)	436 (1.51%)
pulmonic fricative	640 (6.92%)	963 (4.89%)	1603 (5.53%)
other consonant	4197 (45.35%)	9718 (49.3%)	13915 (48.04%)
#_	580 (6.27%)	53 (0.27%)	633 (2.19%)
Total	9254	19712	28966

are fairly similar across context types. Nevertheless, laryngealized vowels tended to occur with somewhat lower frequency in all environments except word initially and immediately following another non-laryngealized vowel.

Table 3.7 summarizes the distributions of occurrences of laryngealized and non-laryngealized vowels across following contexts. Unlike the preceding contexts, the following contexts differ quite drastically from one another. Nearly a third of laryngealized vowels occurred before a glottal stop, compared to only 2% of non-laryngealized vowels. Laryngealized vowels also occurred more frequently in word final position compared to non-laryngealized vowels, although the proportional difference was only

Table 3.7: Proportions of following environments for vocalic segments in Beck (2011b). Percentages are calculated by column.

Following context	$\underset{v}{y}$	v	Total
$\underset{v}{y}$	9 (0.1%)	210 (1.07%)	219 (0.76%)
v	6 (0.06%)	53 (0.27%)	59 (0.20%)
oral stop	1609 (17.38%)	3889 (19.73%)	5498 (18.98%)
glottal stop	2994 (32.36%)	406 (2.06%)	3400 (11.74%)
ejective fricative	29 (0.31%)	138 (0.7%)	167 (0.58%)
pulmonic fricative	619 (6.69%)	2562 (13%)	3181 (10.98%)
other consonant	2085 (22.53%)	9498 (48.18%)	11583 (39.99%)
#	1903 (20.56%)	2956 (15%)	4859 (16.77%)
Total	9254	19712	28966

about 5%. Only 22% of laryngealized vowels occurred before other consonants, far fewer than the 48% of non-laryngealized vowels.

3.3.2 Laryngealization collocates

The previous section provided an overview of segmental distributions with respect to their immediately preceding and following segmental collocates. The current section will investigate the same segmental categories by focusing only on laryngealization values in adjacent segments. Chi-squared tests of independence are used here to determine whether the occurrence of laryngealized segments is significantly related

Table 3.8: Chi-squared residuals of segment and preceding context laryngealization for stops, fricatives, and vowels, as well as all three segment classes together. ‘+’ indicates counts greater than expected, ‘-’ indicates counts smaller than expected. Residuals greater than +/-2 are generally considered to differ significantly from expected values. Compare to B.2.

Preceding Context		Non-laryng	Laryng	χ^2	df	p
Segment Class						
Stops	oral	+21.13	-26.29	3808.9	1	< 0.0001
	glottal	-32.37	+40.29			
Fricatives	pulmonic	+0.02	-0.03	0.03	1	0.87
	ejective	-0.08	+0.13			
Vowels	-laryng	-1.29	+3.89	52.57	1	< 0.0001
	+laryng	+1.88	-5.68			
All	-laryng	+6.23	-12.44	1049.3	1	< 0.0001
	+laryng	-13.10	+26.16			

to the laryngeal contexts in which they appear. Results are reported in terms of the χ^2 value as well as the size of the Pearson residuals of each cell, following (Arppe, 2008). The residuals represent how much the observed counts differed from what would be expected if there were no relationship between cells and were calculated using the *chisq.residuals* function from the *questionr* package (Barnier et al., 2017). Residuals greater than |2| indicate significant contributions to the overall χ^2 value. The raw count data are presented in Appendix B. Yates continuity correction is not used, due to the large number of observations (Yates, 1934). Tests are performed on the entire dictionary corpus, as well as separately on three subsets of the data: stops, fricatives and vowels. Subsequent tests were performed that excluded word boundaries, which were arbitrarily classified as “non-laryngealized”, as well as consonant contexts of stops and fricatives. Removing these contexts resulted in a loss of significance in the chi-squared test of laryngealization between fricatives and following environments.

In preceding contexts, summarized in Table 3.8, stops whose laryngealization matched that of their context occurred with higher frequency than would be expected if there were no relationship between laryngealization of segments and preceding contexts. Stops that opposed their context’s laryngealization were less frequent than expected. Fricative laryngealization was independent of context laryngealization. Vowels matching

Table 3.9: Chi-squared residuals of segment and following context laryngealization for stops, fricatives, and vowels, as well as all three segment classes together. '+' indicates counts greater than expected, '-' indicates counts smaller than expected. Residuals greater than +/-2 are generally considered to differ significantly from expected values. Compare to B.3.

Following Context		Non-laryng	Laryng	χ^2	df	p
Segment class						
Stops	oral	-3.06	+5.67	158.77	1	<0.0001
	glottal	+5.15	-9.53			
Fricatives	pulmonic	+1.88	-4.73	373.94	1	<0.0001
	ejective	-6.89	+17.34			
Vowels	-laryng	+13.92	-35.90	4641.8	1	<0.0001
	+laryng	-20.32	+52.40			
All	-laryng	+6.15	-13.22	1194.3	1	<0.0001
	+laryng	-13.22	+28.41			

the laryngealization of their preceding segment were less frequent than expected, and vowels that did not match were more frequent.

Table 3.9 summarizes the results of the analysis of following contexts. Here, stops that did not match the laryngealization of their following context were more frequent than expected, while stops that did match were less frequent. Fricatives, vowels, and all segments tallied together showed the opposite pattern, with higher rates of segments occurring before contexts that matched their own laryngealization, and lower rates of mismatched laryngealization than expected.

Table 3.10: Chi-squared residuals of segment and following context laryngealization for stops and fricatives after vowels (VC sequences).

Preceding Context		Non-laryng	Laryng	χ^2	df	p
Segment class						
Stops	oral	+23.98	-23.16	2908.3	1	<0.0001
	glottal	-30.49	+29.45			
Fricatives	pulmonic	-0.07	+0.13	0.45	1	0.50
	ejective	+0.29	-0.58			

The above analyses considered laryngealization in adjacent contexts for all segments in the dictionary. However, there are many instances in which stops and fricatives occur in clusters with oral stops, nasals and liquids that may have an effect on the outcome of the chi-squared tests above. In such clusters, the resulting sequence is made up of two non-laryngealized segments. These sequences of matching laryngealization will contribute to the relationship between laryngealization values in the complete dictionary dataset. Additionally, contexts of ejective fricatives are limited in that they do not appear word-finally. In order to further investigate the relationship between laryngealization in consonants and vowels, the data set was limited to only CV or VC sequences where the consonants could be only stops or fricatives. After creating this smaller dataset, chi-squared tests were again performed to test the relationships between laryngealization in adjacent segments.

Table 3.11: Chi-squared residuals of segment and following context laryngealization for stops and fricatives before vowels (CV sequences).

Following Context		Non-laryng	Laryng	χ^2	df	p
Segment class						
Stops	oral	-1.70	+2.71	51.1	1	<0.0001
	glottal	+3.40	-5.41			
Fricatives	pulmonic	+0.48	-0.58	2.67	1	0.10
	ejective	-0.93	+1.11			

Table 3.10 summarizes the results of the analysis of preceding environments for stops and fricatives appearing in VC sequences only. Here, oral stops were more likely to be preceded by non-laryngealized vowels, while glottal stops were more likely to be preceded by laryngealized vowels. In other words, segments were more likely to match in laryngealization values than would be expected in a case of true independence between segments. In the case of fricatives, no relationship was found between the laryngealization of preceding vowels and following fricatives. Table 3.11 summarizes the results of the analysis of following environments of stops and fricatives in CV sequences. Again, laryngealization between adjacent segments was significantly interrelated for stops, but not for fricatives. Unlike the VC analysis, CV

sequences were less likely to show a match between segment laryngealization and context laryngealization.

3.4 Discussion

The above analysis has shown that there is a relationship between laryngealization of segments and their contextual environments. This relationship depends partly on the relative position of the context, and partly on the class of segment being analyzed. Each of these contributing factors are summarized briefly below.

There is an overall tendency for segments to have different laryngealization values than their preceding environments. However, this relationship is not monolithic. Stops, and especially glottal stops, were likely to have the same laryngealization value as their preceding environments, i.e. glottal stops were likely to be preceded by laryngealized vowels. Fricative laryngealization was independent of the preceding environment. Vowels were likely to have different laryngealization categories than their preceding environments, though this effect was small compared to that seen in stops. Subsequent analysis strictly between consonants and preceding vowels showed the same relationships.

The relationship between segments and their following contexts was somewhat different. Here, the overall pattern showed that segments were likely to have different laryngealization values than their following contexts in the initial analyses of the complete data set. When the analyses were broken down by segment type, fricatives and vowels were both revealed to differ from this overall finding, tending to match the laryngealization of their following environments. Stops, however, were likely to have laryngealization values opposite that of their following contexts, in line with the overall finding. Subsequent exclusion of word boundaries from the analysis revealed that fricative laryngealization is independent from laryngealization of following vowels. This change in the effect of following environments is likely due to the relative infrequency of ejective fricatives overall, as well as the choice to code word boundaries as non-laryngealized. When word boundaries were included in the sample, pulmonic fricatives (which are not laryngealized) would have been far more likely to appear

word-finally where ejective fricatives do not occur (cf. 1.1.3), adding to the number of sequences in which laryngealization was the same for both segments. Removing the word boundaries therefore revealed the independence of laryngealization between fricatives and following contexts. Limiting the data in this way confirmed that vowels were likely to match the laryngealization of the segment immediately following, while stops were likely to have the opposite laryngealization value from the segment immediately following. Fricatives did not show any pattern of laryngealization values in relation to their contexts.

By far the most striking finding is the relationship between glottal stops and their preceding vowels. The most likely explanation for this relationship is that the vowels are laryngealized as a result of coarticulation with the following glottal stop. Unlike oral stops, glottal stops lack cues to place, and even abrupt cessation of vocal fold vibration will involve some degree of non-modal phonation as the rate of vibration slows (see 1.3, 2.2.2). Given the nature of glottal stop as a highly variable segment produced at a place decoupled from the articulatory constraints that arise in adjacent oral articulations, some degree of temporal overlap is to be expected. Nevertheless, predictable variations in sound production are generally considered to be allophonic rather than contrastive. Without additional evidence to support the categorization of pre-glottal vowels as laryngealized, the current transcriptions are redundant and likely muddying the waters when it comes to describing the sound system of UNT. The present analysis has established that there is a correlation between laryngealized vowels and following glottal stops. However, the acoustic effects of glottal stops and ejective fricatives on neighboring vowels has yet to be addressed. In the next two chapters, the acoustics of laryngealized and non-laryngealized vowels in laryngeal and oral contexts, as well as ejective fricatives will be analyzed. The goal will be to determine whether categorical representations of laryngealization correlate to acoustic measures.

Further limitations on the conclusions that may be drawn from the present findings arise in part from the nature of the data. Morphological and syllabic structure, word position, and stress placement were not taken into account in the present analysis. Both freestanding lexical forms and affixes listed as separate entries in the dictionary were included in the analysis. The statistical analysis also does not take into account the

sometimes extreme differences in phonotactic patterning between segments belonging to the same manner class. For example, within the set of oral stops, the velar stop /k/ occurs twice as often following laryngealized vowels than does /p/. In fact, /k/ more closely resembles /ʔ/ than either /p/ or /t/, perhaps suggesting that vowel laryngealization may be a secondary cue to the place of stop closure. In that case, again, vowels preceding /k/ would perhaps be better represented in the dictionary as non-laryngealized.

There is the possibility that these findings may be due in part to over- or under-representation of certain sequences as a result of highly frequent meronymic prefixes, as mentioned in 3.3.1. However, removing these sequences from the data set did not alter the overall findings. There is also the possibility that word initial vowels, currently transcribed with laryngealization might more accurately be classified as /ʔv/ resulting in laryngealization on the surface (MacKay & Trechsel, 2013). Such sequences would only serve to strengthen the current finding that stops tend to differ from their following environments in terms of contrastive laryngealization. Prosodic processes that induce laryngealization at the ends of phonological phrases (cf. 1.1.3) may explain the prevalence of laryngealized vowels in word final position. Given the prevalence of word- and phrase- final devoicing or laryngealization, one might expect to find a higher rate of occurrence of laryngealization the closer a segment is to the end of a word. Be that as it may, the basic assumption should be that vowels are phonemically non-laryngealized until they are acted upon by such processes, with dictionary forms representing lexical items unaffected by contextual factors.

Another important aspect of the present findings is the lack of relationship between laryngealization in fricatives and surrounding contexts. If the ejective fricatives were produced with the glottalic airstream, the glottal closure might be expected to begin before frication, potentially inducing some acoustic laryngealization on the preceding vowel in the same way that glottal stops do. No such contextual laryngealization is apparent in the dictionary forms. One possible explanation for the lack of pre-ejective laryngealization is that glottal closure does not begin until after frication onset, long after the vocal folds have stopped vibrating. If so, this would be evidence in favor of interpreting the ejective fricatives as clusters rather than complex glottalic segments.

With respect to following contexts, the cluster analysis is equally as consistent with the data as the ejective analysis. Whether they are clusters or ejectives, their behavior before vowels ought to resemble that of glottal stops. In fact this is the case, as neither glottal stops nor ejective fricatives were related to the laryngealization of their following contexts.

Chapter 4

Phonetics of laryngealized vowels in context

Chapter 3 established that glottal stops are preceded by laryngealized vowels far more frequently than would be expected if such segments were independent of each other. If some laryngealization occurs as the result of proximity to a following glottal stop, then it stands to reason that vowels occurring in that environment will have stronger acoustic cues to laryngealization than vowels occurring elsewhere. The present chapter describes phonetic characteristics of laryngealized and non-laryngealized vowels in the context of laryngealized and non-laryngealized consonants, as they are defined in Chapter 3. A spectral measure of laryngealization was extracted from vowels: the difference in amplitude between the first and second harmonics (H1-H2). Neither measure was found to be strongly affected by the laryngeal category of vowels themselves, however H1-H2 did show strong effects of the laryngeal category of the following consonant.

4.1 Background and hypotheses

A summary of acoustic cues to laryngealization in various languages is presented in section 1.3. Previous descriptions of laryngealization in UNT have not specified particular acoustic or articulatory characteristics that might serve to differentiate laryngealized from non-laryngealized segments. One study of laryngealization in Misantra Totonac, a language related to UNT, measured the F1-F2 vowel space and the difference in amplitude between F0 and F1, a measure similar to H1-H2 (Trechsel & Faber, 1992). The speech of two speakers was analyzed and revealed a high degree of interspeaker

variability in the F1-F2 space, with each speaker using different strategies to maintain the phonation contrast. The difference in amplitude between F0 and F1 was more consistent, with both speakers producing lower values for laryngealized vowels than for non-laryngealized vowels.

In the present investigation, the H1-H2 measure was chosen for its widespread usage and cross-linguistic reliability in distinguishing between phonation types, as well as the ease of comparison that using a well-established measure entails. In some studies, the difference in amplitude between the first two harmonics is adjusted for the value of the first formant and reported as H1*-H2* (Garellek, 2010; Iseli & Alwan, 2004; Hanson et al., 2001). However, the benefit of adjusting for F1 in this way is unclear and may also be compensated for by matching vowel quality to measured items (Keating & Esposito, 2007). In linear mixed effects regression modeling, random effects structure can be specified to control for the effects of factors such as vowel quality. In the present study, vowel quality was included as a random effect in the statistical models, providing a statistical control for the influence of F1.

Based on findings in Chapter 3 and the previous literature on acoustic correlates of linguistic voice quality, two hypotheses will be tested. First, if vowel laryngealization is contrastive, then phonemically laryngealized and non-laryngealized vowels ought to show significantly different values for H1-H2. Specifically, laryngealized vowels are expected to have lower H1-H2 values than non-laryngealized vowels. Second, if vowel laryngealization is related to consonant context, then laryngealization of the immediately adjacent consonants ought also to affect H1-H2 values, with vowels in laryngeal contexts having lower H1-H2 than vowels in non-laryngeal contexts.

4.2 Methods

The present analysis was performed on audio recordings collected in the field and annotated as described in Chapter 2. The spectral measure of laryngealization H1-H2 was extracted from phonemically laryngealized and non-laryngealized vowels adjacent to stops and fricatives, which were classified as laryngealized or non-laryngealized as in Chapter 3 (i.e. glottal stops and ejective fricatives were classified as laryngealized,

and oral stops and pulmonic fricatives as non-laryngealized). Measures were taken at three time points within the vowel, at one third of vowel duration, one half of vowel duration, and two thirds of vowel duration. In the statistical analyses that follow, the middle time point (at one half of the vowel duration) was omitted for simplicity and brevity. In order to assess whether the consonant context might have an effect on the phonation measures reported here, the data were subdivided into two conditions, one taking into account the consonant preceding the vowel (CV), and the second taking into account the consonant following the vowel (VC). In the CV analysis, any effect of the consonant would be expected to be apparent at the first measured time point, while in the VC analysis, the consonant effect would be expected to appear at the last measured time point.

H1-H2 measures were extracted from vowel tokens using a Praat script designed to imitate the measures taken by the VoiceSauce software developed at UCLA (Vicenik, 2009; Shue et al., 2011). Instead of correcting the H1 and H2 measures for F1, vowel quality was included in the linear models as a random intercept, allowing for the model to adjust the estimate for each vowel category. Since vowel quality is largely determined by the first formant (Peterson, 1961; Traunmüller, 1981), including vowel quality in the random structure of the model in this way can be seen as a means of approximating H1*-H2* measures reported in other voice quality literature.

4.3 Results

This section reports data summaries, as well as the results of linear mixed effects regression (lmer) models. Linear mixed modeling was chosen because of its flexibility in analyzing unbalanced data sets, and the possibility of controlling for interdependence between datapoints that have been collected from the same speaker (also known as a repeated measures design). Figure 4.1 illustrates H1-H2 values for all vowels across laryngealization categories of surrounding consonants and three relative time points (at one third, one half, and two thirds of vowel duration). Despite the noisy data indicated by the large error bars, an apparent pattern is visible: laryngealized vowels tend to have lower H1-H2 values than non-laryngealized vowels in all consonant

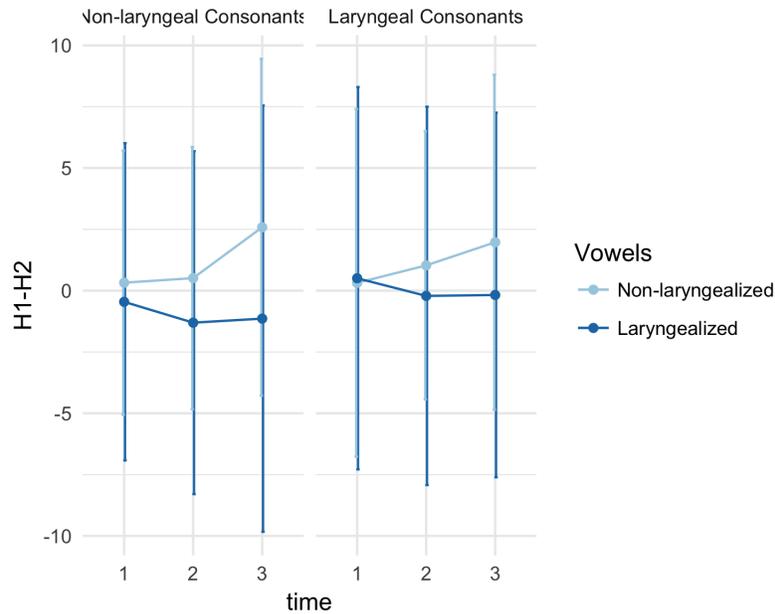


Figure 4.1: $H1-H2$ values at three time points. The vowels are identified according to their laryngeal category as well as that of their consonant context. Both preceding (CV) and following (VC) contexts are included here.

laryngealization contexts. Over the time course of the vowel, $H1-H2$ values increase for non-laryngealized vowels, and decrease for laryngealized vowels, indicating that laryngealized vowels have stronger acoustic markers of non-modal phonation later in their production. The difference in $H1-H2$ values between vowel laryngealization categories is smaller in the context of laryngealized consonants, visible on the right of Figure 4.1. In the analyses that follow, the data were subsetted according to preceding (CV) and following (VC) consonant contexts. In the CV condition ($n = 2626$), vowels were included on the basis of being preceded by any consonant; in the VC condition ($n = 1899$), the data set was made up of vowels that were followed by any consonant. Vowels that were both preceded and followed by consonants were included in both analyses. In the CV condition, the early time point was expected to show greater influence from the consonant, while in the VC condition consonant effects would be expected to appear at the later time point.

The models were fitted using the *lme4* package in R through stepwise model comparisons (Gries, 2013, 2015). The *lmerTest* package (Kuznetsova et al., 2017) was used to calculate p-values based on Satterthwaite's approximation of degrees of freedom.

Post-hoc comparisons were performed using the `lsmeans` package (Lenth, 2016). Model fitting for each analysis began with a maximal fixed effect structure, followed by building up the random structure. After the maximal random structure was attained, the fixed effect structure was backward fitted, removing non-significant interactions and main effects again in a stepwise manner, with ANOVA comparisons between each model step (Baayen et al., 2008; Matuschek et al., 2017). The maximal fixed effects structure included a four-way interaction among vowel laryngealization (**no**, yes), consonant laryngealization (**no**, yes), consonant manner (**fricative**, stop), and time point (**one third**, two thirds), reference levels indicated in bold. Main effects of vowel length category (**short**, long) and stress (**stressed**, unstressed) were also included as control variables. The initial models specified random intercepts for Word and Speaker. Random intercepts for vowel quality were then added to the models, significantly improving model fit in most cases. Random slopes by speaker were added to the models in the following order: Vowel Laryngealization, followed by Consonant Laryngealization, Stress, and Consonant Manner, if possible. In most cases, convergence issues kept the addition of random slopes to a minimum. The details of the random and fixed effects are presented for each model below. In order to reduce undue influence from outliers, data points with residuals outside ± 2.5 standard deviations from the regression line were removed and the models refit to the trimmed data set, following Baayen et al. (2008).

The H1-H2 analysis was subdivided into CV and VC analyses. In both analyses, the initial model including time point as a predictor resulted in complex models with significant three-way interactions between time point, consonant laryngealization, and vowel laryngealization; time point, consonant laryngealization and consonant manner; and time point, vowel laryngealization and consonant manner.¹ In order to further investigate these effects, the models were subsequently divided into separate analyses of the the first and third time points in each of the CV and VC conditions, resulting in four models total. The original models with three-way interactions can be found in Appendix C.

¹In the VC condition, all four of these factors interacted significantly.

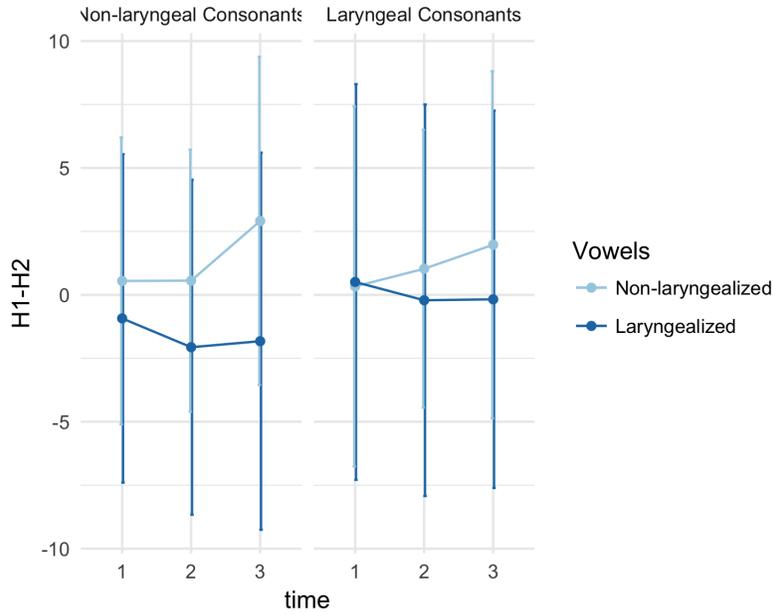


Figure 4.2: H1-H2 values at three time points during vowel production after consonants (CV condition).

