Natural classes in cooccurrence constraints[*]

Gillian Gallagher, New York University

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Abstract

Natural classes are typically defined by some shared phonetic property, though the segments within such a class may differ substantially along other dimensions. This paper explores two such classes in Quechua: the class of [spread glottis] segments, aspirates and [h], and the class of [constricted glottis] segments, ejectives and [ʔ]. While aspirates and ejectives pattern with their glottal counterparts in the cooccurrence phonotactics of the language, nonce word tasks only find weak evidence of these natural classes. Instead, there is evidence for strong phonotactic restrictions on aspirates and ejectives to the exclusion of their glottal counterparts. It is proposed that the preference for classes of laryngeally marked stops is phonetically based, deriving from the salience of the phonetic properties unique to stops.

1 Introduction

Phonological generalizations are stated over features, which pick out the natural class of segments relevant to the phonological pattern. Typically, features reference some phonetic property that is shared by a set of segments (Jakobson Fant & Halle 1952; Chomsky & Halle 1968), and may emerge as a result of the phonologically active classes in a given language (Blevins 2004; Mielke 2008). Within a phonetically defined and phonologically active natural class, however, substantial phonetic diversity may also be found. A natural class based on place of articulation, for example, may include obstruents and sonorants, voiced and voiceless sounds, nasal and non-nasal sounds.

This paper explores the relationship between phonological patterning and phonetic properties by investigating two standardly assumed natural classes in Quechua: [spread glottis] ([sg]) and [constricted glottis] ([cg]) (Parker & Weber 1996; MacEachern 1999). The two laryngeal features [sg] and [cg] refer to articulatory properties, and thus are phonetically definable, but in Quechua they group together segments that are otherwise quite phonetically disparate: aspirated stops and [h] for [sg] and ejective stops and [ʔ] for [cg]. The phonological patterns of Quechua provide support for the [sg] and [cg] classes, in the form of phonotactic restrictions on these natural classes. Other phonotactic restrictions in the language, however, target ejective and aspirate stops to the exclusion of their glottal counterparts. The experiments here suggest that speakers have learned only relatively weak phonotactic restrictions on [sg] and [cg]; phonotactic restrictions on ejective and aspirated stops, however, have a strong effect on speakers behavior on multiple tasks. The proposed explanation for the preference for restrictions on ejectives and aspirates is that the phonetic properties that distinguish ejectives and aspirates from their glottal counterparts are more salient than the properties that group these segments together, and that phonological grammars favor constraints on more salient features.

The broader context for this work is the connection between featural representations and the formal properties of a grammatical statement. Much recent work in phonological learning has evaluated the role of naturalness and structural complexity in how patterns are learned by speakers, both in artificial grammar learning experiments with adults (Moreton 2008; Moreton &

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Pater 2012; Moreton 2012) and infants (Saffran & Thiessen 2003), and in experiments probing what speakers' have learned about their native language (Hayes et al. 2009; Hayes & White 2013). In these studies, more natural patterns and less complex patterns are found to be learned more easily. The definitions of naturalness and complexity, however, are based over features or assume particular featural representations. Similarly, the inductive learner proposed in Hayes & Wilson (2008) uses the featural content of constraints to define both complexity and generality, concepts that are critical to which constraints end up in the grammar. As documented at length in Flemming (1995), as well as other work in phonetically based phonology (Hayes et al. 2004), many phonological patterns that appear complex when represented with standard distinctive features appear quite simple once the correct phonetic properties of the interacting sounds are taken into consideration.

The paper begins by laying out the Quechua data and analytic issues in Section 2. Section 3 presents an acoustic study evaluating the evidence for initial glottal stop. Section 4 addresses phonological representations by probing speakers' behavior on two nonce word tasks, a repetition task and a forced choice judgment task. Section 5 discusses the results and Section 6 concludes.