Table 4.1: Summary of trimmed model of H1-H2 values for vowels following consonants (CV condition) at Time 1.

coef	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	-1.8324	1.9933	5.4235	-0.9193	0.3970
stressunstressed	0.6894	0.3701	3.2312	1.8628	0.1528
vlaryngyes	-0.2832	0.1752	751.6187	-1.6163	0.1065
claryngyes	2.1843	0.5226	3.5866	4.1796	0.0174 *

4.3.1 CV condition

Figure 4.2 shows H1-H2 values for vowels preceded by consonants (CV condition). The values are shown at all three time points and divided by laryngealization of the preceding consonant. The following analysis further subdivides the data into two time points, at one-third (Time 1) and two-thirds (Time 3) of vowel duration.

At Time 1 (see Table 4.1), the best linear mixed effects regression model of H1-H2 included random intercepts for Speaker, Word, and Vowel Quality, and random slopes for Consonant Laryngealization, and Stress by Speaker. Trimming removed 72 datapoints, or 2.74% of the total data set. The final model included only main effects with no interactions and revealed a significant main effect of consonant laryngealization. Main effects of stress and vowel laryngealization were not found to be significant. The

Table 4.2: Summary of trimmed model of H1-H2 values for vowels following consonants (CV condition) at Time 3.

coef	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	1.8847	2.0828	4.8027	0.9049	0.4086
vlaryngyes	-2.7319	0.6340	4.4226	-4.3087	0.0101 *
claryngyes	-0.6465	0.5970	24.8061	-1.0829	0.2893
cmannerstop	-0.1008	0.4115	2202.8833	-0.2450	0.8065
stressunstressed	-1.0412	0.6656	3.2234	-1.5643	0.2095
vlaryngyes:claryngyes	0.9758	0.4794	2149.9218	2.0356	0.0419 *
claryngyes:cmannerstop	3.3446	0.5464	2242.7276	6.1213	0.0000 ***

results of the model indicated that vowels following laryngealized consonants (i.e. glottal stops and ejective fricatives) have higher H1-H2 values than vowels following non-laryngealized consonants (oral stops and non-ejective fricatives) overall.

At Time 3 (see Table 4.2), the best linear mixed effects regression model of H1-H2 included random intercepts for Speaker, Word, and Vowel Quality, and random slopes for Vowel Laryngealization, Consonant Laryngealization and Stress by Speaker. The final model included main effects of Vowel Laryngealization, Consonant Laryngealization, Consonant Manner, and Stress, with interactions between Vowel Laryngealization and Consonant Laryngealization, and Consonant Laryngealization and Consonant Manner. Model trimming removed 83 data points, or 3.16% of the total data set. Because of the significant interaction between vowel laryngealization and consonant laryngealization, the main effect of vowel laryngealization was recalculated using the *lsmeans* package in R. The resulting main effect was found to be marginally significant ($df = 3.63$, $t = 3.72$, $p < 0.05$), with laryngealized vowels having H1-H2 values about 2 dB lower than those of non-laryngealized vowels. This effect is in line with expectations of non-modal vowel phonation established by previous literature.

The interaction between consonant laryngealization and vowel laryngealization at Time 3 is illustrated in Figure 4.3. The main effect of vowel laryngealization is visible in the overall tendency for laryngealized vowels to have lower H1-H2 values than non-laryngealized vowels. However, this effect was only significant when the preceding environment was not laryngealized. Pairwise comparison revealed that laryngealized vowels had significantly lower H1-H2 values than non-laryngealized vowels after non-

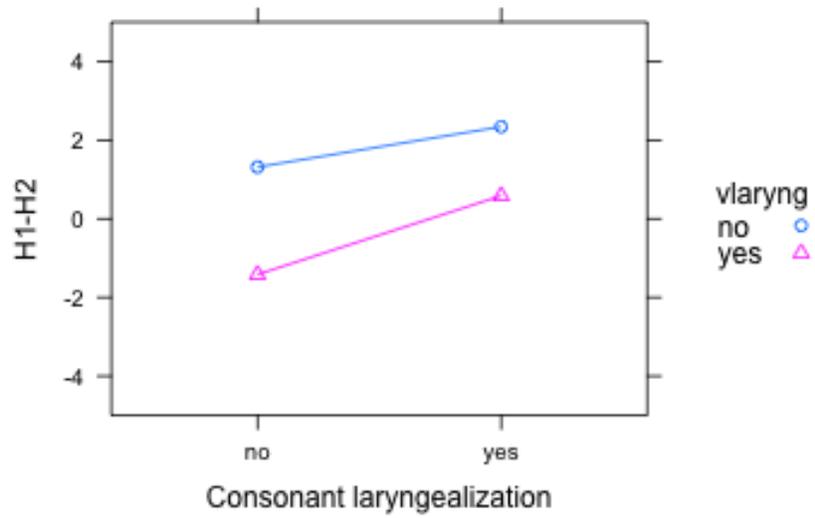


Figure 4.3: Illustration of consonant and vowel laryngealization effects in the CV condition at Time 3.

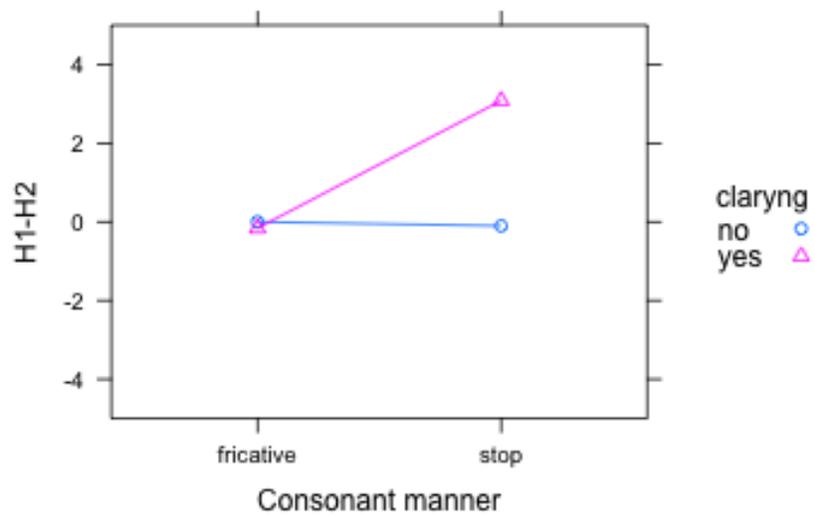


Figure 4.4: Illustration of interaction between consonant laryngealization and consonant manner effects at Time 3 in the CV condition.

laryngealized consonants, (est = 2.7318745, SE = 0.6340364, df = 4.42, t = 4.31, p < 0.05), but there was no significant difference between vowel laryngealization categories after laryngealized consonants. In other words, after glottal stops and ejective fricatives, there was no difference in H1-H2 between vowel laryngealization categories. Within the vowel laryngealization categories, consonant laryngealization had a significant effect for laryngealized vowels, but not for non-laryngealized vowels. That is, laryngealized vowels had significantly higher H1-H2 values after laryngealized consonants than non-laryngealized consonants (est = -2.0016506, SE = 0.5382438, df = 16.49, t = -3.72, p < 0.01). Non-laryngealized vowels, on the other hand, did not differ significantly based on consonant environment, despite appearing to show the same general pattern of increased H1-H2.

Figure 4.4 illustrates the significant interaction between consonant manner and consonant laryngealization. H1-H2 values differed significantly between oral and glottal stop environments (est = -3.19, SE = 0.4920047, df = 11.51, t = -6.48, p < 0.0005), but not between ejective and pulmonic fricatives. After glottal stops, vowels had H1-H2 values approximately 3 dB higher than vowels after any other consonant types. This effect is also visible in the raw data presented in Figure 4.3, above.

4.3.2 VC condition

Figure 4.5 illustrates H1-H2 values for vowels that were followed by consonants (VC condition). Here, vowels in non-laryngealized environments are highly similar to each other regardless of vowel laryngealization category. Both laryngealized and non-laryngealized vowels show H1-H2 values near 0 dB. On the other hand, vowels after laryngealized consonants show greater divergence between vowel laryngealization categories than vowels after non-laryngealized consonants. This difference between the vowel categories increases at later measured time points.

At Time 1, the best model of H1-H2 included random intercepts for Speaker, Word, and Vowel Quality, as well as a random slope by Speaker for Consonant Laryngealization. Main effects of Vowel Laryngealization, Consonant Laryngealization, Consonant Manner, and Stress were also included, as well as an interaction between Consonant Manner and Consonant Laryngealization. Through model criticism, 52 data points, or

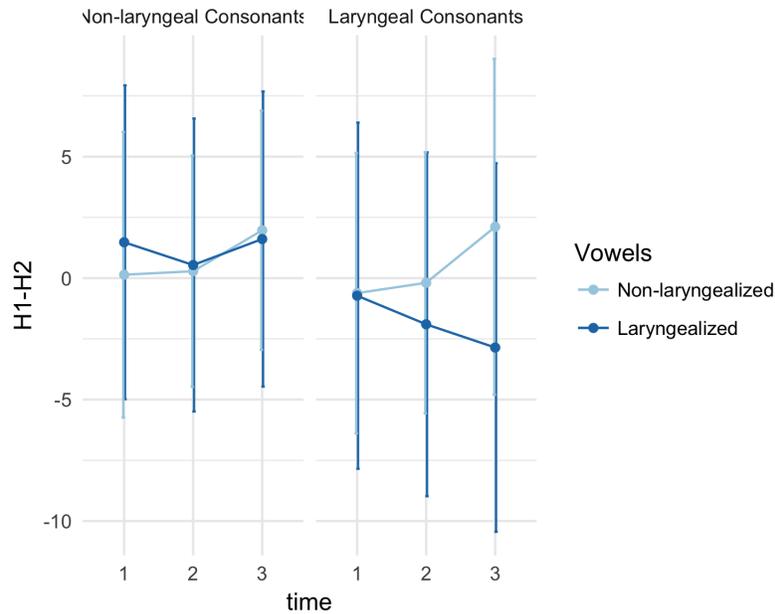


Figure 4.5: H1-H2 values at three time points during vowel production before consonants (VC condition).

2.74%, were trimmed from the model. The output of the trimmed model is presented in Table 4.3. The model showed a significant main effect of Vowel Laryngealization, with a H1-H2 value about 1.3 dB higher on average for laryngealized vowels, an unexpected result given previous findings that non-modal phonation in vowels tends to result in lower H1-H2 values. The main effect of Stress was also highly significant, with higher H1-H2 values for stressed vowels than unstressed vowels. The interaction between Consonant Laryngealization and Consonant Manner, illustrated in Figure 4.6, was also significant. Pairwise comparison revealed significantly lower values before glottal stops than before ejective fricatives (est = 1.47, SE = 0.3497500, df = 1054.15, $t = 4.208$, $p < 0.0005$). Significantly lower values were also found before glottal stops than before oral stops (est = 1.9536577, SE = 0.5089788, df = 5.27, $t = 3.838$, $p < 0.05$). No difference was found between ejective and non-ejective fricative contexts.

At Time 3 of the VC condition, the best model of H1-H2 values included random intercepts for Speaker, Word, and Vowel Quality, and random slopes for Consonant and Vowel Laryngealization by Speaker. The fixed effects structure included main effects of Consonant and Vowel Laryngealization and Consonant Manner, as well as

Table 4.3: Summary of trimmed model of H1-H2 values for vowels preceding consonants (VC condition), time = 1.

coef	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	-1.6213	2.0472	3.9583	-0.7919	0.4731	
vlaryngyes	1.3244	0.2492	934.2322	5.3136	0.0000	***
claryngyes	-0.3328	0.5469	7.0195	-0.6085	0.5620	
cmannerstop	0.1490	0.3009	780.2835	0.4952	0.6206	
stressunstressed	1.0877	0.2504	762.7265	4.3435	0.0000	***
claryngyes:cmannerstop	-1.6209	0.4516	835.8450	-3.5894	0.0004	***

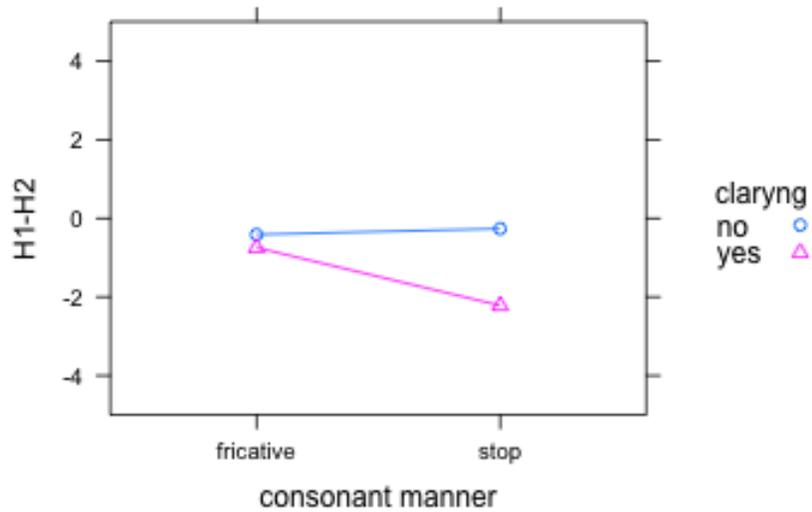


Figure 4.6: Illustration of interaction between consonant manner and consonant laryngealization for VC condition at Time 1.

Table 4.4: Summary of trimmed model of H1-H2 values for vowels preceding consonants (VC condition), time = 3.

coef	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	1.4989	1.7825	4.6260	0.8409	0.4417
claryngyes	1.3198	0.6328	5.4242	2.0856	0.0870
cmannerstop	-1.9756	0.2943	921.7264	-6.7125	0.0000 ***
vlaryngyes	-0.1001	0.7282	3.3200	-0.1375	0.8985
claryngyes:cmannerstop	-4.9326	0.4468	945.9837	-11.0395	0.0000 ***

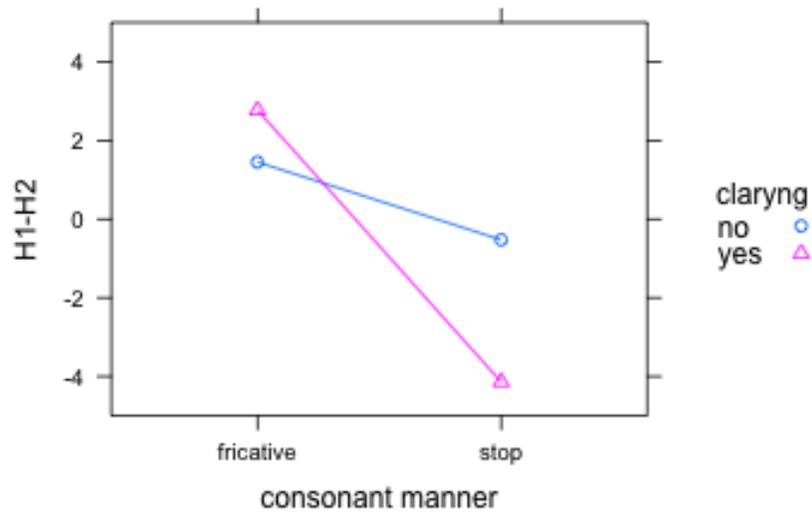


Figure 4.7: Illustration of interaction between consonant manner and consonant laryngealization for VC condition at Time 3.

an interaction between Consonant Manner and Consonant Laryngealization. Model trimming removed 56 data points, or 2.95% of the data.

The model summary output is provided in Table 4.4. The main effect of Consonant Manner was significant, with stop contexts being associated with lower H1-H2 values than fricative contexts (est = -1.571507, SE = 0.2471497, df = 2404.65, t = -6.359, p < 0.0001). A highly significant interaction effect between Consonant Manner and Consonant Laryngealization, illustrated in Figure 4.7 was also found. Pairwise comparison showed that vowels before glottal stops had significantly lower H1-H2 values than vowels before oral stops (est = 3.612859, SE = 0.6042696, df = 4.51, t = 5.979, p < 0.01). Consonant laryngealization of fricatives did not have an effect on preceding vowels.

Table 4.5: Summary of H1-H2 analysis fixed effects. Direction of the effect is indicated by + for increased H1-H2 or - for decreased H1-H2. Stars indicate significance levels.

	CV		VC	
	T1	T3	T1	T3
Vowel laryngealization		* (-)	*** (+)	
Consonant laryngealization	* (+)			
Consonant manner				*** (-)
Stress			*** (+)	
Consonant laryngealization * Consonant manner		***	***	***
Vowel laryngealization * Consonant laryngealization		*		

4.3.3 Summary

Table 4.5 summarizes the statistically significant findings of the H1-H2 analysis presented above.

In the CV condition at Time 1, laryngealized consonants predicted higher H1-H2 values than non-laryngealized consonants. At Time 3, the same effect of consonant laryngealization appeared, but only within laryngealized vowels. Further analysis revealed that this effect was due entirely to the presence of a glottal stop in the preceding environment; ejective fricatives did not have the same effect on vowels that followed them. Also at Time 3, laryngealized vowels had lower H1-H2 values than non-laryngealized vowels, but this effect was restricted to non-laryngeal consonant environments.

In the VC condition at Time 1, the model showed main effects of vowel laryngealization and stress. Laryngealized vowels had higher H1-H2 values than non-laryngealized vowels, and stressed vowels had higher H1-H2 than unstressed vowels. This effect is contrary to findings from other languages that non-modal phonation results in lower H1-H2 values. An interaction effect between consonant manner and laryngealization revealed that vowels before glottal stops had lower H1-H2 values than in any other context. At time 3, the same interaction between consonant manner and consonant laryngealization showed that vowels before glottal stops again had lower H1-H2 values. This effect was even stronger at Time 3 than at Time 1, suggesting that closer proximity to the glottal stop resulted in less modal phonation.

4.4 Discussion

The above analysis has revealed some patterns in acoustic characteristics of laryngealized and non-laryngealized vowels in UNT with respect to their immediately preceding and following consonant environments. This section summarizes the findings and relates them to the hypotheses stated at the beginning of the chapter. The analysis proceeded thus: A spectral measure indicating the difference in amplitude between the first and second harmonics of the spectrum (H1-H2) was extracted from vowel tokens at two time points during the course of vowel production, the first at one-third of vowel duration, and the second at two-thirds of vowel duration. The analyses were divided into two conditions, one where vowels followed consonants (CV), and the other where vowels preceded consonants (VC). Model predictors were all binary factors encoding information about segmental categories.

The first hypothesis was that categorical vowel laryngealization would be cued by a lower H1-H2 in laryngealized vowels and a higher H1-H2 in non-laryngealized vowels. The present analyses show that vowel laryngealization categories in UNT are not reliably related to this measure. Vowel laryngealization was found to have a significant main effect on acoustic measures in only a few cases: at Time 3 in the CV condition and Time 1 in the VC condition (see Table 4.5). At CV Time 3, vowel laryngealization had the effect of lowering H1-H2 values for laryngealized vowels, in line with findings in other languages. However, laryngealized vowels at VC Time 1 had higher H1-H2 values than non-laryngealized vowels, contrary to expectations and previous research.

The second hypothesis was that consonant laryngealization might have an effect on H1-H2 in vowels, with laryngealized consonants (i.e. glottal stops and ejective fricatives) expected to be related to lower H1-H2. This hypothesis was partially supported by the present analyses. Consonant laryngealization did in fact have a significant effect on H1-H2 values, particularly when the consonant was a glottal stop, but the direction of this effect varied. In the CV condition, vowels preceded by a glottal stop had significantly higher H1-H2 values, while in the VC condition, vowels followed by a glottal stop had lower H1-H2 values. These findings were largely independent of the laryngeal category

of the vowels themselves (cf. Tables 4.2 and 4.5), with the exception of the CV analysis at Time 3 where laryngealized vowels after laryngealized consonants had significantly higher H1-H2 values than laryngealized vowels after non-laryngealized consonants (Figure 4.3); no effect was found within non-laryngealized vowels.

In general, the laryngeal category of the consonant was a stronger predictor of acoustically non-modal phonation than that of the vowel. Vowels before glottal stops showed lower H1-H2 values, regardless of whether the vowel was coded as laryngealized. Vowels *following* glottal stops, on the other hand, were produced with *higher* H1-H2 values. These findings align well with the results in Chapter 3, which showed higher than expected counts of laryngealized vowels occurring before glottal stops and non-laryngealized vowels following glottal stops. In a further parallel with Chapter 3, no effect was found for laryngealization in fricatives; all of the consonant effects were due to the presence of glottal stops.

While the present findings do not definitively preclude categorical laryngealization in the vowels of UNT, they do demonstrate the strong influence of consonant context on H1-H2, a measure likely to cue the phonation contrast. The effect of the consonant environment was limited exclusively to vowels adjacent to glottal stops. No effect was found relating fricative laryngealization to H1-H2.

Chapter 5

Acoustic duration of ejective and pulmonic fricatives

This chapter provides an acoustic analysis of the contrast between ejective and pulmonic fricatives in UNT. Recordings of both classes of fricatives were collected in word initial and intervocalic contexts, preceding stressed and unstressed vowels, and preceding laryngealized and non-laryngealized vowels. In addition, pulmonic fricatives were collected in contexts where they preceded the oral stop consonants /p, t, k/ to allow for comparison between ejectives and fricatives in clusters. Duration data are analyzed from three intervals of consonant production: total duration from frication onset to vowel onset, duration of frication only, and duration of post-frication lag, where present. Statistical comparisons of duration reveal similarities between frication in ejective and pulmonic fricatives, and a durational pattern in post-frication closure relating to place of articulation following a cross-linguistic pattern of decreasing duration at places of articulation further back in the vocal tract. These findings suggest ejective fricatives may be phonetic clusters rather than true ejectives.

5.1 Background

Ejective consonants are produced by egressive airflow generated by raising the larynx to compress the air that is trapped in the supralaryngeal cavity. In stops, the necessary compression is achieved via simultaneous closures formed at the glottis and a second oral place of articulation. While these closures are maintained, the larynx moves upward, increasing air pressure in the newly sealed chamber. After compression, the oral closure

is released, followed by release of the glottal closure. In the case of ejective fricatives, however, glottalic production is complicated by the need for sustained outward airflow in order to produce frication. Since the reservoir of available air trapped in the vocal tract is quite small, ejective fricatives are therefore expected to have a relatively short period of frication compared to pulmonic fricatives (Maddieson et al., 2001; Demolin, 2015; Gordon & Applebaum, 2006). Ejective fricatives have also been found to be preceded by silent intervals, either as a result of oral or glottal closure (Gordon & Applebaum, 2006; Demolin, 2002; Ridouane et al., 2015; Shosted & Rose, 2011). For further background on ejective fricatives, see Section 1.2.

Although expected to be short relative to pulmonic fricatives, the ejective fricatives of Tlingit, a Na-Dene language spoken in southern Alaska and western Canada, were found to have surprisingly long durations (Maddieson et al., 2001) when taking into account both frication and closure durations. Despite hypotheses that ejective fricatives ought to be shorter than pulmonic fricatives, the duration from onset of frication to onset of the following vowel was found to be quite similar across both airstream mechanisms: pulmonic fricatives had a mean duration of 223 ms, and ejective fricatives a mean duration of 194 ms. However, closer inspection of the acoustic data revealed that the frication portion of ejective fricatives was 74 ms shorter on average (148 ms) than that of pulmonic fricatives (222 ms). Whereas the total duration from onset of frication to onset of the following vowel was nearly identical to the frication duration for pulmonic fricatives, frication in ejective fricatives tended to be followed by a substantial period of (near) silence before the onset of vowel phonation. In word final position, this silence occurred before the onset of frication rather than after frication ended, an indication that glottal closure occurred before frication onset. Because glottal release was also evident after frication noise ceased, the authors concluded that glottal closure was maintained throughout fricative production.

In addition to duration data, Maddieson et al. (2001) collected intra-oral air pressure data for ejective and pulmonic fricatives at two places of articulation (*s*, *s'*, *ʃ*, *ʃ'*). Inspection of spectrograms and waveforms in relation to the air pressure data revealed very different pressure curves for ejective and pulmonic fricatives. In ejective fricatives, the peak in air pressure occurred later with respect to onset of frication, and lasted

Table 5.1: Summary of findings from Maddieson et al. (2001). Values represent average values across all places of articulation, rounded to the nearest millisecond. Peak air pressure data was reported for *s*, *s'*, *ʔ*, *ɬ* only. Data have been adapted to maximize comparability with Beck (2006) (see Table 5.2).