2 Quechua phonotactics

This paper presents data from speakers of Quechua from the Cochabamba department of Bolivia. The impressionistic, descriptive facts are shared between other varieties of South Bolivian Quechua (the term used by Lewis et al. 2014) and many varieties of Peruvian Quechua, particularly Cusco Quechua (Adelaar with Muysken 2004), grouped together in group IIC of the Quechua language family (Torero 1964). For the rest of the paper, the language will be refered to simply as 'Quechua'.

The phonemic consonantal inventory of Quechua is given in Table 1 (Rowe 1950; Cusihuamán 1976; Bills et al. 1971). The language has a ternary laryngeal contrast between voiceless unaspirated (plain), aspirated and ejective stops (affricates consistently pattern as stops with respect to the phonology of the language), as well as the accompanying glottals [h] and [ʔ]. The phonemic status of the glottal fricative [h] is uncontroversial; the status of glottal stop [ʔ] is less clear, partially motivating the studies presented here.

	labial	dental	postalveolar	velar	uvular	glottal
plain	p	t	tʃ	k	q	
aspirate	p^h	t^h	$tʃ^h$	k^h	q^h	h
ejective	p'	t'	tʃ'	k'	q'	(ʔ)
fricative		s				
nasal	m	n	ɲ			
liquid		l ɾ	ʎ			
glide	w		j			

Table 1: Quechua consonant inventory.

Quechua has three phonemic vowels /i u a/. The high vowels /i u/ lower to [e o] preceding or following a uvular (Bills et al. 1971; Adelaar with Muysken 2004; Laime Ajacopa 2007), and this allophonic process is reflected in the transcriptions throughout the paper. Additionally, velar and uvular stops spirantize in coda position and are transcribed as [x χ].

The laryngeally marked stops and glottal consonants are subject to a range of combinatoric and distributional restrictions (Rowe 1950; Orr & Longacre 1968; Carenko 1975; Mannheim 1991; Parker & Weber 1996; MacEachern 1999; Gallagher 2011). Ejectives and aspirates occur only in roots, which are primarily $C_1V(C)C_2V$, and only in onset (pre-vocalic) position. Ejectives and aspirates may appear in C_1 of a root, or in C_2 if C_1 is not a stop, as shown in (1). Examples throughout the paper come from Laime Ajacopa (2007) or the author's fieldwork.

(1) a.	p'uɲu	'jug'	b.	p^{h}iri	'type of food'
	t'anta	'bread'		t^{h}aski	'to walk'
	tʃ'aki	'dry'		tʃ^{h}uʎa	'sleet'
	k'atʃa	'pretty'		k^{h}uska	'together'
	q'osɲi	'trash'		q^{h}ari	'man'
c.	hap'i	'to grab'	d.	ʎimp^{h}u	'clean'
	sut'i	'clear'		mut^{h}u	'curly'
	satʃ'a	'tree'		itʃ^{h}u	'hay'
	ʎank'a	'to work'		rak^{h}u	'thick'
	loq'o	'hat'		aq^{h}a	'corn beer'

Ejectives and aspirates are both prohibited from occuring in C_2 in roots where C_1 is a stop, whether C_1 is plain, ejective or aspirate. These unattested root types are shown in (2).

(2) a.	*kap'i	b.	*kap^{h}i
	*k'ap'i		*k'ap^{h}i
	*k^{h}ap'i		*k^{h}ap^{h}i

Additionally, there are restrictions between ejectives/aspirates and the glottal consonants, shown in (3) and (4). Aspirates may not occur in [h] initial roots (3c), though ejectives may (3b), and ejectives may not occur in [ʔ] initial roots (4c), though aspirates may (4b). Plain stops and other consonants may all occur in [h] and [ʔ] initial roots, as shown in (3a) and (4a).

(3)	a.	hatun	'big'	b.	hak'u	'flour'	c.	*hak^{h}u
		hampi	'to cure'		hap'i	'to grab'		*hap^{h}i
(4)	a.	ʔapi	'corn porridge'	b.	ʔaq^{h}a	'corn beer'	c.	*ʔap'i
		ʔutʃu	'hot pepper'		ʔuk^{h}u	'inside'		*ʔutʃ'u
		ʔinti	'sun'		ʔitʃ^{h}u	'hay'		*ʔint'i

Glottal stop is non-contrastive in Quechua, and only occurs in initial position. The only phonological evidence that these roots are glottal stop initial, e.g., [ʔinti] 'sun', as opposed to vowel initial, e.g., [inti], comes from the phonotactic restriction on ejectives (Parker & Weber 1996; MacEachern 1999). If roots of the type in (4) are in fact glottal stop initial, then the absence of ejectives in such roots is unsurprising phonologically, since both glottal stop and ejectives are articulated with a constricted glottis and share the feature [constricted glottis] ([cg]). The restriction on pairs of ejectives and the restriction on ejectives in glottal-stop initial words can both be accounted for under a prohibition on multiple [cg] specifications within a root (Parker & Weber 1996; MacEachern 1999; Gallagher 2011), i.e., an Obligatory Contour Principle (OCP) effect (Leben 1973; Goldsmith 1976; McCarthy 1988; Suzuki 1998). An OCP constraint on [spread glottis] ([sg]), which groups together aspirates and [h], accounts for the absence of roots with two aspirates or an [h]-aspirate pair. This analysis is shown in (5).

(5) a. OCP[cg] *k’ap’i *ʔap’i

[cg] [cg] [cg] [cg]

b. OCP[sg] *k^hap^hi *hap^hi

[sg] [sg] [sg] [sg]

If, on the other hand, there are truly vowel-initial roots, then Quechua must be described as having a phonologically arbitrary restriction against ejectives in vowel initial roots. Such a restriction would be stated as in (6), referring to a word boundary followed immediately by a vowel, and then followed non-locally by a [cg] segment.

(6) *#V…[cg]

An arbitrary restriction like that in (6) may be expected to be underlearned relative to a typologically common and phonologically natural restriction like the OCP, as has been found in recent work exploring speakers’ knowledge of natural and unnatural patterns (Hayes et al 2009; Becker et al. 2011; Becker et al. 2012; Hayes and White 2013).

The natural classes of [sg] and [cg] segments are supported by the phonotactic patterns of Quechua, but they also receive phonetic and typological support. Phonetically, segments in these classes share an articulatory property, the spreading or constriction of the vocal folds, as well as some acoustic consequences of this articulation, aspiration noise and breathiness in the case of [sg] or creaky or tense phonation in the case of [cg]. Typologically, there is support for [sg] and [cg] classes from phonotactic patterns in other languages, as discussed in MacEachern (1999) and Gallagher (2011). In Hausa (Chadic), for example, a cooccurrence restriction targets the class of [cg] segments, which consists of ejectives, implosive and [ʔ]. In Souletin Basque, the [sg] class of aspirates and [h] are restricted from cooccurring, and in Sanskrit the [sg] class of voiceless aspirates, voiced aspirates and [h] are restricted. Peruvian and Bolivian variants of Aymara also show restrictions very similar to those in Quechua. There is thus good typological evidence that a shared articulatory state of the glottis may underly the grouping of phonetically diverse sounds into a natural class. In addition to the languages just discussed, however, there are also languages that target a smaller, more phonetically uniform class of sounds with phonotactic restrictions. In Chol (Mayan), for example, ejectives are subject to cooccurrence restrictions but may cooccur freely with the implosive [ɓ] or [ʔ] (Gallagher & Coon 2009). Outside of the domain of cooccurrence restrictions, ejectives and aspirated stops have been found to pattern differently from other laryngeally marked segments in positional neutralization and cluster phonotactics (Lloret 1995; Steriade 1997; Pulleyblank & Howe 2001).