	Frication Duration (ms)	Peak Intra-Oral Pressure (cm H2O)	Post-frication Lag (ms)
Ejective	148	(later, shorter, parabolic peak)	46
ʔ'		13	
s'		16	
Pulmonic	222	(earlier, longer, flat peak)	1
ɬ		5	
s		8	

only briefly, ending at roughly the same time as frication (prior to the post-frication silence, where present). Peak air pressure in pulmonic fricatives, on the other hand, occurred nearly simultaneously with the onset of frication, and was maintained for longer, corresponding to the longer frication duration. These findings are summarized in Table 5.1. The air pressure and acoustic duration data of fricatives classified as ejective in Tlingit were ultimately determined to be consistent with expected properties of fricatives produced with the glottalic airstream.

While the overall durations of ejective fricatives in Tlingit were longer than initially expected, their ejective nature is uncontroversial. The large consonant inventory of Tlingit makes extensive use of the glottalic airstream across many places of articulation and includes six ejective fricatives and three ejective affricates. In contrast, ejective fricatives in UNT would entail a sound system like no other. Unlike Tlingit, UNT has no glottalic stops, suggesting that speakers somehow came to use a complex production mechanism to produce a rare sound type without also using it in simpler and more common ways.

Comparative reconstruction shows that the ejective fricatives originated from fricative + uvular stop clusters in Proto-Totonacan, which became fricative glottal stop clusters in Upper Necaxa as *q became ʔ in this language (Beck, 2006). After this shift, glottal closure began to overlap in time with preceding frication. In order to result in

synchronic ejective fricatives, glottal closure would need to occur early enough that the frication was generated by the glottalic airstream. The timing of glottal closure in relation to frication production has not been demonstrated. Other potential sources of evidence to distinguish the ejective fricatives from fricative + stop clusters, such as phonotactics, are of little help due to identical behavior. The only posited difference between ejective fricatives and fricative + glottal stop clusters is that clusters may appear as two elements split into coda and onset of adjacent syllables, while ejective fricatives may only occur as a complex unit in syllable onset (cf. Section 1.1.4).

Using the findings in Maddieson et al. (2001) as benchmarks and following their methodology, Beck (2006) supported his historical account of ejective fricatives with a small study of aerodynamic and acoustic data elicited from two adult male speakers. The speakers produced seven repetitions of 10 words illustrating ejective fricatives at all three places of articulation. An additional 5 words containing /ʃʔ/ clusters that were the result of prefixation of the third person possessive prefix *ix-* /iʃ/ ‘his/her’ to stems beginning with /ʔ/ were also recorded (this being the only environment where fricative + glottal stop clusters are said to occur, cf. Section 1.1.4). Apart from the cluster items, no deliberate attempt was made to collect items containing pulmonic fricatives, although a single token of /ʃ/ followed by a laryngealized vowel was described as a basis of comparison. Beck (2006) describes the auditory impression of ejective fricatives as “sounding ‘sharper’ than ordinary fricatives” (p. 6) and reports visible glottal raising during the production of ejective fricatives. However, he also notes that instrumental means of distinguishing ejective and pulmonic fricatives in UNT were less reliable than impressionistic classifications.

The statistical analysis in Beck (2006) included only data from post-alveolar fricatives. Intra-oral pressure and airflow data were collected from a small sample produced by a single speaker and consisting of multiple repetitions of three lexical items: *mix'á:m* /mi.ʃ^ʔa:m/ ‘your cornhusks’ (intervocalic ejective fricative, *N* = 7), *ixhawá'cha'* /iʃ.ʔa.'wa.tʃa/ ‘his/her son’ (pulmonic fricative in fricative + glottal stop cluster, *N* = 6), and *ixa'hax'ólh* /i.ʃ^ʔa.ʔa.'ʃ^ʔoʔ/ ‘his/her ear’ (intervocalic pulmonic fricative, *N* = 6). Only the first post-alveolar fricative in each word (in bold, above) was included in the analysis. Statistical analysis showed significant differences between ejective fricatives

Table 5.2: Summary of findings from Beck (2006). Measures were reported for post-alveolar /ʃ/ tokens only. Values represent averages rounded to whole numbers. Significant findings are marked with * in the column heading. Time to peak intra-oral pressure was originally reported as the difference between time to peak airflow and time to peak intra-oral pressure but has been converted here for ease of comparison with other measures.

	Frication Duration (ms)*	Time to Peak Airflow (ms)*	Time to Peak Intra-Oral Pressure (ms)*	Peak Intra-Oral Pressure (cm H20)	Post- frication Lag (ms)*
Ejective	143	25	20	8	9
Pulmonic (Pre- vocalic)	96	21	34	7	3
Pulmonic (ʃʔ Cluster)	101	27	33	9	–

on the one hand and both conditions of pulmonic fricatives on the other hand for all three measures: compared to pulmonic fricatives before vowels and in clusters, ejective segments were found to have a shorter time to peak intra-oral air pressure, a later relative time to peak airflow, and a longer overall duration. The duration of “hiatus”, or lag time between the end of frication and the onset of the following vowel, was found to be longer in ejective fricatives than in pulmonic fricatives. Airflow and peak air pressure data were also collected, but no significant differences were found between ejective and pulmonic fricatives with respect to either measure.

The findings in Beck (2006), summarized in Table 5.2, are surprising for a few reasons. First, the average duration of pulmonic fricatives is remarkably short, at only half the duration of pulmonic fricatives in Tlingit. Second, ejective fricatives are longer than pulmonic fricatives by more than 50%. Given the limited air storage capacity in the glottalic airstream mechanism, there is no simple explanation as to how this increased duration could be produced by speakers. Third, the post-frication lag durations for ejective fricatives are surprisingly small, especially in comparison again to the lags found by Maddieson et al. (2001) in Tlingit (46 ms). These lags are important because the combination of frication + lag duration resulted in approximately equal durations

(~200 ms) from onset of frication to onset of vowel for ejectives and pulmonic fricatives in Tlingit, as well as being an indication of glottal closure during frication. In addition, the reported maxima of airflow and air pressure were more similar to the measurements of pulmonic fricatives reported in Maddieson (2001) than to those of ejective fricatives in the same study.

5.2 Hypotheses

The data from Tlingit confirmed that fricatives of surprisingly long duration can be produced by the glottalic airstream. However, segmental duration was partly determined by periods of silence preceding and following frication. Removing these silences resulted in significantly shorter durations of frication intervals in pulmonic and ejective productions. Beck (2006) found the opposite, with longer frication in ejective fricatives than in pulmonic fricatives. Including following silences into the segmental duration exaggerates this difference rather than minimizing it. Given these unexpected findings, the present chapter presents analyses of frication and lag duration in UNT with a data set consisting of an extensive word list collected from multiple speakers. The word list includes fricative items from all three places of articulation and both laryngeal categories in multiple contexts. The materials and analyses have been designed to investigate the following six hypotheses based on previous findings in both Maddieson et al. (2001) and Beck (2006). These hypotheses address the overarching question of whether the ejective fricatives in UNT are phonetically ejective, or whether they are better described as phonetic clusters.

Frication duration Ejective fricatives will have shorter frication intervals than pulmonic fricatives (due to the limited supply of air available via the glottalic airstream production mechanism). This was the finding reported in Maddieson et al. (2001), even though the duration of frication was substantially longer than was predicted to be possible based on the presumed amount of available air trapped above the glottis during production of an ejective fricative. Beck (2006) found the opposite to be true: ejective fricatives had substantially longer frication intervals than pulmonic fricatives. Conversely, similar frication durations have been used to argue that “ejective” fricatives

were in fact sequences of frication followed by glottal stops in Yapese (Maddieson, 1998).

Presence and duration of lags Pulmonic fricatives will have fewer instances of lag silences, and any such silences that do occur will be substantially shorter than those following ejective fricatives. Maddieson et al. (2001) found that ejective fricatives were produced with 46 ms of lag silence on average (with this lag being present “in general” although the exact number of silences is not reported), while pulmonic fricatives were only rarely followed by such a silence with an average duration of 1 ms. The data reported in (Beck, 2006) was insufficient to make any generalized descriptions of the presence or absence of lag silences.

Total duration Fricative segments from beginning of frication to beginning of the following vowel are of roughly equal length regardless of laryngeal type. This was the finding in Maddieson et al. (2001). When the durations of flanking silences were added to the length of frication, the overall durations of ejective and pulmonic fricatives were of comparable lengths. Combining durations of frication and silent periods in this way also accounted for the apparent lack of word final lengthening in ejective fricatives in comparison to pulmonic fricatives. Ejective fricatives were not found to undergo frication lengthening word finally, but they were flanked by audible glottal bursts (one closure burst preceding frication, and one release burst following frication) and periods of (near-)silence. Taking these component durations into account, ejective fricatives could also be interpreted as lengthened in word final position. In UNT, ejective fricatives may compensate for shorter frication intervals through the addition of flanking silent intervals, even though they do not occur word finally and therefore cannot undergo word final lengthening.

Frication duration Duration of frication in ejective fricatives will be distinct from pulmonic fricatives before vowels as well as from pulmonic fricatives in clusters (Beck 2006). Beck found that ejective fricatives were *longer* than pulmonic fricatives in both

cluster and pre-vocalic contexts, a finding that contradicts Maddieson et al. (2001), who found that ejective frication was shorter than pulmonic frication.

Effect of place Frication and lag durations will not vary according to place of articulation of the fricative segment. Maddieson et al. (2001) found no effect of place on total duration, frication duration, or lag duration. No interaction was found between place and laryngeal type, either. Beck (2006) did not investigate such interactions in UNT. However, place of articulation has been shown to be correlated with varying durations in stop segments (Repp, 1984; Chao & Chen, 2008). On the other hand, place of articulation may have an effect on lag durations in clusters depending on the place of consonant closure.

Effect of external factors on frication and lag silence durations Word position may affect fricative duration (Maddieson et al., 2001). Maddieson et al. (2001) found duration differences between word initial and word final fricatives, with word final pulmonic fricatives being substantially longer than word initial pulmonic fricatives. Since ejective fricatives do not occur word finally (or in coda position, more generally) in UNT, the present study will look at word initial and word medial positions instead. Perhaps word initial tokens will be somewhat longer due to their prominent position. word final lengthening is known to occur in vowel-final stems in UNT (Beck, 2011b). Although this has not been reported for fricatives, and no other word position effects have yet been found, the potential for sensitivity to word position remains.

Factors external to the fricative segments, such as stress and following vowel laryngealization, may affect frication duration or the presence and duration of lag silences (Beck, 2006). Beck describes one instance of a pulmonic fricative followed by a laryngealized vowel. In this case, a brief lag of 7 ms is reported to follow frication¹, which is attributed to the following vowel rather than the fricative. Primary stress often occurs on the final syllable of a word. This fact in conjunction with word final lengthening may suggest that stress could have an effect on segmental duration, including fricatives.

¹Inspection of the spectrogram in Beck (2006)'s Figure 3 calls this duration into question, however. The silent portion appears nearly as long as the frication itself, which is reported at 90 ms.

5.3 Methods

Analyses were performed on the acoustic data collected as specified in Chapter 2. Fricative and affricate segments were classified according to the frication condition in which they occurred, which are described in detail below. All conditions were limited to word initial or intervocalic positions. *Simplex* fricatives (hereafter *simplex.fricative*) are pulmonic fricatives that occur adjacent to vowels and/or word boundaries only and are produced with a single articulatory configuration. In contrast, the remaining frication conditions may be considered complex in that their production involves more than one articulatory configuration. *Fricative first* sequences (*fricative.first*) are those where frication occurs as the first part of a fricative + stop cluster and included tokens of frication before the oral stops /p, t, k/ as well as a few tokens before /ʔ/. *Laryngealized fricatives* (*laryng.fricative*) are segments that have previously been referred to as ejective fricatives (Beck, 2006); they were collected mainly in word initial position before vowels, or word medially between vowels². Because the ejective nature of the fricatives in UNT is under investigation, the present naming convention was chosen in order to differentiate confirmed ejective fricatives from those currently under investigation here. *Affricates* (*affricates*), of which there are two in UNT ([tʃ] and [ts]), are complex segments produced as sequences of complete oral closure followed by frication. Because they are considered to involve two articulatory phases within a single segment, they provide a basis of comparison between *fricative.first* clusters, which are considered sequences of two distinct segments, and *laryng.fricatives*, which are currently under investigation. The following frication conditions were excluded from the statistical analysis for simplicity: word final position, stop + fricative clusters (also called *Fricative second* (*fricative.second*) in Figure 5.4), all other fricative environments, such as before or after nasals, liquids, or glides (e.g. word initial [sl] in *sla'hs'o'hó'jwa'* /slaʔs'ʔ'ʔohwa/ 'a bit salty'), and clusters preceding or following anything other than vowels, as in the word medial sequence [kʃt] that occurs in *xta:'lakxtim* /ʃta:lakʃtim/ 'one's equivalent in age or size' where the second fricative occurs between two stops (see section 1.2). Table 5.3 provides examples of each frication condition according to the control variables

²For a comparison to fricative + glottal stop clusters, see Figures 2.6 and 2.5.

word position (initial or intervocalic), *vowel laryngealization* (of the following vowel), and *vowel stress* (of the following vowel). For brevity (and because of the greater availability of forms), word initial items are shown crossed with laryngealization and frication condition, and word medial items are shown crossed with stress and frication condition.

Table 5.3: Examples of UNT words in various frication conditions. Stress and laryngealization conditions refer to the categorization of the following vowel. Target segments are shown in **bold** in orthographic representations.

Condition	Word Initial		Word Medial	
	stressed	unstressed	laryng	non-laryng
simplex. fricative	<i>sá:sti'</i> [sa:s.ti] 'new'	<i>salún</i> [sa.'lun] 'hoe'	<i>sé'hsi'</i> [seʔ.si] 'sweet'	<i>tasa:tanú:n</i> [ta.sai.ta.'num] 'stuck, fixed in place'
laryng. fricative	<i>s'á'lhwa'</i> [s'əɬ.wə] 'slow movement thought'	<i>x'etím</i> [ʃe.'tim] of 'seeded and de- veined chili'	<i>li:lh'á:n</i> [li:.'ɬ'a:n] 'plough'	<i>tas'awí</i> [ta.s'a.'wi] 'lose, be de- feated'
fricative. first	<i>xka'j</i> [ʃkəh] 'pineapple'	<i>lhtaká'la'</i> [ɬta.'kə.lə] 'board'	<i>li:xpa'tán</i> [li:ʃ.pa.'tan] 'pestle of a <i>mol- cajete</i> (mortar)'	<i>tu:spúlh</i> [tu:s.'puɬ] 'one's toes'
affricate	<i>chí'px</i> [tʃipʃ] 'dense'	<i>tzalá'j</i> [tsa.'lah] 'brittle, fragile, thin (stick)'	<i>chu'chó'hx</i> [tʃu.'tʃoʔʃ] 'banana blos- som'	<i>a:tu:'chi:yé:tlh</i> [a:tu:tʃi:.'jeɬɬ] 'mint'

Forms that were not produced by all speakers, including speech errors and alternative word forms, have been excluded from the analyses, resulting in 121 common lexical items across the four speakers whose data made up the final data set. Further repetitions that were produced after the third one have also been excluded from this analysis. 1452 fricative tokens (121 words x 3 repetitions x 4 participants) were planned

to be included in the analysis. Twelve words included 2 different fricative tokens, increasing the expected number of tokens to 1488. A number of words were excluded from the analyses because they did not occur in one of the following four conditions: *simplex.fricative*, *affricate*, *fricative.first* or *laryng.fricative*. Notably, approximately 20 word list items included instances of ejective fricatives occurring immediately after a glottal stop. Because the statistical analysis was limited to word initial and intervocalic environments, these forms were excluded. In some cases, speakers did not recognize the word that was intended by the word list, or produced fewer than 3 usable repetitions of some words, resulting in a final tally of 1430 tokens of frication and 1114 tokens of lag in the statistical models that follow.

5.4 Results

Results are presented in three parts. First, illustrative spectrograms of fricatives are presented in each of the four frication conditions defined above. Second, durations of acoustic events surrounding frication are summarized, along with indications of how frequently each event type occurred in the data. Finally, statistical analyses compare durations of three event intervals across segment types: frication, post-frication lag, and frication onset to vowel onset.

5.4.1 Spectrographic analysis of fricatives and affricates

This section provides spectrographic illustration of the four conditions defined above. Table 5.4 summarizes the duration data of frication, post-frication lag, and total fricative-to-vowel portions of the sample fricative spectrograms. See section 2.2.2 for details of the acoustic annotation.

Simplex fricatives

Each of the three places of articulation where simplex.fricatives are produced are illustrated below. The lefthand column in Figure 5.1 provides illustrations of pulmonic fricatives. Figure 5.1a shows a pulmonic alveolar between two /a/ vowels, with a brief (18 ms) intervening lag period between the end of frication and onset of the following

Table 5.4: Summary of duration data taken from illustrative spectrograms in Figures 5.1-5.3. NB: pre-frication (lead) silences in affricates (marked with *) are reported in the post-frication lag column to reflect total segment duration.

Segment	Figure	Frication (ms)	Post-frication lag (ms)	Fricative onset to vowel onset (ms)
s	5.1a	112	18	130
ʃ	5.1c	181	18	199
ʧ	5.1e	170	14	184
s'	5.1b	103	61	164
ʃ'	5.1d	141	66	207
ʧ'	5.1f	159	165	324
sp	5.2a	171	175	346
st	5.2b	131	130	260
sk	5.2c	119	83	203
ʃp	5.2d	146	107	253
ʃt	5.2e	185	130	316
ʃk	5.2f	233	168	402
ʧp	5.2g	114	139	252
ʧt	5.2h	134	151	284
ʧk	5.2i	177	150	326
ts	5.3a	74	63*	137
tʃ	5.3b	103	57*	160

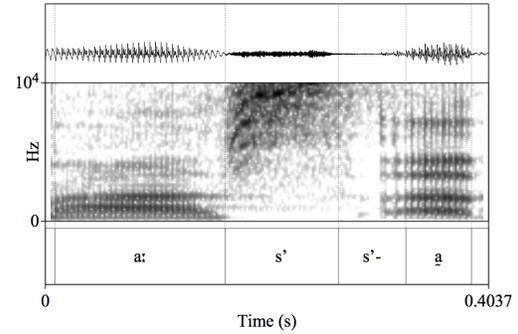
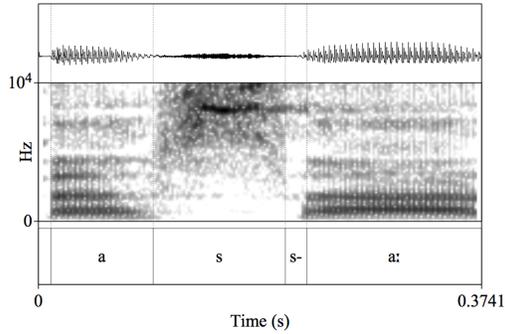
vowel. Frication lasts 112 ms. Figure 5.1c shows a pulmonic post-alveolar fricative separated from the following vowel by a brief lag period. Frication lasts approximately 181 ms and the lag 18 ms. Figure 5.1e illustrates a pulmonic lateral fricative also followed by a short lag before the onset of the following vowel. The frication lasts 170 ms and shows a formant-like structure with elevated spectral energy in several frequency bands.

Laryngealized Fricatives

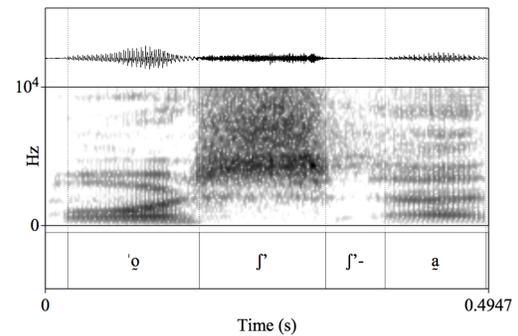
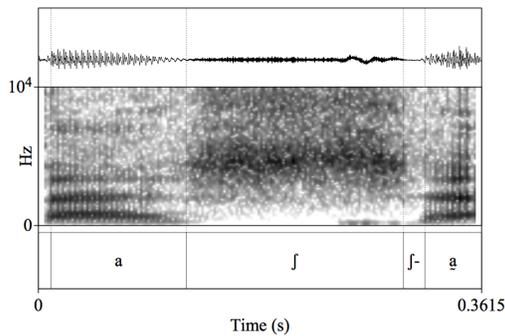
The righthand column of Figure 5.1 provides illustrations of laryngealized fricatives at each place of articulation. Figure 5.1b shows an example of /s'/ between two vowels, along with an intervening lag portion that includes some irregular pulsing of the vocal folds (represented by the vertical striations that are visible in the spectrogram). These segments were taken from the word item *ma:s'a'ta:nán* /ma:s'ata:'nan/ 'raise children'. In this case, frication lasted approximately 103 ms. The post-frication lag lasted approximately 61 ms, with the silent portion of this lag making up 38 ms of that time. Figure 5.1d shows a laryngealized post-alveolar fricative between two laryngealized vowels. The frication period lasts around 141 ms, followed by a lag of 66 ms. Neither the preceding nor the following vowel shows an appreciable change in the temporal regularity of the glottal pulses. Figure 5.1f illustrates a token of the laryngealized lateral fricative. Frication lasts 159 ms and is followed by a lag of 165 ms (the last 29 ms of which involve erratic glottal pulsing).

Fricative-first clusters

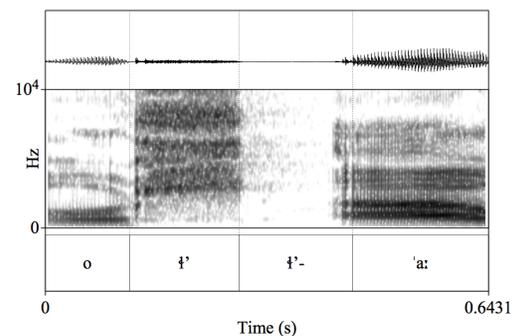
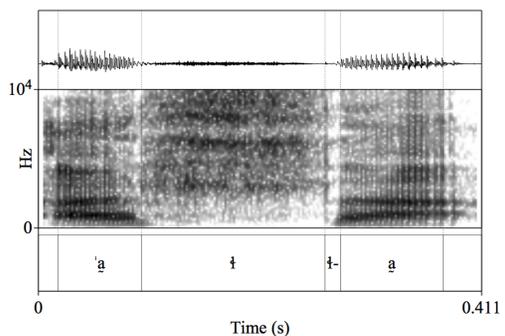
Figure 5.2 provides one example of each combination of fricative and stop places of articulation. Figure 5.2a shows a word medial /sp/ cluster before a stressed vowel. Frication lasts 171 ms, followed by a bilabial closure of 161 ms, and a release burst of 14 ms. Figure 5.2b shows a /st/ cluster in word medial position before a stressed vowel. Frication lasts for approximately 131 ms, followed by an alveolar closure of 122 ms, and a release burst of 8 ms. Figure 5.2c shows a word medial /sk/ cluster preceding an unstressed vowel. Frication lasts for 119 ms, followed by a 62 ms velar closure. The release burst lasts 21 ms. Figures 5.2d-5.2f illustrate the post-alveolar fricative before labial, alveolar, and velar stops. In the /ʃp/ sequence, frication lasts 146 ms, followed



(a) /s/ in *tasa:tanú:lh* /tasa:ta'nurɫ/ 'stuck, fixed in place' (b) /s'/ in *ma:s'a'ta:nán* /ma:s'ata:nan/ 'raise children'.



(c) /ʃ/ in *taxa'há* /taʃa'ʔa/ 'scratch oneself' (d) /ʃ'/ in *cha:'hó'x'a'* /tʃa:'ʔof'a/ 'tree bark'



(e) /ʧ/ in *pixhá'ha'* /piʃ'ʔaʔa/ 'large (bunch or bouquet)' (f) /ʧ'/ in *holh'á:wa'* /ʔoʃ'a:wa/ 'leathery, thick, stiff, not flexible' (right).