While OCP constraints on [sg] and [cg] account for some of the unattested consonant pairs in Quechua roots, restrictions on ejective-aspirate pairs (*[k’ap^hi], *[k^hap’i]), as well as restrictions on ejectives and aspirates in plain stop initial roots (*[kap'i], *[kap^{h}i]), suggest reference to the classes of ejective and aspirated stops independent of their glottal counterparts. While these restrictions could be captured with additional constraints on [sg] and [cg], Gallagher (2011) proposes that ejectives and aspirates are grouped together under the acoustically based feature [long VOT], referring to the distinctive voice onset time (VOT) lag in aspirates and ejectives. Given the feature [long VOT], a single constraint can rule out all combinations of stops in C_1 and ejectives or aspirates in C_2: *[-cont, -son][long VOT] (see Mackenzie 2013 for a proposal of this type). Alternatively, distinct constraints may refer to features picking out aspirates and ejectives separately: *[-cont, -son][aspirate] and *[-cont, -son][ejective]. The phonotactic restrictions of Quechua thus provide support for grouping ejectives and aspirates with their glottal counterparts, in the natural classes [sg] and [cg], but also for referring to ejectives and aspirates to the exclusion of their glottal counterparts, as summarized in Table 2.

natural class	supporting phonotactics		
[sg]	$\boxed{\text{*k}^h\text{-p}^h}$	*h-p^h	
[cg]	$\boxed{\text{*k'-p'}}$	*ʔ-p'	
[long VOT] *or* [aspirate] and [ejective]	$\boxed{\text{*k}^h\text{-p}^h}$	*k'-p^h	*k-p^h
	$\boxed{\text{*k'-p'}}$	*k^h-p'	*k-p'

Table 2: Natural classes supported by phonotactic restrictions. Boxing indicates forms that support multiple natural classes.

The main goal of this paper is to test the reality of the natural classes in Table 2 in Quechua by examining native speakers' behavior for evidence of phonotactic restrictions on these classes. If Quechua speakers have learned the articulatory based features [sg] and [cg], then the absence of [h]-aspirate and [ʔ]-ejective pairs should be represented as OCP restrictions and are expected to have a strong effect on speakers' behavior, comparable to restrictions specific to aspirates and ejectives. Alternatively, the distinctive acoustic properties of ejectives and aspirates may lead speakers to attend asymmetrically to the phonotactic patterning of these segments to the exclusion of their glottal counterparts, resulting in stronger effects for restrictions based on [long VOT] or [aspirate]/[ejective].

Before assessing the status of the [sg] and [cg] natural classes in speakers' grammars, the production study in Section 3 begins by evaluating acoustic evidence for initial glottal stop. Once the phonetic basis for the [cg] natural class is quantified, Section 4 presents examines results of two nonce word studies for evidence of restrictions on [sg] and [cg] classes.

3 Production study: evaluating glottal stop

To evaluate the presence of glottal stop in vowel initial roots in Quechua, such roots were recorded in three contexts: isolation, e.g., [inti] 'sun', phrase medial post-vocalic, e.g., [k'atʃa inti] 'pretty sun', and phrase medial post-consonantal, e.g., [yuraχ inti] 'white sun'. All vowel initial roots in this study are in prosodically prominent positions, which have been shown to increase the likelihood of a non-contrastive glottal stop (Pierrehumbert & Talkin 1991; Pierrehumbert 1995; Dilley et al. 1996; Garellek 2013; Garellek 2014): isolation words are necessarily phrase initial, and in the two-word phrases used here the target word bears the phrasal accent. Quechua is a strictly suffixing language, so roots are always word initial; 'root initial' and 'word initial' thus refer to the same position.

In addition to evaluating the distribution of glottal stop preceding vowel initial roots, voice quality in the initial vowel of a vowel initial root was also examined by measuring the harmonics-to-noise ratio (HNR). Voice quality in vowel initial roots was compared to voice quality following an ejective, which unambiguously has a glottal closure, and following a plain stop, which does not. This comparison serves to determine whether vowel initial and ejective initial roots share phonetic properties that may underlie their phonological patterning.

3.1 Participants

The participants were twelve native speakers of Quechua from the Cochabamba department of Bolivia. All participants were bilingual in Spanish and had a university education. The production task required reading, and thus participants needed to be proficient in reading Quechua. While there is a standard orthography for Bolivian Quechua that is taught in schools, most Quechua speakers are only literate in Spanish and are not comfortable reading in Quechua. The participants for this study, then, were both highly educated and had made a conscious effort to become fluent readers of Quechua. Eight males and four females completed the study, aged 25-45.