Figure 5.1: Pulmonic and ejective fricatives at three places of articulation, produced by speaker GMM.

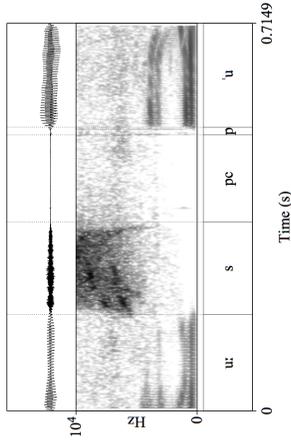
by a lag of 107 ms including closure burst. Frication in the /ʃt/ example lasts 185 ms, followed by a lag of 130 ms. Figure 5.2f shows 233 ms of frication, and 168 ms of lag. Figures 5.2g-5.2i illustrate lateral fricatives in clusters with oral stops. In the /ɬp/ sequence, frication lasts 114 ms followed by 139 ms of silence during the stop closure. Frication duration is 134 ms in the /ɬt/ cluster, followed by 151 ms of closure before the onset of vowel phonation. In the final configuration, /ɬk/, frication is even longer at 177 ms, followed by 150 ms for the /k/ closure. These sample spectrograms illustrate the similarities between the ejective fricatives and fricative + stop clusters, with long silent intervals between the offset of frication and the onset of vowel phonation.

Affricates

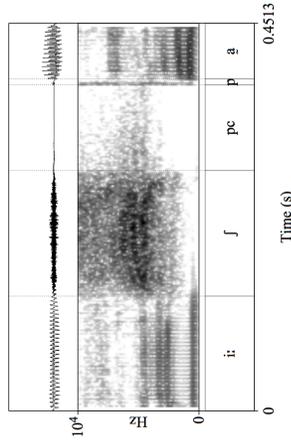
Figure 5.3 illustrates one token each of the alveolar affricate /ts/ (5.3a) and the post-alveolar affricate /tʃ/ (5.3b). The alveolar closure in /ts/ is approximately 63 ms, followed by 74 ms of frication. In /tʃ/ the closure lasts 103 ms, followed by 57 ms of frication. Note that in both cases the release of alveolar closure is visible as a broad spectrum band of energy across all visible frequencies, but that this burst has not been segmented separately from the frication that is contiguous with it.

5.4.2 Duration of acoustic events in frication production

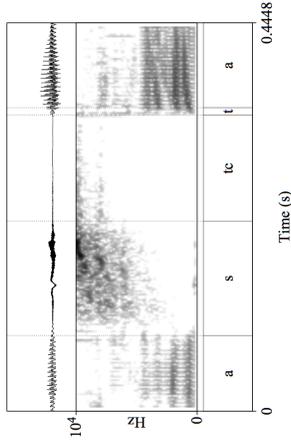
Figure 5.4 summarizes the mean durations of acoustic events that occurred in the vicinity of frication in each condition. Duration data for simplex stops occurring in environments analogous to those of frication (word initially before vowels, or word medially between vowels) have also been included as a point of reference for comparing the duration of affricates and clusters. All conditions were potentially made up of five types of events: *silence preceding frication* (lead), a *burst preceding frication* (lead.burst), *frication noise* (frication), *silence following frication* (lag), and a *burst following frication* (lag.burst). In the affricate condition, bursts indicating the release of oral closure were segmented as part of the frication intervals because they could not be differentiated from the frication noise, resulting in the apparent lack of release bursts. (See Chapter 2 for more information on segmentation and annotation procedures.) The colored



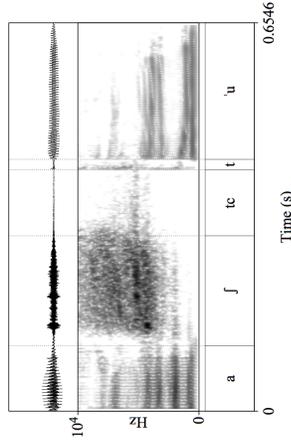
(a) tu:spúlh /tu:s. 'puł/ 'one's toes'



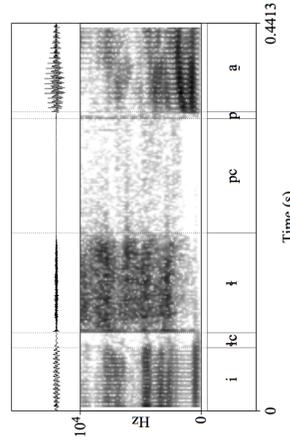
(d) li:x.pa'tán /li: [pə'tan/ 'pestle of a molcajete'



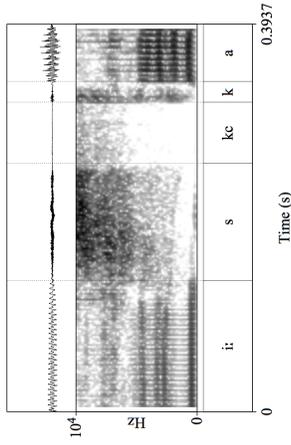
(b) xastánkú' /ʃas. 'tan.ku/ 'youngest sibling'



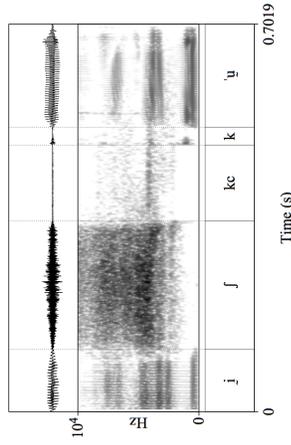
(e) helhtaxtú' /heł.taʃ. 'tu/ 'fade (color)'



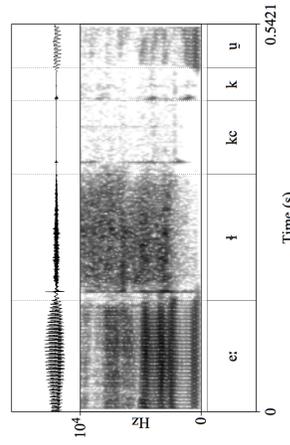
(g) kilhpa'nlhú'lu' [kił.pan. ʔu.lu] 'jowly, with swollen cheeks'



(c) li:s.ka.láj.wa' /li:ska 'lahwa/ 'danger'

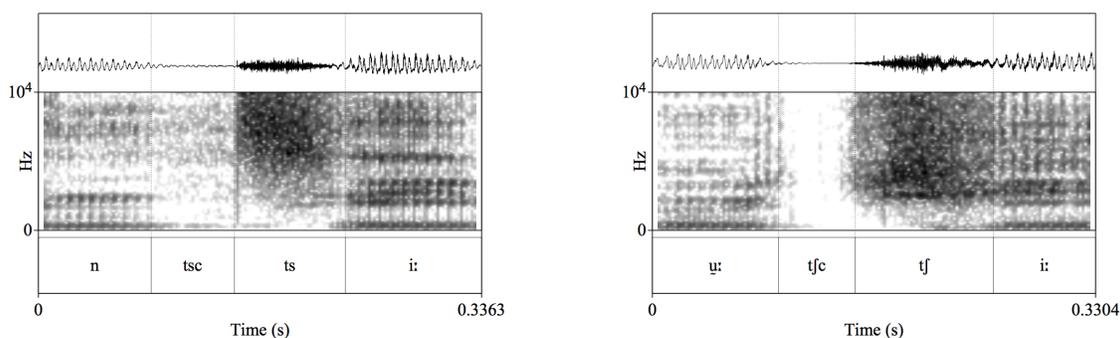


(f) chi'xkú' [tʃi'.kú] 'man' (right)



(i) he:lhku'tán [ʔe:ł.ku. 'tan] 'smell of sweat'

Figure 5.2: Fricative + stop clusters at three places of frication and frication constriction, produced by speaker GMM.



(a) *tzi'ntsi:pá'hlhcha' /tsɪntsi:páʔtʃa/*
'cuatomate, small, tomato-like wild fruit'.

(b) *a:'tu:'chi:yé:klh /a:tʃi:'je:kʃ/ 'mint'.*

Figure 5.3: Affricates produced by speaker HFM

bars represent average durations of each event type with error bars indicating 95% confidence intervals.

By comparing the average durations of the events that did occur, some similarities and differences may already be observed between the conditions presented here. Laryng.fricative and fricative.first conditions bear a strong resemblance to each other with respect to both the overall durational profiles of their production, as well as the average durations of frication and lag events (see Figure 5.4). Both categories are produced with longer average durations than either the affricate or simplex.fricative conditions, as would be expected for sequences of two segments rather than a single complex segment such as an affricate, or a simplex segment such as a pre-vocalic fricative. Note also the similarity between overall length of affricate and simplex.fricative conditions despite the differences in their complexity; while affricate segments have longer lead silences than simplex tokens, their shorter frication intervals even out the total duration.

Frication was sometimes produced with lead and/or lag silence in all conditions, though the frequency of these silences varied by condition. The relative frequency of occurrence of each event type in each condition is summarized in Table 5.5. In addition to the frication conditions, simplex stops (that is, stops adjacent to vowels only) are also provided as a point of reference and basis of comparison. Laryng.fricatives and fricative.first clusters bear a strong resemblance to each other both in the types of events that occur during their production, as well as in terms of their (overall and component)

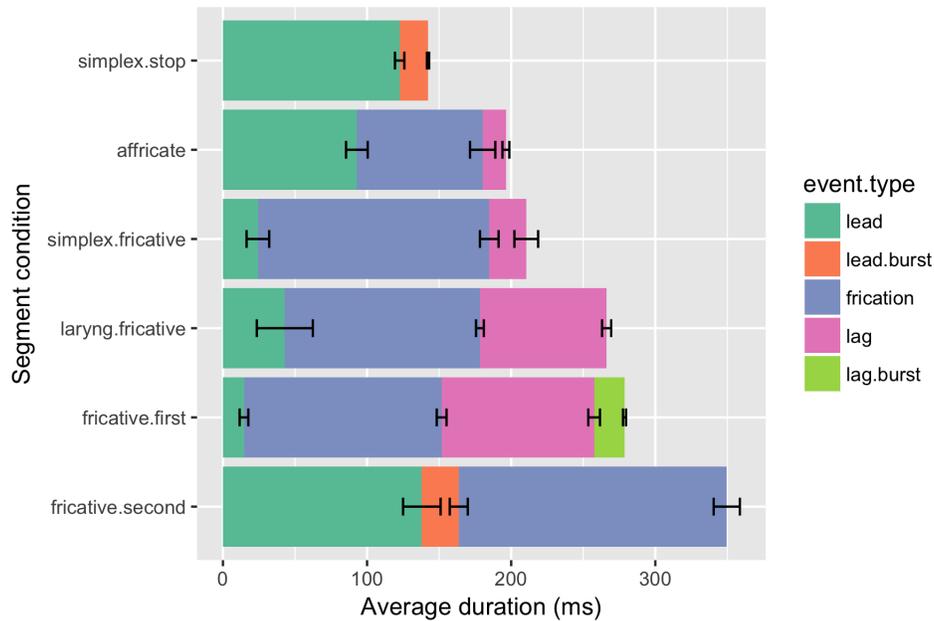


Figure 5.4: Mean duration of acoustic events during production of segments involving frication. Error bars represent 95% confidence intervals. Simplex stops (*simplex.stop*) are included here as a point of reference.

durations. These similarities contrast with the other remaining conditions. Lead silence occurred in less than 5% of *simplex.fricatives*, and less than 2% of *laryng.fricatives* and *fricative.first* clusters. Lead silence occurred in only just over 48% of *affricate* productions, a condition that would be expected to require complete closure prior to frication. This fairly low frequency is largely due to word initial tokens, in which the beginning of closure often could not be easily determined. Similarly, frequency of lag silence occurrence varied according to condition. Lag silences occurred in less than 15% of *affricates*, and less than 22% of *simplex.fricatives*. This is in stark opposition to the *laryng.fricative* condition, which was produced with lag silence 95% of the time, and *fricative.first* condition, which was produced with lag silence over 99% of the time. An additional difference between the *laryng.fricative* condition and the *fricative.first* condition is the lack of lag bursts in the former. This is due in part to the segmentation conventions, which did not indicate glottal bursts due to their variable and erratic appearance.

Table 5.5: Tabulation of event frequency in frication production. Numbers in parentheses represent counts of each event in the data set; percentages were calculated based on these condition-based counts.

	lead	lead.burst	frication	lag	lag.burst
simplex.stop	100% (947)	80.4% (762)	0	0	0
affricate	48.3% (73)	(-) ^a	100% (151)	14.6% (22)	0
simplex.fricative	4.1% (8)	0	100% (196)	21.9% (43)	0
laryng.fricative	1.5% (9)	0	100% (615)	95% (582)	0
fricative.first	1.9% (9)	0	100% (468)	99.8% (467)	90.0% (421)
fricative.second	100% (32)	18.8% (6)	96.9% (31)	0	0

^a Bursts were not segmented separately from frication noise. See Section 2.2.2.

5.4.3 Statistics

In the statistical analysis, the data have been restricted from those reported in section 5.4.2. First, the fricative.second condition has been entirely excluded from the statistical analysis due to low numbers of tokens. Only 31 tokens of fricative.second frication occurred in non-word final (i.e. word medial) position throughout the entire data set. In addition, further conditions, such as sequences involving liquids or nasals, or sequences longer than two consonant segments in length were excluded from the analysis on similar grounds. Due to the low relative frequency and small overall numbers of occurrence, pre-frication (lead) silences have also been excluded (see Table 5.5).

Data from the remaining 1430 fricative tokens were analyzed using linear mixed effects regression analysis, as in Chapter 4. Separate models were fit to each of the following dependent measures: total (frication onset to vowel onset) duration, frication duration, and lag duration. Duration measures were log-transformed to improve the normality of their distributions. The model fitting procedure began with random intercepts specified for Word and Speaker to account for inherent differences between speakers and lexical items. The fixed effects structure included two-way interactions between all pairings of the independent variables (reference levels in bold): condition (**laryng.fricative**, fricative.first, simplex.fricative, or affricate), word position (**initial** or medial), place of articulation (**alveolar**, post-alveolar, or lateral), stress (of the following vowel; **unstressed** or stressed), and vowel laryngealization (of the following vowel;

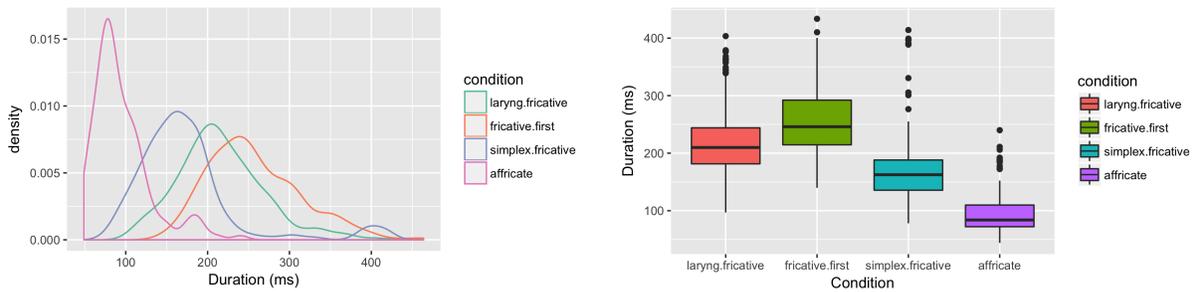
no or yes). Interactions between condition and place of articulation could not be assessed because there is no lateral affricate attested in the segmental inventory of UNT, resulting in an empty cell in the statistical model. The data set was insufficient in size to allow for reliable conclusions to be drawn with respect to three-way interactions between predictors, so such interactions were not included in the models. Random slopes by speaker, which allow the model to compensate for variance due to consistent patterns within a given speaker's output, were determined individually for each model by adding each predictor in the following order: condition, word position, vowel laryngealization of the following vowel, place of articulation, and stress of the following vowel. After the addition of each random slope, the resulting model was compared to the previous, simpler model using ANOVA to determine the goodness of model fit (Baayen, 2006). The additional complexity in random structure was accepted into the model only if it resulted in significantly improved model fit. Interactions between factors were not tested in the random structure, again due to the limited size of the data set.

After constructing the maximal possible random structure that achieved the best model fit (within the limitations specified above), the fixed effects were then backward fitted by removing the least significant interactions and predictors, as long as doing so did not significantly decrease the goodness of model fit. Details of the fixed effect and random effect structures of each model are reported separately in the individual sections below. After arriving at the best fixed and random effects structures, each model was subjected to criticism in which residuals that fell outside ± 2.5 standard deviations from the regression line were identified. The data points associated with these outlier residual values were then excluded, and the models refit to the remaining values to ensure that effects were not overly influenced by outliers, as well as to improve normality of the residual distribution.

Finally, after model fitting and model criticism were complete, multiple comparisons of conditional means were performed using the `lsmeans` package. Comparisons of least squares (LS) means allow for the partial effects of predictors to be evaluated against other partial effects without increasing the risk of Type I statistical errors.

Table 5.6: Total duration in four conditions. Summary statistics (means, medians, standard deviations, standard errors) are indicated for each condition as well as the overall distribution.

Total duration (ms)					
	Mean	Median	SD	SE	N
affricate	98.36	83.97	58.29	4.74	151
simplex.fricative	179.15	163.62	73.33	5.24	196
laryng.fricative	218.09	210.29	59.76	2.41	615
fricative.first	259.72	247.45	66.49	3.08	465
Overall	213.63	209.59	79.63	2.11	1427



(a) Density plot of total durations by condition (b) Total durations by condition. Differences between all pairs were significant.

Figure 5.5: Summary of total duration distributions by frication condition.

The results of each model are presented with following reference levels for each factor: condition (laryng.fricative, v2laryngeal = no

Total duration

The total durations from onset of frication to onset the following vowel across the condition types simplex.fricative, laryng.fricative, fricative.first and affricate are illustrated in Figure 5.5a. Affricates were found to have the shortest total durations. Within the remaining three conditions, fricative.first items were the longest, followed by laryng.fricative, and simplex.fricative, with considerable overlap between conditions. Descriptive statistics summarizing the distributions of durations in each condition are presented in Table 5.6. Three data points were excluded from the analysis because they were missing the lag duration data, bringing the total data set down to 1427 data points from 1430.

A linear mixed effects regression model was fit to the data as spelled out in section 5.4.3. The best model included interactions between condition and vowel laryngealization, condition and stress, condition and word position, and between vowel laryngealization and place. Although neither the effect of word position, nor the interaction between word position and condition were significant, removal of the interaction resulted in decreased goodness of fit. The interaction was therefore retained in the final model. The model specified random slopes by speaker for word position and place, meaning that each speaker might vary somewhat in the ways in which word position and place affect the total duration. Allowing for this by-speaker variation significantly improved the goodness of model fit. As a result of model criticism, 35 data points, or 2.45% of the data, were trimmed³. The trimmed model is summarized in Table 5.7.

³However, trimming the data did not result in normally distributed residuals, likely indicating that the model was missing information that would account for the variability.

Table 5.7: Summary of linear mixed effects regression model of total duration from onset of frication to onset of following vowel (N = 1427).

coef	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	5.4677	0.0702	6.8185	77.8802	0.0000	***
conditionfricative.first	0.1438	0.0517	120.4509	2.7797	0.0063	**
conditionsimplex.fricative	-0.3024	0.0598	217.4712	-5.0608	0.0000	***
conditionaffricate	-0.7603	0.0632	245.0148	-12.0260	0.0000	***
v2laryngealyes	-0.1254	0.0381	527.3923	-3.2951	0.0010	**
v2stressstressed	0.1994	0.0430	136.0534	4.6328	0.0000	***
wordposmedial	-0.1259	0.0627	8.4812	-2.0085	0.0774	
placepostalveolar	-0.1460	0.0407	28.0098	-3.5879	0.0013	**
placelateral	-0.0847	0.0395	113.6976	-2.1435	0.0342	*
conditionfricative.first:v2laryngealyes	0.0882	0.0429	578.6095	2.0535	0.0405	*
conditionsimplex.fricative:v2laryngealyes	0.2035	0.0591	492.7427	3.4456	0.0006	***
conditionaffricate:v2laryngealyes	-0.1106	0.0612	742.6632	-1.8074	0.0711	
conditionfricative.first:v2stressstressed	-0.1453	0.0575	230.5044	-2.5291	0.0121	*
conditionsimplex.fricative:v2stressstressed	-0.1921	0.0870	143.5211	-2.2082	0.0288	*
conditionaffricate:v2stressstressed	-0.4729	0.0743	403.3724	-6.3671	0.0000	***
conditionfricative.first:wordposmedial	0.0017	0.0592	148.7945	0.0287	0.9771	
conditionsimplex.fricative:wordposmedial	-0.0507	0.0718	164.9282	-0.7063	0.4810	
conditionaffricate:wordposmedial	0.1060	0.0801	274.9668	1.3234	0.1868	
v2laryngealyes:placepostalveolar	0.1854	0.0455	474.7367	4.0715	0.0001	***
v2laryngealyes:placelateral	0.1066	0.0502	565.1744	2.1219	0.0343	*

The main finding of the model is a significant effect of condition. A pairwise comparison between least-squares means of all conditions revealed that all conditions differed significantly from each other ($p < 0.005$). Figure 5.5b illustrates the mean durations from onset of frication to onset of the following vowel in each condition. This figure, and all following figures, was generated from the trimmed data set, excluding data points that fell outside of ± 2.5 standard deviations of the mean. The differences between the condition means is quite visibly apparent, with fricative.first items having longer average durations than laryng.fricatives, shorter durations in simplex.fricative and affricate conditions.

Significant main effects were also found for vowel laryngealization, stress, and place. These main effects participated in one or more two-way interactions, all of which were significant; these interactions are presented in Figure 5.6. Because of the presence of these interactions, interpretation of the main effects must be tempered by the comparison of conditional means performed with the *lsmeans* package. Rather than comparing the overall mean of a factor across conditions, we are instead able to compare means that have been averaged over the levels in factors that are not present in the interaction. This comparison allows us to see past some of the variability that is due to causes outside of the interactions of interest.

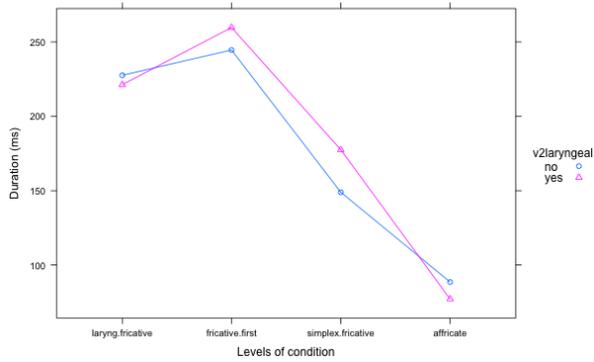
There was a significant interaction between vowel laryngealization and condition, illustrated in Figure 5.6a, with laryng.fricatives being significantly shorter than fricative.first items only when the following vowel was laryngealized ($df = 250.17$, $t = -4.293$, $p < 0.001$). The effect of vowel laryngealization was significant only in simplex.fricative and affricate conditions. In the affricate condition, total duration was shorter when the following vowel was laryngealized ($df = 728.51$, $t = 3.175$, $p < 0.05$). In simplex fricatives, total duration was longer when the following vowel was laryngealized ($df = 461.62$, $t = -3.167$, $p < 0.05$).

The interaction between condition and stress, illustrated in Figure 5.6b, revealed that the durational differences between the laryng.fricative and fricative.first conditions was only significant when the following vowel was unstressed ($df = 139.43$, $t = -5.410$, $p < 0.0001$). In addition, the effect of stress was significant only in the laryng.fricative ($df = 133.05$, $t = -4.482$, $p < 0.0005$) and affricate ($df = 848.7$, $t = 5.024$, $p < 0.0001$) conditions,

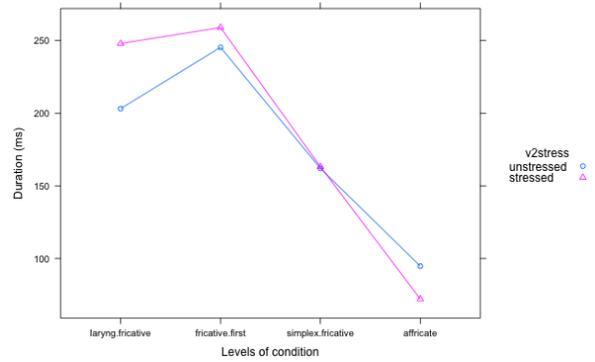
where stress on the following vowel resulted in greater total duration, while in the affricate condition, a following stressed vowel decreased total duration.

The model also showed a significant interaction between vowel laryngealization and place of frication. The lsmeans comparison revealed that the effect of place was enhanced when the following vowel was not laryngealized. Despite this result, the effect was nevertheless quite small, as is indicated by the 30 ms range of the y-axis in Figure 5.6c, which illustrates the interaction between vowel laryngealization and place. The difference between alveolar and postalveolar fricatives was greater before non-laryngealized vowels than before laryngealized vowels ($df = 28.07$, $t = 3.585$, $p < 0.05$). All other pairwise comparisons failed to reach significance.

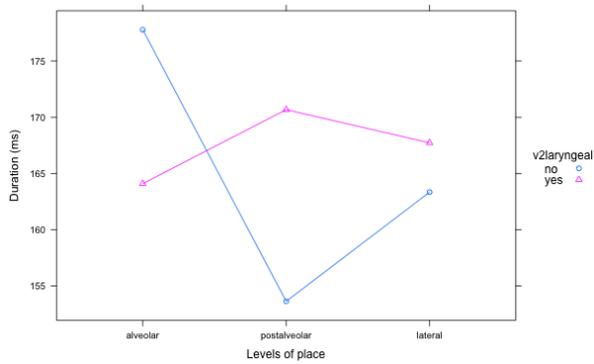
The results of this model indicate that condition had a significant influence on total duration. Fricative + stop clusters had the longest durations, followed by ejective fricatives, simplex fricatives, and finally, affricates. Vowel laryngealization, stress, and place of frication also had significant effects. These predictors participated in interactions that showed that differences between the various factor levels only appeared significant in relatively few comparisons, with inconsistent results. The differences between laryng.fricative and fricative.first conditions were significant only before unstressed vowels and before laryngealized vowels. The main effect of stress was only significant in laryng.fricatives and affricates; vowel laryngealization was only significant in simplex.fricative and affricate conditions; the effect of place was enhanced between alveolar and post-alveolar fricatives when preceding a non-laryngealized vowel. Despite the interaction between place and vowel laryngealization, the effect was quite small, and no other place effect was significant.



(a) Interaction plot of condition x vowel laryngealization.



(b) Interaction plot of condition x stress.



(c) Interaction plot of place x vowel laryngealization.

Figure 5.6: Interaction effects from model of total duration

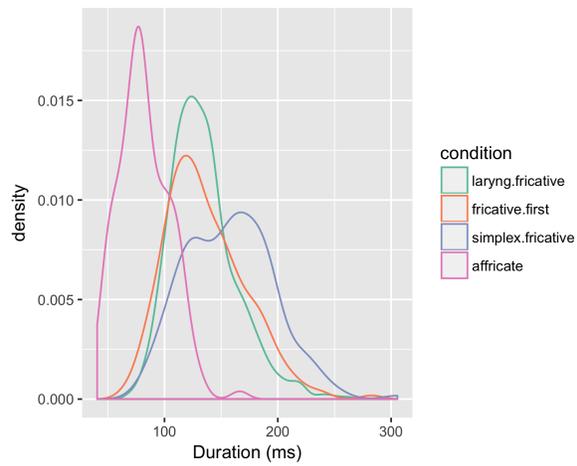
Table 5.8: Frication duration in four conditions. Summary statistics (means, medians, standard deviations, standard errors) are indicated for each condition.

	Duration (ms)				
	Mean	Median	SD	SE	N
affricate	87.28	79.17	54.56	4.44	151
simplex.fricative	160.55	158.63	45.83	3.27	196
laryng.fricative	135.38	130.2	34.12	1.38	615
fricative.first	137.14	130.55	37.46	1.73	468
Overall	134.33	128.86	43.47	1.15	1430

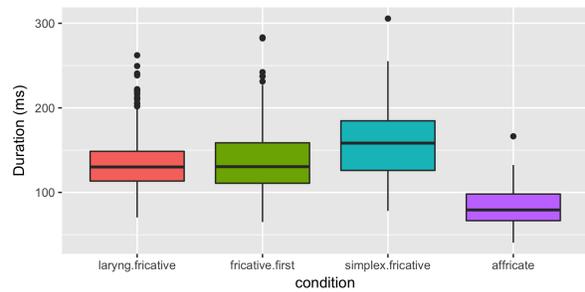
Frication duration

The distributions of frication durations for each of the four conditions is illustrated in a density plot in Figure 5.7a. The data appear to be somewhat divided by condition, with affricates having the shortest frication intervals and simplex.fricatives the longest. Simplex.fricatives are also widely distributed in the range of durations, with the suggestion of a bimodal distribution. Laryng.fricatives and fricative.first segments appear to have frication intervals of comparable duration, continuing the pattern of similarities between the laryngealized fricatives and fricative-initial clusters. There is substantial overlap between all conditions except for affricates, which are markedly shorter. Table 5.8 provides summary statistics of duration data for frication in the four segment conditions.

The best linear mixed-effects model of frication duration included random intercepts by speaker and word, random slopes for vowel laryngealization and word position by speaker, and interactions among the fixed effects between condition and vowel laryngealization, condition and stress, condition and word position, and between vowel laryngealization and place of articulation. Trimming removed 27 data points, corresponding to 1.89% of the data, and resulted in normally distributed residuals. The trimmed model is summarized in Table 5.9.



(a) Density plot of frication intervals.



(b) Frication durations by condition. Differences between all pairs were significant except between laryng.fricative and fricative.first conditions.

Figure 5.7: Summary of frication duration distributions by frication condition.

Table 5.9: Summary of linear mixed effects regression model of frication duration (N = 1430).

coef	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	4.9672	0.0740	4.9433	67.0861	0.0000	***
conditionfricative.first	-0.0152	0.0437	136.3694	-0.3481	0.7283	
conditionsimplex.fricative	0.0562	0.0522	225.2882	1.0752	0.2835	
conditionaffricate	-0.5560	0.0560	262.1392	-9.9350	0.0000	***
v2laryngealyes	-0.0941	0.0410	24.1915	-2.2921	0.0309	*
v2stressstressed	0.1582	0.0367	146.3012	4.3149	0.0000	***
wordposmedial	-0.1269	0.0552	7.2171	-2.3005	0.0539	*
placepostalveolar	-0.1026	0.0311	240.4922	-3.3037	0.0011	**
placelateral	-0.0749	0.0335	211.5120	-2.2353	0.0264	*
conditionfricative.first:v2laryngealyes	0.0428	0.0390	490.2559	1.0990	0.2723	
conditionsimplex.fricative:v2laryngealyes	0.1516	0.0534	438.6484	2.8383	0.0047	**
conditionaffricate:v2laryngealyes	-0.0458	0.0567	654.4760	-0.8077	0.4196	
conditionfricative.first:v2stressstressed	-0.0631	0.0503	244.9984	-1.2543	0.2109	
conditionsimplex.fricative:v2stressstressed	-0.0009	0.0741	154.8787	-0.0117	0.9907	
conditionaffricate:v2stressstressed	-0.2871	0.0677	452.4925	-4.2419	0.0000	***
conditionfricative.first:wordposmedial	-0.0239	0.0502	166.8000	-0.4748	0.6356	
conditionsimplex.fricative:wordposmedial	0.0603	0.0616	177.9500	0.9792	0.3288	
conditionaffricate:wordposmedial	0.4576	0.0713	311.3013	6.4141	0.0000	***
v2laryngealyes:placepostalveolar	0.1852	0.0412	411.2193	4.4943	0.0000	***
v2laryngealyes:placelateral	0.1139	0.0458	473.6831	2.4881	0.0132	*

The most important result of the model is the significant main effect of condition. A pairwise comparison of least-squares means between all four conditions showed significant differences between all conditions ($p < 0.005$) except between laryng.fricative and fricative.first conditions ($df = 148.17$, $t = 1.457$, $p = 0.47$). Frication was longest in simplex.fricatives, and shortest in affricates, with laryng.fricatives and fricative.first clusters falling between the other two categories. Figure 5.7b illustrates the distributions of duration of frication in each of the four conditions. The similarity between the laryng.fricative and fricative.first categories is visually apparent, as are the differences between all other conditions.

All main effects were found to be significant, but except for condition the size of the main effects were relatively small. All of the main effects also participated in at least one significant interaction, illustrated in Figure 5.8, complicating the a priori interpretation of the main effects. In order to investigate the interactions, pairwise comparisons were performed between all combinations of factors participating in significant interactions.

The main effect of stress was significant ($df = 305.07$, $t = 3.003$, $p < 0.005$), with frication having longer duration before stressed vowels than unstressed vowels. The interaction between condition and stress was assessed in a paired lsmeans comparison that found that although all fricatives tended to show the effect of stress, the difference in duration before stressed and unstressed vowels was only significant in the laryng.fricative condition ($df = 146.3$, $t = 4.314$, $p < 0.001$). Figure 5.8a illustrates the interaction between condition and stress.

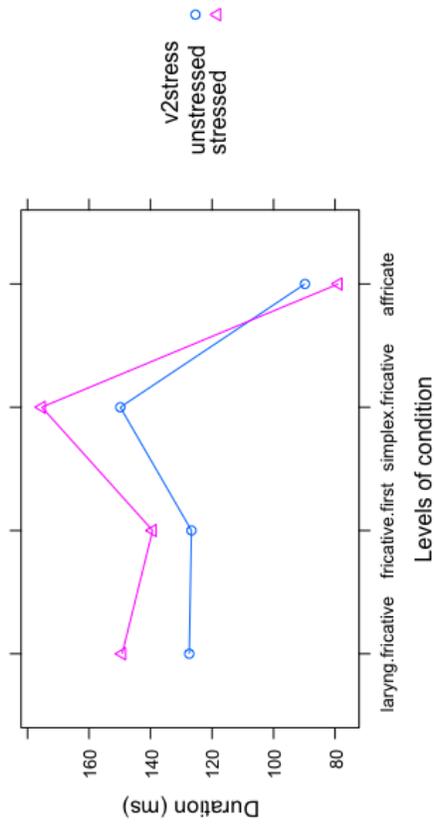
The main effect of word position approached but did not attain significance in post hoc tests, with shorter frication occurring in word medial position. Figure 5.8b shows the LS mean comparisons across word position and condition levels. Pairwise comparison of conditional means revealed that the effect of word position was only significant in the affricate condition, where it showed a pattern opposite that of the other conditions ($df = 23.86$, $t = 4.356$, $p < 0.005$). All other conditions differed from affricate durations in both initial and medial position, but notably the laryng.fricative and fricative.first conditions did not differ from each other in either word position.

The main effect of vowel laryngealization was not found to be significant within any of the four condition levels in post hoc comparisons. The interaction between vowel

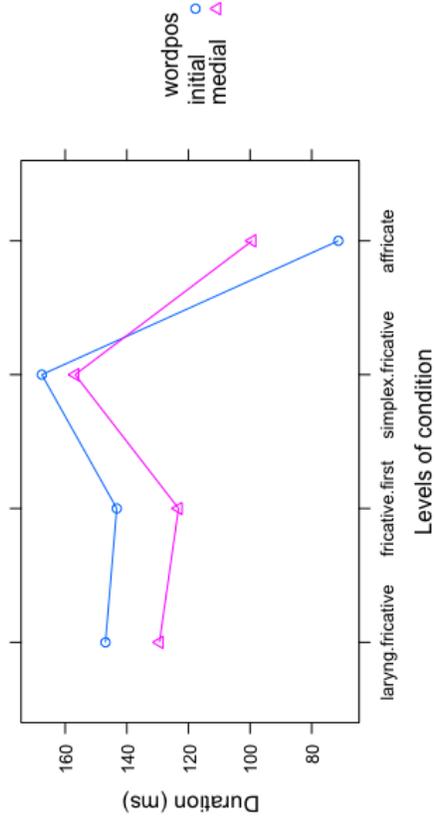
laryngealization and condition is shown in Figure 5.8c. None of the within-condition pairs differed significantly based on vowel laryngealization, although the effect of vowel laryngealization did approach significance in the simplex.fricative condition ($df = 60.26$, $t = -3.047$, $p = 0.0634$). Laryng.fricatives did not differ from fricative.first items regardless of of vowel laryngealization.

Figure 5.8d illustrates the subtle interaction between the factors place and vowel laryngealization. Post-alveolar and lateral fricatives were longer before laryngealized vowels, while alveolar fricatives were longer before non-laryngealized vowels. The differences between vowel laryngealization pairs were only significant in the post-alveolar place, however ($df = 17.34$, $t = 3.399$, $p < 0.05$), with a very small magnitude of difference between the vowel laryngealization conditions.

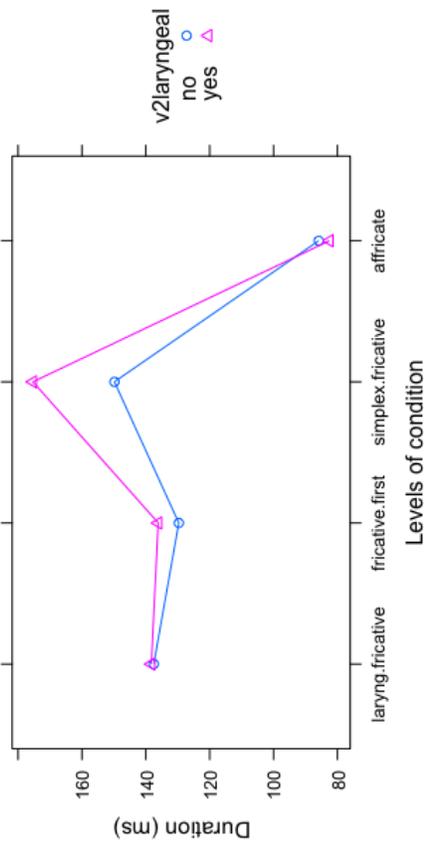
The results of this model indicate that condition is again a significant predictor of duration. However, unlike total duration, frication duration did not differ between laryng.fricative and fricative.first conditions regardless of interactions with other predictors. The model further contained interactions and showed effects of stress of the following vowel, laryngealization of the following vowel and position in the word, but these effects did not produce consistent significant differences for all conditions.



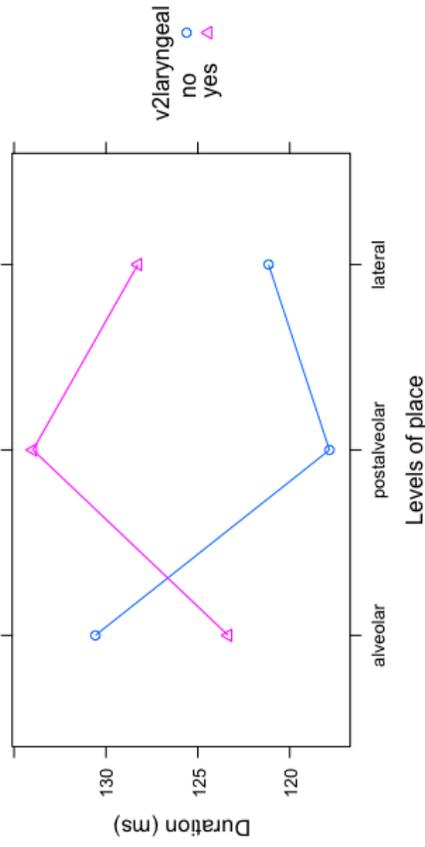
(a) Interaction plot of condition and stress. Stress was only significant among laryngealized fricatives.



(b) Interaction effect of condition and word position. Word position was only significant among affricates.

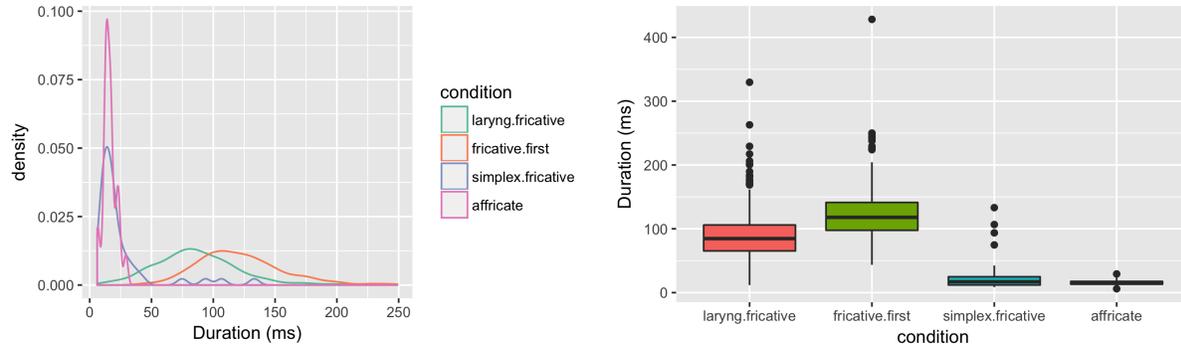


(c) Interaction effect of condition and vowel laryngealization. No pairings within conditions were significant, but simplex.fricatives approached significance at $p = 0.06$.



(d) Interaction effect of vowel laryngealization and place on frication duration. Vowel laryngealization was only significant among post-alveolar fricatives.

Figure 5.8: Interaction effects from model of frication duration



(a) Density plot of lag durations by condition.

(b) Lag durations by condition.

Figure 5.9: Summary of lag duration distributions by frication condition.

Post-frication lag duration

A total of 1107, or roughly 77%, of frication tokens were produced with post-frication lag. The majority of lag productions occurred in the fricative.first (463) and laryng.fricative (582) conditions. The remaining tokens were produced across the simplex.fricative (43) and affricate (22) conditions. Lag periods were considered to include any periods of silence/closure as well as consonant release bursts or other erratic sounds, such as glottal bursts, that occurred before the onset of modal vowel phonation. Figure 5.9a illustrates the distributions of duration data across all four conditions. Table 5.10 provides summary statistics of lag duration in each of the four conditions. Lag durations in affricate and simplex.fricative conditions were quite short in addition to being less frequent overall. Fricative.first lags appear to be somewhat longer than laryng.fricative lags, but both distributions are very widely spread with a high degree of overlap between the two conditions.

A linear mixed-effects regression model was fit to the lag data from all four conditions. The best model included main effects of condition, frication place, and word position, as well as interactions between place of frication and word position, place of frication and stress, and word position and stress. Random slopes of condition, word position, and stress by speaker were also included. Interactions with condition were not included in the model due to the small numbers of tokens in affricate and simplex.fricative conditions. The model was trimmed during criticism, resulting in the

Table 5.10: Lag duration in four conditions. Summary statistics (means, medians, standard deviations, standard errors) are indicated for each condition as well as the overall distribution.

Duration (ms)					
	Mean	Median	SD	SE	N
affricate	16.11	15.38	5.4	1.15	22
simplex.fricative	25.67	17.02	26.75	4.08	43
laryng.fricative	87.91	84.45	38.92	1.61	582
fricative.first	123.89	117.98	41.95	1.96	460
Overall	99.01	96.87	47.14	1.42	1107

removal of 28, or 2.53%, of the data points. The trimmed model is summarized in Table 5.11.

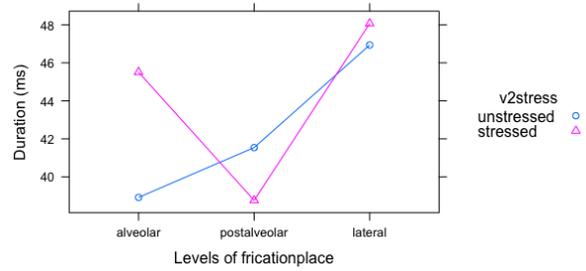
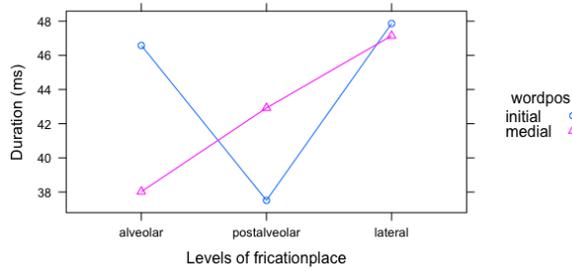
As with previous models, the main effect of condition was highly significant. A pairwise comparison revealed that all conditions differed significantly from each other except for the simplex.fricative and affricate conditions. The effect of condition is illustrated in Figure 5.9b, which shows that laryng.fricative lag periods are shorter than those of fricative.first condition. Both laryng.fricative and fricative.first items have longer lags than either of the simplex.fricative or affricate conditions, which are of comparable duration.

Table 5.11: Summary of linear mixed effects regression model of lag duration including all four conditions (N = 1107).

coef	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	4.5332	0.0878	10.9339	51.6322	0.0000	***
conditionfricative.first	0.3402	0.0805	6.5995	4.2252	0.0045	**
conditionsimplex.fricative	-1.2863	0.2167	3.8357	-5.9356	0.0046	**
conditionaffricate	-1.5736	0.1443	3.9165	-10.9087	0.0004	***
fricationplacepostalveolar	-0.1036	0.0738	163.9262	-1.4037	0.1623	
fricationplacelateral	0.0935	0.0827	106.3854	1.1303	0.2609	
wordposmedial	-0.3994	0.0846	69.9077	-4.7204	0.0000	***
v2stresstressed	-0.0400	0.0998	13.7680	-0.4012	0.6944	
v2laryngealyes	-0.0843	0.0351	402.9234	-2.4028	0.0167	*
fricationplacepostalveolar:wordposmedial	0.3375	0.1100	138.0113	3.0697	0.0026	**
fricationplacelateral:wordposmedial	0.1877	0.1162	128.6923	1.6151	0.1087	
fricationplacepostalveolar:v2stresstressed	-0.2256	0.1077	273.3722	-2.0947	0.0371	*
fricationplacelateral:v2stresstressed	-0.1326	0.1052	227.2147	-1.2605	0.2088	
wordposmedial:v2stresstressed	0.3929	0.1014	209.4187	3.8760	0.0001	***

Main effects of word position, stress and vowel laryngealization were also significant, with slightly longer durations occurring in word initial position, before stressed vowels, and before non-laryngealized vowels. The model also showed that all included interactions, illustrated in Figure 5.10, were also significant. None of the word position pairs differed from each other within frication place, but in post-alveolar fricatives, the direction of the effect was opposite to those in alveolar and lateral places. A similar pattern emerged in the interaction between place of frication and stress. This change in sign across places of frication is likely the source of the significant interaction effect in both cases. However, the magnitude of these effects was quite small, with the greatest duration differences only amounting to about 10 ms between factor levels. It is unlikely that speakers are able to make use of such small differences in duration (cf. Hawkins 1977, who reports just noticeable difference on the order of 25 ms), so while these results may be significant, they are of questionable importance. Likewise, the interaction between stress and word position indicates that initial fricatives had longer lags before unstressed vowels and shorter lags before stressed vowels, and vice versa for medial fricatives, but the effect is again so small (around 10 ms) as to be disregarded as unlikely to be useful in identifying these segments.

In sum, the results of the model in Table 5.11 indicates a strong effect of condition once again. *Laryng.fricative* and *fricative.first* conditions differ from one another as well as from the *simplex.fricative* and *affricate* conditions, which are not statistically different from each other. Although other effects were reported in the model as significant, post hoc tests show that pairs within factors rarely differ significantly. When they do, the effects are exceedingly small.



(a) Interaction effect of frication place and word position on lag duration across all four conditions.

(b) Interaction effect of frication place and stress on lag duration across all four conditions.



(c) Interaction effect of stress and word position on lag duration across all four conditions.