3.2 Materials

The stimuli are given in Table 3. Twelve vowel initial roots were selected, 4 each with initial /a i u/. These roots were presented either in isolation, or in post-vocalic or post-consonantal position within a two word phrase. In post-vocalic position, the preceding vowel was always the low vowel [a]; the preceding consonant in post-consonantal position was variable. In addition to vowel initial words, which were of primary interest, twelve plain stop and twelve ejective initial words were included as isolation words in order to assess baseline voice quality in glottal and non-glottal environments.[1] Stress in Quechua is penultimate, so all target words have stress on the initial syllable with the exception of [i'miʎa] 'young girl' and [u'susi] 'daughter'.

3.3 Procedure

The stimulus items were presented in Bolivian Quechua orthography using the experimental software PsyScope X B77 (Cohen et al. 1993). In Bolivian Quechua orthography, vowel initial roots are written as vowel initial, and ejectives are marked with a following apostrophe, e.g., <inti> [inti] 'sun', <p'acha> [p'atʃa] 'clothes'. Items were randomized and the experiment was self-paced. Participants were seated in front of a MacBook Air laptop with Audio Technica headphones; they were instructed to read what appeared on the screen and to then press the space bar to proceed. Responses were recorded with a Marantz PMD560 digital recorder and an Audio Technica 831b microphone. Items were not presented in a carrier phrase.

[1] Two ejective-initial words, [p'esqo] 'bird' and [p'olqo] 'sock', contain uvular consonants, resulting in lowering of /i u/ to [e o].

	vowel initial		**plain initial**		**ejective initial**	
	ajtʃa	‘meat’	tʃaki	‘foot’	tʃ’aki	‘dry’
	aʎqo	‘dog’	katʃi	‘salt’	k’aŋka	‘rooster’
	ajʎu	‘village’	patʃa	‘earth’	p’atʃa	‘clothes’
	atoχ	‘fox’	para	‘rain’	t’anta	‘bread’
	inti	‘sun’	tʃiri	‘cold’	k’iti	‘area’
	itʃʰu	‘hay’	kiʎa	‘moon’	tʃ’isi	‘evening’
isolation	iŋka	‘Inca’	pitʃaj	‘to sweep’	t’ika	‘flower’
	imiʎa	‘young girl’	kiru	‘tooth’	p’esqo	‘bird’
	utʃu	‘chile’	tʃuʎpa	‘mummy’	t’uru	‘brother’
	uma	‘head’	tuʎu	‘skinny’	p’olqo	‘sock’
	ususi	‘daughter’	kuti	‘time’	k’uʎu	‘wood’
	urpi	‘pigeon’	tukuj	‘everything’	tʃ’uru	‘shell’
	post-vocalic		**post-consonantal**			
	puka ajtʃa	‘red meat’	aɴqas ajtʃa	‘blue meat’		
	jana aʎqo	‘black dog’	kuraχ aʎqo	‘old dog’		
	k’atʃa ajʎu	‘pretty village’	hatun ajʎu	‘big village’		
	puka atoχ	‘red fox’	juraχ atoχ	‘white fox’		
	wira imiʎa	‘fat young girl’	kuraχ imiʎa	‘older young girl’		
phrase	k’atʃa inti	‘pretty sun’	hatun iŋka	‘big Inca’		
	jana iŋka	‘black Inca’	juraχ inti	‘white sun’		
	jana itʃʰu	‘black hay’	aɴqas itʃʰu	‘blue hay’		
	puka utʃu	‘red chile’	aɴqas utʃu	‘blue chile’		
	jana uma	‘black head’	hatun uma	‘big head’		
	k’atʃa ususi	‘pretty daughter’	juraχ urpi	‘white pigeon’		
	jana urpi	‘black pigeon’	kuraχ ususi	‘older daughter’		

Table 3: Production study stimuli.