Figure 5.10: Interaction effects from lag duration model summarized in Table 5.11

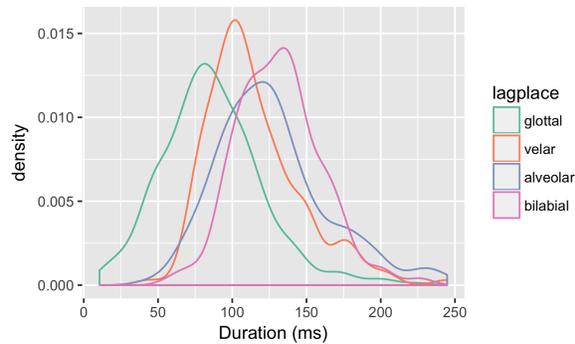
Post-frication lag in ejectives and clusters

In the preceding model of lag duration, the effect of condition was highly significant. However, the conditions appear to fall into two groups, with simplex.fricatives and affricates on one side, and laryng.fricatives and fricative.first clusters on the other. Despite finding significant differences between all conditions, the differences between these two groups is rather larger than the differences within them. In addition, the frequencies of lag occurrence in each condition were highly imbalanced, with far fewer affricate and simplex.fricatives items than laryng.fricative and fricative.first items, perhaps undermining the efficacy of the model in characterizing the data. Because of this imbalance, a further analysis was conducted on a data set restricted to only the two conditions with high numbers of lag periods: laryng.fricative and fricative.first ($N = 1042$).

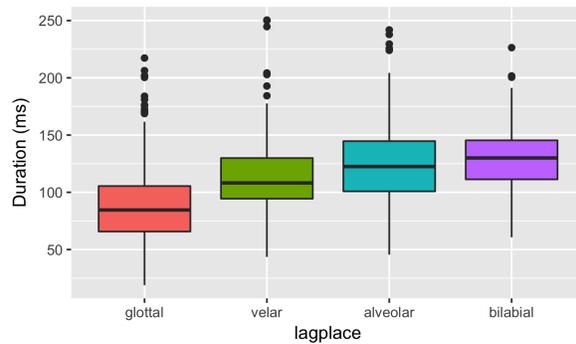
In order to further investigate the potential differences among laryng.fricatives and fricative.first tokens, the lag durations were classified according to their place of articulation. In clusters, this place is identified according to the identity of the stop consonant; in laryng.fricatives, the place was identified as 'glottal'. A new factor, called *lagplace* was added to the restricted dataset to encode these places (bilabial, alveolar, velar, glottal, with **glottal** serving as the reference level). This factor will allow for a comparison to previous findings relating place of articulation to stop closure duration. In addition to the laryng.fricatives item, 41 fricative.first items were also produced with a following glottal closure as a result of the cluster occurring across a morpheme boundary. In order to avoid conflating fricative + glottal stop clusters with potential ejective fricatives, these items were removed from the dataset.

Summary statistics for the remaining 1001 observations across lag place values are summarized in Table 5.12. The distributions of lag durations by place of closure are presented in Figure 5.11. Note that the place of frication was also included in the present model, as in previous models.

A linear mixed effects regression model was built for duration of post-frication lags in laryng.fricative and fricative.first items, coded for place of lag closure as described above. The duration data was log-transformed before model fitting began. The factors lag place, frication place, word position, stress, and vowel laryngealization were included



(a) Density plot of lag durations by place of closure.



(b) Lag durations by place of closure.

Figure 5.11: Summary of lag duration distributions included in model summarized in Table 5.13.

Table 5.12: Lag duration in four closure places. Summary statistics (means, medians, standard deviations, standard errors) are indicated for each closure place as well as the overall distribution.

	Duration (ms)				
	Mean	Median	SD	SE	N
bilabial	133.95	130.53	39.43	3.68	115
alveolar	129.77	122.87	47.24	3.79	155
velar	116.54	108.19	35.04	2.87	149
glottal	87.91	84.45	38.92	1.61	582
Overall	103.92	99.16	44.33	1.40	1001

as main effects in the best model. Random slopes of lag place and stress by speaker were also included, meaning that speakers might vary in the ways in which stress and lag place affect their outputs. The model also included interactions between lag place and stress, and frication place and word position. Model trimming removed 30 data points, or 3% of the data.⁴ The trimmed model is summarized in Table 5.13.

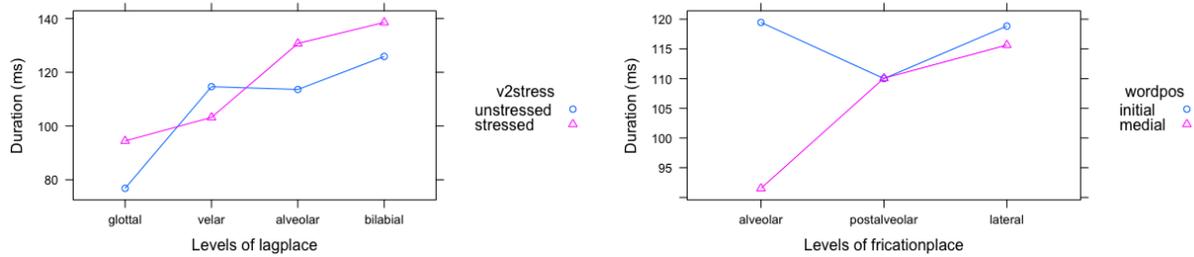
The model showed a significant effect of lag place, with durations increasing as place of lag closure moved further forward in the vocal tract. A pairwise comparison within the levels of lag place showed that these durations differed significantly between the bilabial and glottal places ($df = 13.30$, $t = -4.482$, $p < 0.005$), and between glottal and alveolar places ($df = 6.19$, $t = -3.45$, $p < 0.05$). No other pairs differed significantly from one another. Main effects of stress, word position, and vowel laryngealization were also observed. Lags were longer before stressed vowels, shorter in word medial position, and shorter before laryngealized vowels.

The model also showed two significant interactions, shown in Figure 5.12. The first occurred between lagplace and stress. While there is a general trend of longer lag durations preceding stressed vowels, this pattern was reversed when the lag closure occurred at the velar place. Once again, however, this effect was very small (see Figure 5.12a). The second interaction took place between word position and frication place, illustrated in Figure 5.12b. This interaction revealed that the effect of word position on lag durations was only present when frication was produced at the alveolar place ($df = 83.41$, $t = 3.858$, $p < 0.005$). Word initial tokens with an alveolar place of frication have far longer lag durations (+30 ms) than medial tokens.

⁴Although normality was improved, trimming did not result in normal residuals.

Table 5.13: Summary of linear mixed effects regression model of lag duration of laryng.fricative and fricative.first conditions only. Fricative.first clusters with lags occurring at the glottal place have also been removed (N = 1001).

coef	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	4.4709	0.0817	9.2411	54.7242	0.0000	***
lagplacevelar	0.4004	0.1100	6.3525	3.6387	0.0098	**
lagplacealveolar	0.3914	0.1052	6.5248	3.7189	0.0085	**
lagplacebilabial	0.4941	0.0909	10.0492	5.4357	0.0003	***
v2stressstressed	0.2067	0.0698	7.4221	2.9625	0.0197	*
fricationplacepostalveolar	-0.0823	0.0656	106.8316	-1.2551	0.2122	
fricationplacelateral	-0.0052	0.0674	80.8360	-0.0764	0.9393	
wordposmedial	-0.2662	0.0690	83.4076	-3.8584	0.0002	***
v2laryngealyses	-0.1034	0.0312	317.8737	-3.3087	0.0010	**
lagplacevelar:v2stressstressed	-0.3118	0.0941	295.5765	-3.3147	0.0010	**
lagplacealveolar:v2stressstressed	-0.0665	0.0969	257.5402	-0.6861	0.4933	
lagplacebilabial:v2stressstressed	-0.1110	0.1323	275.0579	-0.8389	0.4022	
fricationplacepostalveolar:wordposmedial	0.2667	0.0925	92.8476	2.8837	0.0049	**
fricationplacelateral:wordposmedial	0.2389	0.1033	82.8800	2.3138	0.0232	*



(a) Interaction of lag place and stress in laryng.fricative and cluster conditions only. (b) Interaction of frication place and word position in laryng.fricative and cluster conditions only.

Figure 5.12: Interaction effects from lag duration model summarized in Table 5.13.

In summary, this model took into account the place of closure in fricative.first clusters, and analyzed laryng.fricative items as though they were clusters with a place of closure at the glottis. This analysis found few differences between lag durations according to the place of closure associated with the lag period: laryngealized fricatives were significantly shorter than fricatives at bilabial and alveolar places only. These differences were part of a possible continuum of closure duration from front to back of the vocal tract. Vowel laryngealization had a small but significant effect on lag duration, with laryngealized vowels leading to shorter lag durations. The interaction between place of frication and stress of the following vowel was also significant, with slightly longer lag durations in alveolar and lateral fricatives before stressed vowels, and slightly shorter lag durations in post-alveolar fricatives before stressed vowels. The interaction between frication place and word position revealed longer lag durations word initially than word medially, but only for alveolar fricatives.

5.5 Discussion

This section summarizes the findings from previous sections and relates them to the hypotheses as they were set out at the beginning of the chapter. Table 5.14 recapitulates the present findings, as well as the data from Maddieson et al. (2001) and Beck (2006), for ease of comparison.

Overall, laryng.fricatives did not exhibit the expected durational characteristics of ejective fricatives. Frication duration was comparable to fricatives preceding oral

Table 5.14: Summary of findings from Maddieson et al. (2001), Beck (2006), and the present paper. Data represent mean durations in milliseconds.

Language	Source	Condition	Frication	Lag	Total
UNT	Beck (2006)	Ejective	143	9	152
		Simplex	96	3	99
		F.first	101	27	–
UNT	Puderbaugh (2019)	Ejective	135	88	218
		Simplex	161	26	179
		F.first	137	124	260
Tlingit	Maddieson et al. (2001)	Ejective	148	46	194
		Simplex	222	1	222
		F.first	–	–	–

stops in clusters. Frication was longer in the simplex.fricative condition than in the laryng.fricative condition, but the same was true when comparing simplex.fricatives before vowels to fricative.first clusters. Total duration differed across all conditions, largely due to differences in lag durations. Post-frication lag silences indeed might indicate a difference between simplex (pulmonic) and ejective fricatives, but the inclusion of fricatives in clusters to the analysis suggests an alternate explanation: segments previously described as ejective fricatives can be analysed as sequences of fricatives + stops, just as they were at their historical origins. The duration of glottal closures fits neatly into a cross-linguistically attested pattern of shorter durations at places of articulation that are further back in the vocal tract and would be consistent with an analysis of these sequences as clusters rather than ejective fricatives (Repp, 1984; Chao & Chen, 2008). This analysis would constitute an alternative to positing the existence of a separate and (cross-linguistically) unusual sound class in UNT, for which the present data do not provide empirical support.

5.5.1 Review of hypotheses with current findings

Frication duration Frication was expected to differ in duration between ejective and pulmonic fricative categories. Specifically, ejective fricatives were expected to have

shorter frication intervals than pulmonic fricatives based on the constraints of the glottalic airstream mechanism and findings on other languages (Maddieson et al., 2001). This was not found to be the case. Ejective fricatives did not differ significantly in frication duration from pulmonic fricatives regardless of whether the pulmonic fricative occurred in fricative + stop clusters or prevocally (as in simplex pulmonic fricatives). On the other hand, affricates, which are undisputed in their status as complex, doubly-articulated segments, were in fact produced with shorter frication intervals.

Presence and duration of lags Ejective fricatives are generally expected to be produced with lag silences more often than frication in simplex pulmonic conditions due to physiological constraints on the resumption of vocal fold vibration after release of glottal closure. This was also the expectation in the current study, and it was indeed borne out: laryng.fricatives were produced with lags 95% of the time, compared to only 21.9% of simplex.fricatives, and 14.6% of affricates (cf. Table 5.5). However, fricative.first clusters were produced with lag silence 99% of the time, a rate comparable to that of laryng.fricative tokens.

A further expectation was that lags would be longer for ejective fricatives than simplex fricatives. Again this expectation was met: lag periods were substantially longer in the laryng.fricative condition than in simplex.fricative, where they were both highly infrequent, and exceedingly brief even when present. However, there is another possible source of lag silences, namely closure that occurs during the production of fricative + stop clusters. In the case of laryng.fricatives, the closure place was coded as 'glottal', as indeed it would be regardless of whether they are truly ejective or in fact fricative + glottal stop clusters. Analyzing the lags in this way revealed that while the laryng.fricatives have the shortest lag durations, they were not significantly different from lags resulting from velar stop closure in clusters. In fact, no two adjacent places of articulation differed significantly in terms of lag duration, suggesting a gradual continuum with long closures occur at the bilabial place, and shorter durations further back in the vocal tract.

Total duration Based on prior findings in Maddieson et al. (2001), total duration was expected to be roughly equal between laryng.fricative and simplex.fricative segments when considering the total time from onset of frication to onset of the following vowel. These total durations were compared for simple pulmonic fricatives before vowels, pulmonic fricatives before stops as part of a cluster, and ejective fricatives before vowels. The analysis found that ejective fricatives were significantly longer than simple pulmonic fricatives, and similar in duration to fricative + stop clusters. Each of these three conditions was significantly different from the others, a question that was further addressed by way of separate analyses of frication and lag durations in each condition.

Frication duration Previous studies found that frication duration differed between ejective fricatives and pulmonic fricatives (Maddieson et al., 2001). Beck (2006) found frication duration in ejective fricatives to be distinct from both intervocalic pulmonic fricatives, and pulmonic fricatives preceding stops as the first element of a fricative + stop cluster. In the present chapter, duration measures of laryng.fricatives were found to overlap substantially with simplex.fricative or fricative.first conditions in most cases. In fact, none of the three conditions differed significantly from the others in the analysis of frication duration. These similarities suggest the same airstream production mechanism across all three frication conditions. The differences in total durations can be attributed almost entirely to the varying durations of post-frication lag silences.

Effect of place Place of frication was not expected to affect frication duration. Indeed, in line with previous findings in Tlingit, place of frication did not appear to have much of an effect. In the analysis of frication duration, place differences, although significant, were so small that they are unlikely to be relevant to speakers or linguistic descriptions.

Place of closure was also included in the analysis of lag durations. Although place of frication did not have an effect on lag duration, place of closure did. By analyzing the laryng.fricatives with a glottal place of closure, their lag intervals fit nicely into a continuum of stop closure durations, starting with longer closures for bilabial stops, and gradually shortening at each subsequent position further back in the vocal tract.

The establishment of this pattern allows for an interpretation of laryng.fricatives as cluster sequences rather than complex glottalic segments.

Effect of external factors on frication duration and lag silences Previous studies found an effect of word position in Tlingit, namely that word final pulmonic fricatives had longer frication intervals than non-final ones, and that word final ejective fricatives were preceded, rather than followed, by a period of silence that effectively increased their total durations as well. In the present chapter, word position did not significantly affect frication duration between word initial and word medial tokens, although a tendency for longer frication to occur in word initial position was observed. Lag duration varied according to place of frication and word position. While no word position differences were observed in the post-alveolar and lateral places, alveolar fricatives were significantly shorter in word medial than in word initial position.

Some differences in lag durations have previously been attributed to factors occurring outside the immediate segment, particularly in adjacent vowels. In the present chapter, vowel laryngealization and stress of the following vowel were included in all component analyses of duration in ejective and pulmonic fricatives. Although they improved the model fit and were sometimes found to be significant predictors, the effects were always small and often inconsistent across levels of other predictors.

The effect of vowel laryngealization appears to be limited to the lag period only and does not extend to the duration of preceding frication. Stress, on the other hand, appeared to have more uniform effects whereby fricatives before stressed vowels tended toward longer durations of both frication and lag intervals, although again the magnitude of the effect was very small.

5.5.2 Conclusion

There are essentially two options in our interpretation of the ‘ejective’ fricatives of UNT: either they are clusters, or they are produced with the glottalic airstream, utilizing glottal closure to manipulate air pressure. In the first case, the lag closure would be associated with a distinct consonant segment, /ʔ/; in the second case, lag closure would be an epenthetic by-product of the articulatory configurations necessary for glottalic

speech. If the closure were epenthetic, we might expect the lag time to be somewhat short, akin to the findings of Ohala (1997) regarding epenthetic [p] in English words such as 'hamster'. Note that although the lag periods reported for ejective fricatives in Tlingit were referred to as 'long', their mean duration was only 46 ms. The glottal lags measured in the present study were on average nearly twice that, at 88 ms.

On the other hand, we can instead interpret these glottal lags as part of the stop series. The resulting pattern follows a well-known pattern that occurs in many languages: as place of closure moves deeper into the vocal tract, closure duration becomes shorter (Cho & Ladefoged, 1999). Glottal stops are formed at the place of articulation at the furthest back point of the vocal tract, so their closure durations would be expected to be shorter than any others. This was indeed the pattern that we saw here: when the lags were categorized according to their place of closure (or presumed place, in the case of ejective fricatives), the lags of laryng.fricatives were the shortest of all. Comparisons between lag places showed that pairs of adjacent places did not differ significantly from one another, suggesting a gradual continuum of closure duration based on place of articulation rather than a categorical distinction based on different speech mechanisms. This pattern, coupled with the statistical model showing no significant differences between most places of lag closure, supports the analysis of what have heretofore been referred to as "ejective fricatives" in UNT as fricative + stop clusters.

Chapter 6

Discussion and Conclusions

This thesis began with a question about laryngealization in Upper Necaxa Totonac, which has been described as having contrastive laryngealization in vowels as well as a contrast between ejective and pulmonic fricatives. The goal of this thesis was to shed some light on these contrasts and provide insight into whether they have been aptly described. Alternative hypotheses regarding these phenomena were also presented, namely, that phonetically laryngealized vowels might in many cases be the result of coarticulation with glottal stops, and that ejective fricatives might be better described as phonetic fricative + glottal stop clusters. These questions were addressed in three chapters. The first of these chapters (Chapter 3) explored segmental collocates present in the UNT dictionary, including both vowels and consonants. The remaining two chapters focused on acoustic aspects of vowels (Chapter 4) and fricatives (Chapter 5) separately.

The present chapter proceeds first by summarizing and evaluating the findings in each of the three chapters, organized by segment type. The summary begins with the fricatives, which are more straightforward, and continues with the vowels. Suggestions for possible follow-up research are included in each section. The chapter concludes with a summary of the contributions of this thesis.

6.1 Fricatives in Upper Necaxa Totonac

The previously supposed contrast between ejective and pulmonic fricatives in UNT was investigated from two perspectives. The first, presented in Chapter 3, looked at

segmental laryngealization in context with the hypothesis that laryngealized vowels might be more likely to occur adjacent to other segments involving glottal closure, such as ejective fricatives. Chapter 5 considered acoustic duration as evidence for or against ejective production. Results of the contextual analysis showed that fricative laryngealization is independent of laryngealization in surrounding segments, meaning that laryngealized vowels were no more likely to occur adjacent to ejective fricatives than pulmonic fricatives. The acoustic analysis showed that UNT ejective fricatives are produced with overall longer durations than pulmonic fricatives, due to the combination of long frication intervals followed by substantial glottal closure.

In the most uncontroversial scenario of canonical glottalic egressive airflow, the glottis must be closed in order to facilitate the compression and subsequent release of oral air pressure. If the ejective fricatives were produced by the glottalic airstream mechanism, the glottis would have to be closed before the onset of frication in order to allow for the compression of ambient air in the vocal tract before release. In such a scenario, we might expect a phonetically ejective fricative to have an effect on preceding vowels similar to that of the glottal stops, which were found to be highly correlated with preceding laryngealized vowels (see Section 6.2 for further details). No such relationship was observed, suggesting that glottal closure does not occur at or before the onset of frication. On the other hand, if the ejective fricatives are phonetically clusters, glottal closure would not be expected to occur until after frication (or at least, not until some time after frication onset). In the cluster scenario, we should expect the fricatives to have the same pattern of co-occurrence with vowel laryngealization as pulmonic fricatives, that is, no relationship at all. In fact, this is what we do see. Likewise, we would also expect fricative + glottal stop clusters to behave like glottal stops with respect to their following environment. Again, the results of the collocational analysis are consistent with such expectations in that no discernible pattern was observed. The ejective fricatives of UNT show collocational patterns similar to those of pulmonic fricatives in their preceding environments, and patterns similar to those of glottal stops in their following environments, exactly as would be expected for fricative + glottal stop sequences.

The analysis of phonetic characteristics of the contrast between ejective and pulmonic fricatives focused on the duration of the component acoustic events on either side of frication in three conditions: simplex fricatives, ejective fricatives and fricative + stop clusters. The analysis was limited to instances of each condition that occurred before vowels word initially or between vowels word medially. First, each condition was segmented into its component events based on the acoustic signal. Due to their presumed production mechanism, ejective fricatives would be expected to be preceded by an interval of silence more often than pulmonic fricatives. While some tokens were produced with this lead silence, it was highly infrequent overall, regardless of the frication condition. The bulk of the analysis focused instead on the durations of frication and following (lag) silent intervals. Some differences were found between ejective fricatives and pulmonic fricatives, especially regarding the duration of lag silences and overall duration from onset of frication to onset of the following vowel (an interval that allows for the comparison of total duration across pulmonic, ejective, and cluster conditions). Contrary to expectations, ejective fricatives had frication intervals equal in duration to pulmonic fricatives, followed by substantially longer periods of silence. These silences, in conjunction with frication, resulted in longer overall durations from the onset of frication to the onset of the following vowel. This is again counter to expectations of ejective fricatives, which have been found to have duration roughly equal to that of pulmonic fricatives when measured from frication onset to vowel onset, as a result of shorter frication followed by a silent interval (cf. Section 5.1).

The overall longer duration of ejective fricatives in comparison to pulmonic fricatives is puzzling: a long lag silence could easily be integrated into an account based on the glottalic mechanism, but the long frication interval is inexplicable given the limited reservoir of air available to the glottalic airstream. Luckily, an alternative hypothesis is at our disposal. Rather than positing a rather unusual sound in an otherwise simple segmental system, we can instead consider the possibility that they are in fact clusters of fricatives followed by glottal stops. Analyzing the ejective fricatives as clusters would assume a pulmonic airstream to initiate and sustain frication, and provide an explanation for the lengthy silence that follows as necessary to indicate a stop closure in the cluster. Taken as a unit from onset of frication to onset of the following vowel,

the ejective fricatives appeared inexplicably longer than pulmonic fricatives, but when compared to fricative + oral stop clusters they were of roughly equal total duration.

Despite the overall similarity in duration between ejective fricatives and clusters, there were differences with respect to the duration of lag silences following frication. In order to investigate these differences further, lag periods were annotated according to their place of articulation, with ejective fricatives being labeled as “glottal”. Comparisons of lag duration across these place of articulation categories revealed a continuum of closure duration that parallels findings from numerous languages of increasing duration as the place of stop closure approaches the front of the mouth. The ejective fricative closures fit nicely into this pattern due to their closure intervals being the shortest. This pattern, in conjunction with frication intervals of equal duration in simplex, ejective and cluster conditions, supports the hypothesis that the ejective fricatives would be better described as fricative + glottal stop clusters.

The acoustic evidence notwithstanding, a final pronouncement on the phonetic nature of UNT ejective fricatives also requires articulatory measurements and perceptual studies. Ejective speech is produced by way of the glottalic airstream, which requires glottal closure and has repercussions on oral airflow. Further analysis of such articulatory factors might still favor the analysis of ejective fricatives as complex segmental units rather than clusters. A limited set of airflow data has been used to argue for the ejective analysis in the past (Beck, 2006), but the findings were substantially different from airflow measures of ejective fricatives in other languages. A larger airflow study with multiple speakers and a balanced word list would improve the strength of claims that could be made based on such findings. Electroglottography (EGG) could be used to verify glottal closure during fricative production, if present. Together, airflow and EGG measurements would provide definitive evidence for the articulatory mechanism used in the production of ejective fricatives in UNT. Articulatory analysis would also provide information about the variability of production in these segments across speakers. It is possible that some speakers do produce ejective forms while others do not, or that speakers produce ejective forms in certain linguistic or conversational contexts but not in others.

Phonological evidence for the analysis of ejective fricatives as complex units is hard to come by, since they occur in precisely the same phonotactic environments as fricative + stop clusters. In fact, since UNT allows fricative + stop clusters at all places of articulations for stops except glottal, analyzing the ejectives instead as clusters would fill an apparent gap. Beck (2006) has suggested that syllable structure might be a potential avenue for distinguishing ejective fricatives from clusters. Fricative + stop clusters have been described as splitting into coda and onset segments across syllable boundaries, while ejective fricatives, on the other hand, appear only in syllable onset position (c.f. Table 1.4, Beck 2006), but this analysis has not been empirically tested. In order to do so, speakers could be trained on presumably unambiguous CV syllable types, then tested on clusters and ejective fricatives in a variety of word positions as a means of testing the syllabification argument. Although somewhat unnatural, a simple approach to eliciting speaker judgments of syllable boundaries might be asking them to separate words into syllables (or “beats”) by speaking slowly and clapping on each beat. The task would require no special equipment, though audio recording of the task would be advisable for transparency, and the data could be collected fairly quickly. Linguist judgments notwithstanding, speaker judgments are necessary for establishing distinct patterns in syllabification between clusters and ejective fricatives. In lieu of such evidence of syllable structure, and in light of the current findings presented in this thesis, a cluster analysis of the ejective fricatives would be simpler and more straightforward from a phonological point of view. It would also resolve the typological oddity of a system with ejective fricatives, but no ejective stops.

6.2 Vowels in Upper Necaxa Totonac

Laryngealized vowels were found in the segmental corpus analysis of Chapter 3 to be followed by glottal stops far more frequently than would be expected if the two segment types were independent of each other. More than 70% of glottal stops were preceded by laryngealized vowels in the corpus, and nearly a third of laryngealized vowels occur before glottal stops. These correlations were stronger than any other segment pairs, which generally did not show relationships between laryngeal categories.

Chapter 4 investigated this pattern of co-occurrence by comparing laryngealized and non-laryngealized vowels in a variety of segmental contexts using the difference in amplitude between the first and second harmonics (H1-H2), which has been correlated with categories of non-modal phonation in several languages, where lower values indicate creak or laryngealization. The analysis showed that the laryngeal category of the vowel was only rarely a significant predictor of the H1-H2 value of the vowel, but that segmental context was highly predictive of such values. Vowels that preceded glottal stops had lower H1-H2 values, a profile similar to laryngealized vowels across many languages.

Conversely, vowels that followed glottal stops had H1-H2 values roughly 2 dB higher than vowels following fricatives from either laryngeal category or oral stops, again regardless of the reported laryngealization category of the vowel.

Any effects of vowel laryngealization that were present did not reliably occur in the first two-thirds of vowel duration as has been previously found in cases of contrastive laryngealization (Blankenship, 2002; Garellek, 2010; Gordon, 2001). Rather, the location of the effect in the present study appeared to be related to the position of the adjacent glottal stop, with stronger indications of laryngealization later in the vowel, closer to following glottal stop contexts.

The present findings show that, on the one hand, H1-H2 does not appear to be associated with the transcribed vowel laryngealization. On the other hand, this measure does show a strong relationship to vowels followed by glottal stops. This association should not be surprising, given the frequent appearance of glottal stops as intervals of non-modal or creaky phonation in the acoustic signal (see Figure 2.4 for some examples of glottal stop production). Consequently, differentiating sequences of laryngealized vowels followed by glottal stops from non-laryngealized vowels followed by glottal stops is difficult, if not impossible. Without an acoustic distinction between laryngealized and non-laryngealized vowels, transcription of laryngealized vowels in some cases and non-laryngealized vowels in others is misleading, indicating a contrast where it may be impossible to maintain or identify. Merely stipulating a contrast is not enough; at a minimum, a phonetic description of the contrast between laryngealized and non-laryngealized vowels before glottal stops is necessary. Whether or not the contrast is

justified, a corpus analysis such as the one performed in Chapter 3 can serve to identify redundant transcriptions of predictable allophonic variation for further investigation, or as a means to replace them in a straightforward and systematic way.

None of this is to say that there is no phonation contrast among vowels in UNT, rather that the presence of laryngealization in a certain environment is suspiciously predictable. Further study into the nature of the contrast is certainly warranted. One approach might be to annotate a data set according to both categorical laryngealization (as indicated by transcription) and audible laryngealization identified by both trained linguist listeners and native speakers of Upper Necaxa Totonac. Once the data is annotated, multiple potential measures of phonation contrasts could then be extracted and analyzed from each of these data sets, with comparisons between the most fruitful measures in each case revealing the acoustic characteristics that are likely to be most salient in each analysis. This would be beneficial on at least two fronts. First, it would highlight similarities and differences between linguist judgments and native speaker judgments, which could be used to improve the accuracy of linguistic annotations. A high correspondence across the data sets would be an indication that linguist judgments are in line with speaker perceptions, while variable outcomes would demonstrate the influence that training and experience have on classification judgments. Second, it would result in a collection of detailed information about the phonetic profile of laryngealization, which could lead to better descriptions, which improves the identification of phonological patterns and potentially affects higher order linguistic analyses as a result.

In order for a contrast to be maintained between two phonological categories, there must be information about that contrast contained in the phonetic signal. If there is a contrast between laryngealization categories in vowels, then a detailed and many-pronged acoustic study ought to be able to describe some characteristic or clusters of characteristics that they share in common. Although contrast cannot be demonstrated on the basis of phonetics alone, the acoustic signal is nevertheless the first evidence of phonological categories linguists have access to, whether via their ears or through acoustic analysis.

6.3 Contributions of the thesis

This thesis has provided analysis of understudied contrasts related to laryngealization in Upper Necaxa Totonac. The sounds that have been referred to as ejective fricatives are very similar to fricative + stop clusters. There is no indication that they are produced with a non-pulmonic airstream, and therefore describing them as an exotic sound type is not necessary. The laryngealized vowels did not differ from non-laryngealized vowels in terms of H1-H2. Rather, the proximity of a following glottal stop appeared to influence vowel production, resulting in non-modal phonation later in the vowel. The findings presented here may be useful in producing transcriptions that are more consistent with the acoustic data, which in turn could affect phonological and other higher order linguistic analyses. The thesis has also identified future research that could further confirm or question these conclusions. Similar analyses could be performed for other Totonac languages to shed light on the disparate analyses of laryngealization across the family and the consequences for comparative reconstruction. The findings of such research have the potential to inform our understanding of the relationship between phonetics, phonology and fieldwork, as well as reconstruction of historical developments in the language family.

References

- Arana Osnaya, E. (1953). Reconstruccion del prototonaco. *Revista mexicana de estudios antropologicos*, (pp. 123–130).
- Arppe, A. (2008). *Univariate, bivariate, and multivariate methods in corpus-based lexicography – a study of synonymy*. PhD thesis.
- Aschmann, H. P. (1946). Totonaco phonemes. *International Journal of American Linguistics*, 12(1), 34–43.
- Baayen, R. H. (2006). *Analyzing Linguistic Data*. Cambridge University Press.
- Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, 59(4), 390–412.
- Bao, M. (2009). Phonetic realization of glottal stop in Shugni. *The Journal of the Acoustical Society of America*, 126, 2181.
- Barnier, J., Briatte, F., & Larmarange, J. (2017). questionr: Functions to Make Surveys Processing Easier.
- Bauer, L. (2015). English phonotactics. *English Language and Linguistics*, 19(3), 437–475.
- Beck, D. (2004). *Upper Necaxa Totonac*. Muenchen: Lincom Europe.
- Beck, D. (2006). The emergence of ejective fricatives in Upper Necaxa Totonac. *U. Alberta Working Papers in Linguistics*, 1, 1–18.
- Beck, D. (2008). Ideophones, adverbs, and predicate qualification in Upper Necaxa Totonac. *International Journal of American Linguistics*, 74(1), 1–46.
- Beck, D. (2011a). *Nuevo diccionario del idioma totonaco del Río Necaxa*. Self-published.
- Beck, D. (2011b). *Upper Necaxa Totonac Dictionary*. Berlin: Mouton DeGruyter.
- Blankenship, B. (2002). The timing of nonmodal phonation in vowels. *Journal of Phonetics*, 30, 163–191.
- Boersma, P. & Weenink, D. (2018). Praat: doing phonetics by computer [Computer program].
- Bowern, C. (2008). *Linguistic Fieldwork: A practical guide*. New York: Palgrave MacMillan, 1st edition.

- Brown, C. H., Beck, D., Kondrak, G., Watters, J. K., & Wichmann, S. (2011). Totozoquean. *International Journal of American Linguistics*, 77(3), 323–372.
- Catford, J. C. (2010). On the classification of stop consonants (1939). *Journal of the International Phonetic Association*, 40(3), 287–291.
- Chao, K.-y. & Chen, L.-m. (2008). A Cross-Linguistic Study of Voice Onset Time in Stop Consonant Productions. *Computational Linguistics and Chinese Language Processing*, 13(2), 215–232.
- Cho, T. & Ladefoged, P. (1999). Variation and universals in VOT: evidence from 18 languages. *Journal of Phonetics*, 27(2), 207–229.
- Demolin, D. (2002). The search for primitives in phonology and the explanation of sound patterns: The contribution of fieldwork studies. In C. Gussenhoven & N. Warner (Eds.), *Laboratory Phonology 7* (pp. 455–514). The Hague: Walter De Gruyter.
- Demolin, D. (2015). Dynamics and articulatory control in Amharic ejectives. Presented at LabPhon15, Cornell University.
- DiCano, C. T. (2010). Itunyoso Trique. *Journal of the International Phonetic Association*, 40(2), 227–238.
- DiCano, C. T. (2011). *Perceptual cues of laryngeal contrasts in Trique*. Technical report.
- Dowle, M. & Srinivasan, A. (2017). *data.table: Extension of 'data.frame'*. R package version 1.10.4.
- Elías-Ulloa, J. (2016). The role of prominent prosodic positions in governing laryngealization in vowels: A case study of two panoan languages. In H. Avelino, M. Coler, & L. Wetzels (Eds.), *The Phonetics and Phonology of Laryngeal Features in Native American Languages*. Brill.
- Esling, J. H., Fraser, K. E., & Harris, J. G. (2005). Glottal stop, glottalized resonants, and pharyngeals: A reinterpretation with evidence from a laryngoscopic study of Nuuchahnulth (Nootka). *Journal of Phonetics*, 33, 383–410.
- Esposito, C. M. (2006). *The Effects of Linguistic Experience on the Perception of Phonation*. PhD thesis, UCLA.
- Esposito, C. M. (2010a). The effects of linguistic experience on the perception of phonation. *Journal of Phonetics*, 38(2), 306–316.
- Esposito, C. M. (2010b). Variation in contrastive phonation in Santa Ana Del Valle Zapotec. *Journal of the International Phonetic Association*, 40(2), 181–198.
- García-Vega, M. (2014). Acoustic properties of vowels in Upper Necaxa Totonac. In *Workshop on American Indigenous Languages, UCSB Department of Linguistics, May 2nd-3rd, 2014*.
- Garellek, M. (2010). The acoustics of coarticulated non-modal phonation. *UCLA Working Papers in Phonetics*, 108, 66–112.
- Garellek, M. (2013). *Production and perception of glottal stops*. PhD thesis.

- Gerfen, C. & Baker, K. (2005). The production and perception of laryngealized vowels in Coatzospan Mixtec. *Journal of Phonetics*, 33(3), 311–334.
- Gordon, M. (2001). Laryngeal timing and correspondence in Hupa. In *UCLA Working Papers in Linguistics*, volume 7.
- Gordon, M. & Applebaum, A. (2006). Phonetic structures of Turkish Kabardian. *Journal of the International Phonetic Association*, 36(02), 159.
- Gordon, M. & Ladefoged, P. (2001). Phonation types: A cross-linguistic overview. *Journal of Phonetics*.
- Gries, S. T. (2013). *Statistics for Linguistics with R: A Practical Introduction*. Berlin and New York: Mouton DeGruyter, 2 edition.
- Gries, S. T. (2015). The most under-used statistical method in corpus linguistics: Multi-level (and mixed-effects) models. *Corpora*, 10(1), 95–125.
- Hanson, H. M., Stevens, K. N., Kuo, H.-K. J., Hill, M., Chen, M. Y., & Slifka, J. (2001). Towards models of phonation. *Journal of Phonetics*, 29, 451–480.
- Henton, C., Ladefoged, P., & Maddieson, I. (1992). Stops in the world's languages. *Phonetica*, 49, 65–101.
- Herrera Zendejas, E. (2014). *Mapa fónico de las lenguas mexicanas: formas sonoras 1 y 2, 2nd edition*. Mexico, D.F.: El Colégio de México.
- Iseli, M. & Alwan, A. (2004). An improved correction formula for the estimation of harmonic magnitudes and its application to Open Quotient Estimation. In *Proceedings of ICASSP* (pp. 669–672). Montreal.
- Keating, P. & Esposito, C. (2006). Linguistic Voice Quality. In *SST 2006 Proceedings*.
- Keating, P. & Esposito, C. (2007). Linguistic Voice Quality. *UCLA Working Papers in Phonetics*, 105(105), 85–91.
- Keating, P., Esposito, C. M., Garellek, M., Khan, S., & Kuang, J. (2011). Phonation contrasts across languages. In *Proceedings of the XVII International Congress of Phonetic Sciences* (pp. 1046–1049).
- Kim, Y. & Valdovinos, M. (2014). The interaction of laryngealized vowels, stress, and falling pitch in Mariteco Cora. In R. Bennett, R. Dockum, E. Gasser, D. Goldenberg, R. Kasak, & P. Patterson (Eds.), *Proceedings of the Workshop on the Sound Systems of Mexico and Central America* New Haven.
- Kirchner, R. & Varelas, E. (2002). A cue-based approach to the phonotactics of Upper Necaxa Totonac. In *7th Workshop on Structure and Constituency in the Languages of the Americas*.
- Kung, S. S. (2007). *A Descriptive Grammar of Huehuetla Tepehua*. PhD thesis, University of Texas at Austin.
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, 82(13), 1–26.

- Ladefoged, P. (1971). *Preliminaries to Linguistic Phonetics*. Chicago: University of Chicago.
- Lam, Y. (2012). Oportunidad, ideología y la pérdida del totonaco del río Necaxa [Opportunity, ideology and the loss of Upper Necaxa Totonac]. In P. Levy & D. Beck (Eds.), *Las lenguas totonacas y tepehuas: Textos y otros materiales para su estudio [The Totonac and Tepehua languages: Texts and other reference materials]* (pp. 519–543). Mexico City, Mexico: Universidad Nacional Autónoma de México.
- Lenth, R. V. (2016). Least-squares means: The R package lsmeans. *Journal of Statistical Software*, 69(1), 1–33.
- Levy, P. (1987). *Fonología del totonaco de Papantla, Veracruz*. Mexico City, Mexico: Instituto de Investigaciones Filológicas, Universidad Nacional Autónoma de México.
- Levy, P. (2015). La fonología prosódica del totonaco de Coatepec: Los textos totonacos de N. A. McQuown (1938-1940). In *Memorias del VII Congreso de Idiomas Indígenas de Latinoamérica, 29–31 de octubre de 2015, Universidad de Texas en Austin*.
- Levy, P. & Beck, D., Eds. (2012). *Las lenguas totonacas y tepehuas: Textos y otros materiales para su estudio [The Totonac and Tepehua languages: Texts and other reference materials]*. Mexico City, Mexico: Universidad Nacional Autónoma de México.
- MacKay, C. J. (1994). A Sketch of Misantra Totonac Phonology. *International Journal of American Linguistics*, 60(4), 369–419.
- MacKay, C. J. & Trechsel, F. R. (2011). Relaciones internas de las lenguas totonaco-tepehuas. In *Memorias del V Congreso de Idiomas Indígenas de Latinoamérica, 6-8 de octubre de 2011, Universidad de Texas en Austin* (pp. 2–26).
- MacKay, C. J. & Trechsel, F. R. (2013). A Sketch of Pisaflores Tepehua Phonology. *International journal of American Linguistics*, 79(2), 189–218.
- Mackay, C. J. & Trechsel, F. R. (2015). Totonac-Tepehua Genetic Relationships. *Amerindia*, 37(2), 121–158.
- Mackay, C. J. & Trechsel, F. R. (2018). An alternative reconstructino of Proto-Totonac-Tepehua. *International Journal of American Linguistics*, 84(1), 51–92.
- Maddieson, I. (1984). *Patterns of Sounds*. Cambridge, United Kingdom: Cambridge University Press.
- Maddieson, I. (1998). Why make life hard? - resolutions to problems of rare and difficult sounds types. In *Proceedings of the Twenty-Fourth Annual Meeting of the Berkeley Linguistics Society: General Session and Parasession on Phonetics and Phonological Universals* (pp. 367–380).
- Maddieson, I. (2001). Good timing : Place-dependent voice onset time in ejective stops. *Eurospeech*, (pp. 1–4).
- Maddieson, I. (2013). Glottalized Consonants. In M. S. Dryer & M. Haspelmath (Eds.), *World Atlas of Linguistic Structures*. Leipzig: Max Planck Institute for Evolutionary Anthropology.

- Maddieson, I. & Precoda, K. (1990). Updating UPSID. *UCLA Working Papers in Phonetics*.
- Maddieson, I., Smith, C. L., & Bessell, N. J. (2001). Aspects of the phonetics of Tlingit. *Anthropological Linguistics*, 43(2), 135–176.
- Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., & Bates, D. (2017). Balancing Type I error and power in linear mixed models. *Journal of Memory and Language*, 94, 305–315.
- McFarland, T. A. (2009). *The phonology and morphology of Filomeno Mata Totonac*. PhD thesis.
- McGraw, R. (2009). *Language Attitudes and Opportunities for Speaking a Minority Language What Lies Ahead for Ozelonacaxtla Totonac?* PhD thesis.
- McQuown, N. (1940). *A Grammar of the Totonac Language*. PhD thesis, Yale University.
- McQuown, N. A. (1990). *Grámatica de la lengua totonaca (Coatepec, Sierra Norte de Puebla)*. México: UNAM.
- Moran, S., McCloy, D., & Wright, R., Eds. (2014). *PHOIBLE Online*. Leipzig: Max Planck Institute for Evolutionary Anthropology.
- Ohala, J. J. (1997). Emergent Stops. In *Proc. 4th Seoul International Conf. on Linguistics [SICOL]*, number 2 (pp. 84–91).: Linguistic Society of Korea, Seoul.
- Peterson, G. E. (1961). Parameters of vowel quality. *Journal of Speech and Hearing Research*, 4, 10–29.
- Pickett, V. B., Villalobos, M. V., & Marlett, S. a. (2010). Isthmus (Juchitán) Zapotec. *Journal of the International Phonetic Association*, 40(03), 365–372.
- Puderbaugh, R. (2015). Contextual Effects on the Duration of Ejective Fricatives in Upper Necaxa Totonac. *Proceedings of the 18th International Congress of Phonetic Sciences (ICPhS 2015)*.
- Puderbaugh, R. (2019). Phonetics and phonotactics of vowel laryngealization in upper necaxa totonac. *Proceedings of the 19th International Congress of Phonetic Sciences (ICPhS 2019)*.
- Quick, P. (2003). *A grammar of the Pendau language of central Sulawesi, Indonesia*. PhD thesis, Australian National University.
- R Core Team (2017). R: A language and environment for statistical computing.
- Repp, B. H. (1984). Closure duration and release burst amplitude cues to stop consonant manner and place of articulation. *Language and Speech*, 27(3), 245–254.
- Ridouane, R., Gendrot, C., & Khatiwada, R. (2015). Mehri ejective fricatives: an acoustic study. In The Scottish Consortium for ICPhS 2015 (Ed.), *Proceedings of the 18th International Congress of Phonetic Sciences* (pp. Paper number 995, 1–5). Glasgow, UK: University of Glasgow.
- Shosted, R. K. & Rose, S. (2011). Affricating ejective fricatives: The case of Tigrinya. *Journal of the International Phonetic Association*, 41(1), 41–65.

- Shue, Y.-l., Keating, P., Vicenik, C., & Yu, K. (2011). Voicesauce: A program for voice analysis. In *ICPhS XVII*, number August (pp. 1846–1849).
- Silverman, D., Blankenship, B., Kirk, P., & Ladefoged, P. (1995). Phonetic structures in Jalapa Mazatec. *Anthropological Linguistics*, 37(1), 70–88.
- Slifka, J. (2006). Some physiological correlates to regular and irregular phonation at the end of an utterance. *Journal of Voice : Official Journal of the Voice Foundation*, 20(2), 171–86.
- Traunmüller, H. (1981). Perceptual dimension of openness in vowels. *The Journal of the Acoustical Society of America*, 69(5), 1465–1475.
- Trechsel, F. R. & Faber, A. (1992). Acoustic properties of plain and laryngealized vowels in the Misantra dialect of Totonac. Ms.
- Vicenik, C. (2009). Praat voicesauce imitator.
- Watters, J. K. (1980). Aspects of Tlachichilco Tepehua (Totonacan) Phonology. *Summer Institute of Linguistics. SIL-Mexico Workpapers*, 4, 85–129.
- Watters, J. K. (1988). *Topics in Tepehua Grammar*. PhD thesis.
- Watters, J. K. (2010). Phrase-final glottals in Tlachichilco Tepehua. In *Annual Meeting of the Society for the Study of the Indigenous Languages of the Americas, Baltimore, Maryland, January 2010* (pp. 1–17).
- Whalen, D. H. (2016). Acoustic realization of a distinctive, frequent glottal stop: The Arapaho example. *The Journal of the Acoustical Society of America*, 139(4), 2212–2213.
- Wittenburg, P., Brugman, H., Russel, A., Klassmann, A., & Sloetjes, H. (2006). ELAN: a Professional Framework for Multimodality Research. In *Proceedings of LREC 2006, Fifth International Conference on Language Resources and Evaluation*.
- Yates, F. (1934). Contingency Tables Involving Small Numbers and the χ^2 Test. *Supplement to the Journal of the Royal Statistical Society*, 1(2), 217–235.

Appendix A

Supplement to Chapter 2

Wordlist The following wordlist was compiled from the *Upper Necaxa Totonac Dictionary* (Beck, 2011b), its derivative practical dictionary *Nuevo diccionario del idioma totonaco del Río Necaxa* (Beck, 2011a), and a paper on UNT phonotactics by Kirchner & Varelas (2002). IPA transcriptions are derived from the orthographic representations in the *Dictionary*, shown in the second column here (UNT), and intended to indicate phonemic contrast. Syllabification is based on simple CV(C) construction rules with ejective fricatives appearing in syllable onsets only.

Table A.1: UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
ɑː.ˈtuːs	aːˈtúːs	in awhile	simplex
ɑ.ʔa.ta.puː.ˈʃʔaːja	aˈhatapuːxˈáːyaʔ	soot from cooking fires built up on spiderwebs on the roof of a house	ejective
ɑʔ.ˈʔoːma	aˈhɫhˈóːmaʔ	water and lime mixture for making nixcomel	ejective
ɑʔ.sˈa.wi.ˈni	aˈhsˈawiníʔ	trickster, deceiver	ejective
a.ka.kuː.ˈluːkɫ	akakuːlúːkɫ	scorpion	cluster
ɑː.tuː.tʃiː.ˈjeːtɫ, ɑː.tuː.tʃiː.ˈjeːkɫ	aːˈtuːˈchiːyéːtɫh, aːˈtuːˈchiːyéːkɫh	mint	affricate, cluster
tʃɑː.ˈʔoːʃɑ	chaːˈhóːxˈaʔ	treebark	affricate, ejective
tʃɑ.ˈʔaːn	chaˈháːn	be washed roof beam	affricate

Table A.1: Complete UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
tʃa.'na:	chaná:	sweat (pot, bottle), be beaded with condensation	affricate
tʃi.li.'likʃ	chili'lí'kx	calcite (calcium carbonate crystals), used for lime	affricate
tʃipʃ	chi'px	dense	affricate
tʃiʃ.'ku	chi'xkú'	man	affricate
tʃu.'tʃoʔʃ	chu'chó'hx	banana blossom	affricate
ʔe:tʃi.'wiʃ	he:chiwíx	Ocomantla (village)	affricate, simplex
ʔe:.'ʔa:ʃ	he:há:'x	its shell (turtle, armadillo, snail)	simplex
ʔe:mi.'ja:ʃ	he:miyá:lh	be standing facing the other way	simplex
ʔe:ta.wa.'ka:ʃ	he:tawaká'lh	1) be on the back of sth 2) have sth on one's back	simplex
ʔe:.'ʔo:ʃ'a	helhhó:x'a'	one's lips	simplex
ʔe:ʃ.ku.'tan	he:lhku'tán	smell of sweat	cluster
ʔe:ta.ʃ.'tu	helhtaxtú	fade (color)	cluster
ʔen.ʔa.li:.'s'o.li	henhali:s'óli'	1) Northern Tamandu 2) elephant	
'ʔo.ʃ'a	hó'x'a'	its skin, its hide	ejective
ʔo.ʃ'a.ʔa:.'ʔwa:ʔ	ho'x'a'ha:lhwa:'h	eggs with soft, flexible or leathery shells (lizards, turtles, etc.	ejective
ʔo.'ʔa:wa	holh'á:wa'	leathery, stiff, not flexible	ejective
i:.'ti'n	i'lh'tí'n	1) faeces; 2) eggs of flies, mosquitoes, e	cluster
i:ʃ.ʔen.i:ʃ.ma.'kan	i'xhe:n i'xmakán	back of one's hand	cluster
ka:s'e.'wi.wi	ka:'s'ewíwi'	cool (climate)	ejective
ka:ʃ'a.'ʔa:ʔ	ka:'x'a'há:'h	bright (place)	ejective

Table A.1: Complete UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
kiɬ.ʔo'.fʔ̥	kilhhó'x'a'	one's lips	cluster, ejective
kiɬ.p̄an.ɬ̄u.lu	kilhpa'nlhú'lu'	1) jowly, with swollen cheeks; 2) toothless	cluster, simplex
laʔ.ʔ'a:	la'hllh'á:	cut sth into fine strips (meat)	ejective
laʔ.ʔ'o.n̄i	la'hllh'óni'	flames	ejective
la.ka.man.sa:.'nas	lakamansa:nás	a girl who blushes (term of endearment)	simplex
li:.'ʔ̄a:n	li:lh'á:'n	plough	
li:.'ʔ̄o.'.lu:	li:lh'olú:	snore because of something	
lis.ka.'lah.w̄a	li:skalájwa'	danger	
li:f.p̄a.'tan	li:xpa'tán	pestle of a molcajete	
lu.'l̄oʔf	luló'hx	1) stringy endocarpal material that contains seeds of squash or melons; 2) rotten material inside of an old gourd	
ɬa.'pa	lhapá	cover sth (with cloth, sheet, mulch, etc.	
ɬapɬ	lhaplh	completely wet	
ɬe.ʔe:.'nin	lhe'he:nín	cut sugarcane	
ɬka:k.'nan	lhka:knán	be hot (weather)	
ɬpa.'ma.m̄a	lhpa'máma'	cuddly, soft and furry	
'ɬkah.w̄a	lhkájwa'	1) disgusting; 2) mean, aggressive, vulgar; 3) immoral	
ɬka.'wat	lhkawát	dry, stiff, hard	
ɬpa.'paʔ	lhpapá'h	wrinkled, old and bent out of shape	

Table A.1: Complete UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
ʈt̪a.ʔ̪ah	lh̪ta'há'j	1) thick and flat; 2) lying flattened or face down; 3) flat up against a surface; 4) having a single-piece roof (house)	
ʈt̪a.'k̪a.l̪a	lhtaká'la'	board	
ʈt̪a.'yat	lhtayát	looking out of the corner of one's eye	
ʈ'a:.'n̪a	lh'a:'ná'	1) (Pt. pu:tayán) fish net; 2) material for making nets	ejective
ʈ'e.'ʔe:l̪i	lh'e'hé:'li'	unfinished, rough, pock-marked	ejective
ʈ'e.'li	lh'elí	wheeze heavily	ejective
ʈ'j̪.wi.'li:	lh'i'wilí:	1) flatten sth out by pressing down on it; 2) set down sth heavy	ejective
ʈ'o:.'ma.w̪a	lh'o:máwa'	half-cooked	
ʈ'o.'ʔo.l̪u	lh'o'hólu'	pocked, rough, bumpy	
ʈ'o.l̪u	lh'ólu'	unfinished, rough, pock-marked	
ma:s'̪a.ʔ̪a:'ni:	ma:s'a'ha:'ní:	make sby sweat	
ma:s'̪a.ta:'nan	ma:s'a'ta:nán	raise children	
ma:s'̪eʔ.'ni:	ma:s'e'hní:	1) provide shade for sth, protect sth from the sun; 2) provide shelter for sth from the rain	
ma:s'̪o.'ʔo:	ma:s'o'hó:	salt sth	
ma:s.k̪a:'ki:	ma:ska:kí:	dry sth	
ma:.'ʃ̪a.ʔe:'nin	ma:x'a'he:nín	1) be illuminated; 2) shine; 3) light up, glow (of fireflies, glow worms); 4) be reflective; 5) be clear	

Table A.1: Complete UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
m̩aʔ.ʼʃu:	ma'hxú:	peel a thick slice of skin off sth (banana, mango, avocado)	
pa:ʃ.ʼkat ka.ʼtʃi:ʔ	pa:xkát ka'tzí:lh	thank you	
pi:.'s'a:m	pi:s'á:m	splinter	
p̩i.pé'ʔs	pi'pé'hs	its scale (eg fish -rp)	
piʃ.ʼʔa.ʔa	pixhá'lha'	large (bunch or bouquet)	
piʃ.ʼpam.wa	pixpámwa'	having long hair, having puffy hair	
poʔʔ	po'hlh	1) dark, lightless; 2) having clouded vision, seeing spots before one's eyes, feeling faint; 3) feeling fed up, irritated or lethargic	
pu:ʔe.ʼʔe	pu:lhe'hé	count sth	
'pu:ʃ'a	pú:x'a'	stream	
puks	puks	overcast, gloomy	
sa.'sa	sa'sá	turn grey (hair)	
sa.'lun	salún	hoe	
'seʔ.s̩i	sé'hsi'	sweet	
'skat.l̩i	ska'tli'	1) learn sth; 2) learn to do sth	
ska.'ma.m̩a	skamáma'	quiet, serious, staid	
slaʔ.s'ʔ.ʼʔoj.wa	sla'hs'o'hó'jwa'	a bit salty	
spaʔ.ta.'ti:	spa'lhtatí:	caress sby to help them sleep	
spa.'ma.m̩a	spamáma'	velvety	
st̩a.h.'ni	sta'jni'	1) wet; 2) bloody	
sta.'wa:	stawá:	weave sth out of roots, reeds or cords (net, basket, etc.)	

Table A.1: Complete UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
s'a.ʔa:.'na	s'a'ha:'ná'	sweat	
's'a.ta	s'á'ta'	1) child, baby, young of any animal; 2) doll; 3) (ni) one's infant	
s'ał	s'alh	loosely, not well-placed	
's'ał.wa	s'á'lhwa'	1) slow of movement or thought (of people and animals); 2) calm; 3) serious, quiet	
s'e:.'ʔe:	s'e:'hé:	etch sth, cut a groove in sth	
's'eʔ.ti	s'é'hti'	unidentified vine with solid, heart-shaped leaves, used by shaman to wrap chicks in before burying them alive	
s'e.ti.'naʔ	s'etiná'h	Chigger, Harvest Mite	
s'o.ʔa.'na	s'o'haná'	person who hugs	
s'oʔ.ta.'maʔ	s'ohtamá'h	unidentified plant that ejects its seeds when they are mature	
s'o.li.'ni	s'oliní'	whistler, musician	
ʃ'a:.'na	x'a:ná'	corn-shucker	
ʃ'a.ʔa:ʔ	x'a'há:'h	1) daylight; 2) moonlight; 3) (ni) its light, its shine	
ʃ'a.'tan.ʔa	x'a'tánha'	reddish, color of ripe fruits such as guavas	
ʃ'e.'ʔe.li	x'e'hé'li'	rough, pock-marked	
ʃ'e.'tim	x'etím	seeded and de-veined chili	
ʃ'o:.'lu.lu	x'o:lúlu'	unidentified species of large green lizard	
ʃ'op.'li:	x'o'plí:	slim down, get thin	

Table A.1: Complete UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
ʃ'o.nun.'ʔo:	x'onunhó:'	unidentified blood-sucking arthropod that lives in houses, lays eggs in clothing	
ʃa:.'ʔan	xa:'hán	take a steam bath	
'ʃa:.'ʃli	xá:xli'	tepache, a drink made from fruit juices and fermented pineapple rinds	
ʃas.tan.ku	xastánku'	1) youngest sibling; 2) socially inferior person	
ʃkaḥ	xka'j	pineapple	
ʃka.'nan	xkanán	bite, sting	
ʃli:ma.'ʔa:s	xli:ma'há:'s	a long time ago, at a definite or experienced time in the past [a long time (Kirchner)]	
ʃpa.'ta	xpa'tá	grind something with a molcajete	
ʃpi.pi.'le:ʔ	xpi'pi'lé:h	butterfly	
ʃta.'pu	xta'pú	1) dam sth (water) to make a pool; 2) dredge sth out, remove stones from sth (stream) to make it deeper; 3) trap or fish or shrimp by creating a pool on the edge of sth (river) and letting it dry up	
ʃta:lak.'ʃtim	xta:lakxtím	the same, evenly	
ʃu:.'wił	xu:wíłh	dried minnows	
ta:la.'ʔa.s'a.'wi	ta:'la'has'awí	1) win sth away from sby; 2) win a thing that sby doesn't want to give up using sth	
ta:lak.s'a.'tan	ta:'laks'a'tán	infant of one's own age	
ta:sa.'nin	ta:'sa'nín	1) gossip; 2) story, fiction	

Table A.1: Complete UNT wordlist. See Chapter 5 for details on conditions.

IPA	UNT	English	Condition(s)
t̩aːʃ'aː	taːx'á:	shuck sth (corn) with sby	
ta.ʔeʃ'a.ma:n	tahelh'amá:n	joke	
ta.'laː.ʃ'a	talá:x'a'	unidentified tree with a long, wide seedpod	
tam.pu.'ɬu:	tampu'lhú:	pull sth up by the roots	
tan.ʔeː.ʃ'a.'ʔa:	tanhe:x'a'há:	begin to lighten on the horizon at dawn	
ta.pi.s'aː.naː.'paʔ.ɬma	tapi:s'aː.naː.'pá'hlhma'	unidentified species of plant, used to treat wounds	
ta.s'a.'wi	tas'awí	1) lose, be defeated (fight, bet, game); 2) break a promise, not do what one says	
ta.saː.ta.'nu:n	tasa:tanú:n	stuck, fixed in place	
ta.'ʃ'a:n	tax'á:n	shucked (corn)	
ta.ʃ'a.'ʔe:t	tax'a'hé:t	1) daylight, sunlight; 2) aurora; 3) (ni) its light, its inherent brightness (light source), its sparkle	
ta.ʃa.'ʔa	taxa'há	scratch oneself	
te.he:ʃ.'ka:n	teje:xká:n	water running in the street	
tsa.'lah	tzalá'j	brittle, fragile, thin (stick)	
tsɪn.tziː.'paʔ.ɬ.tʃa	tzi'ntzi:pá'hlhcha'	cuatomate, small, tomato-like fruit (possible <i>Solanum glaucescens</i>)	
tu:s.'puɬ	tu:spúlh	one's toes	
wah.taʃ.tu.'tʃa	wajtaxtuchá	1) leave, get out; 2) turn out; 3) come up (sun, moon)	

Appendix B

Supplement to Chapter 3

Table B.1: Segment ID grid by which segments and collocates were coded for analysis

	a	e	i	o	u	lary	stress	long	fric	stop	nas	approx	vowel	alv	postalv	lat	velar	bilab	seg	
'a:	T	F	F	F	F	T	T	T	F	F	F	F	T	F	F	F	F	F	F	T
'e:	F	T	F	F	F	T	T	T	F	F	F	F	T	F	F	F	F	F	F	T
'i:	F	F	T	F	F	T	T	T	F	F	F	F	T	F	F	F	F	F	F	T
'o:	F	F	F	T	F	T	T	T	F	F	F	F	T	F	F	F	F	F	F	T
'u:	F	F	F	F	T	T	T	T	F	F	F	F	T	F	F	F	F	F	F	T
a:	T	F	F	F	F	T	F	T	F	F	F	F	T	F	F	F	F	F	F	T
e:	F	T	F	F	F	T	F	T	F	F	F	F	T	F	F	F	F	F	F	T
i:	F	F	T	F	F	T	F	T	F	F	F	F	T	F	F	F	F	F	F	T
o:	F	F	F	T	F	T	F	T	F	F	F	F	T	F	F	F	F	F	F	T
u:	F	F	F	F	T	T	F	T	F	F	F	F	T	F	F	F	F	F	F	T
'a:	T	F	F	F	F	T	T	F	F	F	F	F	T	F	F	F	F	F	F	T
'e:	F	T	F	F	F	T	T	F	F	F	F	F	T	F	F	F	F	F	F	T
'i:	F	F	T	F	F	T	T	F	F	F	F	F	T	F	F	F	F	F	F	T
'o:	F	F	F	T	F	T	T	F	F	F	F	F	T	F	F	F	F	F	F	T

Table B.1: Segment ID grid by which segments and collocates were coded for analysis

	a	e	i	o	u	lary	stress	long	fric	stop	nas	approx	vowel	alv	postalv	lat	velar	bilab	seg
'u	F	F	F	F	T	T	T	F	F	F	F	F	T	F	F	F	F	F	T
a	T	F	F	F	F	T	F	F	F	F	F	F	T	F	F	F	F	F	T
e	F	T	F	F	F	T	F	F	F	F	F	F	T	F	F	F	F	F	T
i	F	F	T	F	F	T	F	F	F	F	F	F	T	F	F	F	F	F	T
o	F	F	F	T	F	T	F	F	F	F	F	F	T	F	F	F	F	F	T
u	F	F	F	F	T	T	F	F	F	F	F	F	T	F	F	F	F	F	T
ʔ	F	F	F	F	F	T	F	F	T	F	F	F	F	F	F	T	F	F	T
s'	F	F	F	F	F	T	F	F	T	F	F	F	F	T	F	F	F	F	T
ʃ	F	F	F	F	F	T	F	F	T	F	F	F	F	F	T	F	F	F	T
ʔ	F	F	F	F	F	T	F	F	F	T	F	F	F	F	F	F	F	F	T
'a	T	F	F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	T
'a:	T	F	F	F	F	F	T	T	F	F	F	F	T	F	F	F	F	F	T
'e:	F	T	F	F	F	F	T	T	F	F	F	F	T	F	F	F	F	F	T
'i:	F	F	T	F	F	F	T	T	F	F	F	F	T	F	F	F	F	F	T
'o:	F	F	F	T	F	F	T	T	F	F	F	F	T	F	F	F	F	F	T
'u:	F	F	F	F	T	F	T	T	F	F	F	F	T	F	F	F	F	F	T
a:	T	F	F	F	F	F	F	T	F	F	F	F	T	F	F	F	F	F	T
e:	F	T	F	F	F	F	F	T	F	F	F	F	T	F	F	F	F	F	T
i:	F	F	T	F	F	F	F	T	F	F	F	F	T	F	F	F	F	F	T
o:	F	F	F	T	F	F	F	T	F	F	F	F	T	F	F	F	F	F	T
u:	F	F	F	F	T	F	F	T	F	F	F	F	T	F	F	F	F	F	T
'e	F	T	F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	T
'i	F	F	T	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	T
'o	F	F	F	T	F	F	T	F	F	F	F	F	T	F	F	F	F	F	T
'u	F	F	F	F	T	F	T	F	F	F	F	F	T	F	F	F	F	F	T
a	T	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T
a	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T
i	F	F	T	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T

Table B.1: Segment ID grid by which segments and collocates were coded for analysis

	a	e	i	o	u	lary	stress	long	fric	stop	nas	approx	vowel	alv	postalv	lat	velar	bilab	seg
o	F	F	F	T	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T
u	F	F	F	F	T	F	F	F	F	F	F	F	T	F	F	F	F	F	T
j	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	T
l	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F	F	T
r	F	F	F	F	F	F	F	F	F	F	F	T	F	T	F	F	F	F	T
w	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T	T
b	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	F	T	T
d	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F	F	F	F	T
k	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	T	F	T
tʃ	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	T	F	F	T
m	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	T	T
n	F	F	F	F	F	F	F	F	F	F	T	F	F	T	F	F	F	F	T
ŋ	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T	F	T
p	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	F	T	T
s	F	F	F	F	F	F	F	F	T	F	F	F	F	T	F	F	F	F	T
ʃ	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T	F	F	F	T
t	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F	F	F	F	T
ts	F	F	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	T
tʃ	F	F	F	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T
x	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	T	F	T
#	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F

Table B.2: Chi-squared tests of preceding contexts for stops, fricatives, and vowels individually, and all three segment classes together. Percentages are calculated from the matrix total. Counts in bold contributed most to the Chi-squared value. Compare to 3.8.

		Preceding Context		Total	χ^2	df	p
		Non-laryng	Laryng				
Segment Class							
Stops	oral	6833 (54.99%)	1882 (15.14%)	8715	3808.9	1	< 0.0001
	glottal	718 (5.78%)	2994 (24.09%)	3712			
	Total	7551	4876	12427			
Fricatives	pulmonic	4645 (72.15%)	1793 (27.85%)	6438	0.03	1	0.87
	ejective	313 (4.86%)	123 (1.91%)	436			
	Total	4958	1916	6874			
Vowels	-laryng	17587 (60.72%)	2125 (7.34%)	19712	52.57	1	< 0.0001
	+laryng	8509 (29.38%)	745 (2.57%)	9254			
	Total	26096	2870	28966			
All	-laryng	46155 (67.12%)	9932 (14.44%)	56087	1049.3	1	< 0.0001
	+laryng	8815 (12.82%)	3862 (5.62%)	12677			
	Total	54970	13794	68764			

Table B.3: Chi-squared tests of following contexts for stops, fricatives, and vowels individually, and all three segment classes together. Compare to Table 3.9.

		Following Context		Total	χ^2	df	p
		Non-laryng	Laryng				
Segment class							
Stops	oral	8690 (55.33%)	2910 (18.53%)	11600	158.77	1	<0.0001
	glottal	3468 (22.08%)	637 (4.06%)	4105			
	Total	12158	3547	15705			
Fricatives	pulmonic	5192 (82.52%)	664 (10.55%)	5856	373.94	1	<0.0001
	ejective	243 (3.86%)	193 (3.07%)	436			
	Total	5435	857	6292			
Vowels	-laryng	18958 (65.45%)	754 (2.60%)	19712	4641.8	1	<0.0001
	+laryng	6222 (21.48%)	3032 (10.47%)	9254			
	Total	25180	3786	28966			
All	-laryng	53804 (69.40%)	9933 (12.81%)	54797	1194.3	1	<0.0001
	+laryng	9933 (12.81%)	3862 (4.8%)	13795			
	Total	63737	13795	77532			

Table B.4: Chi-squared tests of independence between laryngealization in consonants (stops and fricatives only) and preceding vowels. Percentages are calculated based on the total number of observations in each 2 x 2 matrix.

		Preceding Context			χ^2	df	p
		Non-laryng	Laryng				
Segment class				Total			
Stops	oral	3889 (43.71%)	1609 (18.08 %)	5498			
	glottal	406 (4.56%)	2994 (33.65%)	3400			
	Total	4295	4603	8898	2908.3	1	<0.0001
Fricatives	pulmonic	2562 (76.52%)	619 (18.48%)	3181			
	ejective	138 (4.12%)	29 (0.87%)	167			
	Total	2700	648	3348	0.45	1	0.50

Table B.5: Chi-squared tests of independence between laryngealization in consonants (stops and fricatives only) and following vowels. Percentages are calculated based on the total number of observations in each 2 x 2 matrix.

		Following Context			χ^2	df	p
		Non-laryng	Laryng				
Segment class				Total			
Stops	oral	6800 (56.19%)	2882 (23.82%)	9682			
	glottal	1876 (15.15%)	543 (4.49%)	2419			
	Total	8676	3425	12101	51.1	1	<0.0001
Fricatives	pulmonic	963 (47.23%)	640 (31.38%)	1603			
	ejective	243 (11.92%)	193 (9.47%)	436			
	Total	1206	833	2039	2.67	1	0.10

Appendix C

Supplement to Chapter 4

The models presented here were built with data from Time points 1 and 3. Due to multiple interactions in the data, subsequent analyses in Chapter 4 subdivided the data into smaller groups based on time point, simplifying the models and allowing for more straightforward interpretation of the effects and interactions, where present. Models of the complete data sets for each measure and CV/VC condition are presented here.

The best linear mixed effects regression model of H1-H2 included random intercepts for Speaker, Word, and Vowel Quality, and random slopes by for Vowel Laryngealization, Consonant Laryngealization, and Stress by Speaker. Main effects of Vowel Laryngealization, Consonant Laryngealization, Consonant Manner, Stress, and Time were included in the model, resulting in significant three-way interactions between all fixed effects terms except for stress. Stress was excluded from interactions due to missing data in some conditions. The model output summary

Table C.1: Summary of trimmed model of H1-H2 values for vowels following consonants (CV condition.) Highly significant three-way interactions warranted further analyses with time split into separate models.

coef	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	-1.0463	1.9509	5.7196	-0.5363	0.6119
vларыngyes	1.4120	0.5495	24.4747	2.5698	0.0167 *
clарыngyes	1.4943	0.5705	12.6677	2.6191	0.0216 *
time3	2.7102	0.4255	4912.4777	6.3703	0.0000 ***
cmannerstop	-0.4646	0.3827	4036.4073	-1.2140	0.2248
stressunstressed	-0.0556	0.4614	3.2300	-0.1205	0.9112
vларыngyes:clарыngyes	-1.1580	0.4489	4018.9641	-2.5795	0.0099 **
vларыngyes:time3	-5.4144	0.5311	4913.2138	-10.1942	0.0000 ***
clарыngyes:time3	-2.0824	0.4762	4912.5359	-4.3725	0.0000 ***
vларыngyes:cmannerstop	-1.1137	0.4509	4428.0903	-2.4699	0.0136 *
time3:cmannerstop	-0.4513	0.4496	4912.4512	-1.0038	0.3155
clарыngyes:cmannerstop	1.4468	0.4592	3895.0249	3.1506	0.0016 **
vларыngyes:clарыngyes:time3	2.2403	0.5131	4912.5038	4.3661	0.0000 ***
vларыngyes:time3:cmannerstop	2.6963	0.5266	4913.5071	5.1198	0.0000 ***
clарыngyes:time3:cmannerstop	2.0125	0.5240	4913.0020	3.8402	0.0001 ***

Table C.2: Summary of trimmed model of H1-H2 values for vowels preceding consonants (VC condition.) Significant three- and four-way interactions warranted further analyses with time split into separate models.

coef	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	-1.4921	1.8841	4.2065	-0.7919	0.4707
vларыngyes	1.1324	0.4947	1442.4843	2.2891	0.0222 *
clларыngyes	0.6192	0.4865	17.8723	1.2728	0.2194
cmannerstop	-0.1636	0.3410	2148.0665	-0.4798	0.6314
time3	2.8181	0.2766	3529.3637	10.1881	0.0000 ***
stressunstressed	0.5192	0.2283	11.3347	2.2742	0.0433 *
vларыngyes:clларыngyes	-2.1791	0.7583	1713.2899	-2.8737	0.0041 **
vларыngyes:cmannerstop	1.1599	0.6489	1481.9870	1.7875	0.0741
clларыngyes:cmannerstop	-2.5461	0.6260	2847.3002	-4.0671	0.0000 ***
vларыngyes:time3	-1.4471	0.5515	3529.8918	-2.6239	0.0087 **
clларыngyes:time3	0.8364	0.4312	3531.2087	1.9396	0.0525
cmannerstop:time3	-2.1404	0.3885	3529.5896	-5.5101	0.0000 ***
vларыngyes:clларыngyes:cmannerstop	1.6690	0.9839	2140.3561	1.6963	0.0900
vларыngyes:clларыngyes:time3	1.9340	0.8579	3531.6078	2.2545	0.0242 *
vларыngyes:cmannerstop:time3	-0.2100	0.7197	3530.4575	-0.2918	0.7704
clларыngyes:cmannerstop:time3	-1.0639	0.7659	3530.6530	-1.3890	0.1649
vларыngyes:clларыngyes:cmannerstop:time3	-3.7098	1.1579	3531.3639	-3.2040	0.0014 **