3.4 Analysis

All vowel initial words were coded for the presence of a glottal stop based on examination of the waveform for evidence of aperiodicity; F0 contours were also consulted. Tokens were classified as ‘glottalized’ if the waveform was aperiodic, or if a clear glottal burst was present. Most often, aperiodic vowels had irregularly spaced, low amplitude pitch pulses, often accompanied by depressed F0. The criteria for aperiodicity were based on those used in previous work (Dilley et al. 1996; Redi & Shattuck-Hufnagel 2001; Garellek 2013, 2014), though previous studies also relied on a percept of glottalization for a token to be coded as glottalized. In the current study, glottalization was often present for only a very short interval, with perhaps only two pitch periods showing irregularity, and many tokens with visible aperiodicity did not sound glottalized. Consequently, in the current study a percept of glottalization was not required to classify a token as glottalized. Figure 1 shows an example of a vowel initial token with no irregularity (a), a glottal burst (b), and an aperiodic waveform (c).

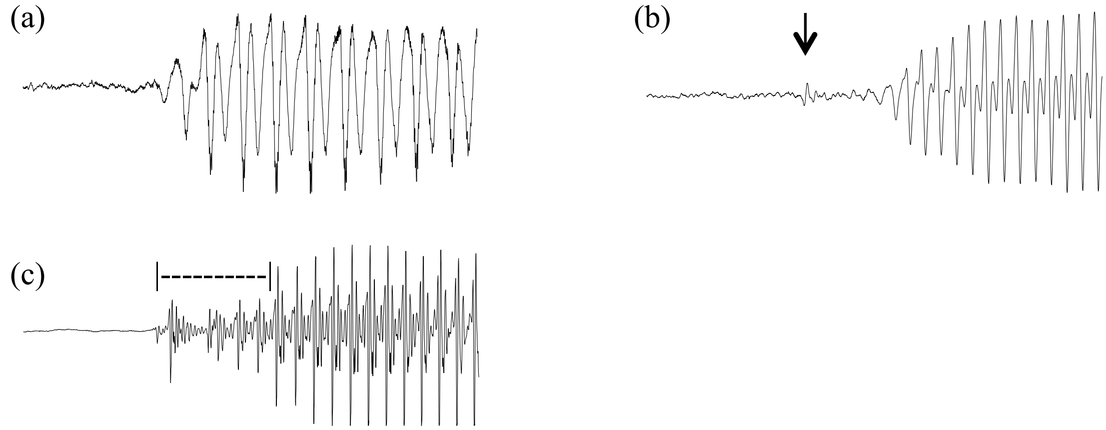

Figure 1: Sample waveforms illustrating (a) no irregularity in [imiʎa] from speaker M2, (b) a single glottal pulse in [urpi] from speaker F3 (c) aperiodicity in [atoχ] from speaker F1. An arrow indicates the glottal pulse in (b) and a line indicates the duration of aperiodicity in (c).

In addition to impressionistic coding of vowel initial words, the HNR for the first half of the vowel was measured for all items, using the 'voice report' function in Praat (Boersma & Weenink 2014). Vowels were segmented from the onset of periodicity or aperiodic noise (when present) until the offset of F2. Lower HNR is expected in tokens with aperiodic noise, which is likely indicative of glottal closure. Two types of comparisons were done on voice quality measures. First, acoustic measures were used to supplement the impressionistic coding of vowel initial words as glottalized or not. Second, voice quality measures were compared between isolation tokens of vowel, ejective and plain stop initial words to determine whether voice quality serves to group vowel and ejective initial words.

3.5 Results

3.5.1 Presence of glottal stop preceding vowel initial words

The proportion of vowel initial roots with evidence of glottal stop is shown in Figure 3. Overall, vowel initial words are frequently (72% of the time) produced with clear visual evidence of a glottal stop, which manifests most often as aperiodicity in the initial portion of the vowel. Nine percent of tokens had only a single pulse corresponding to the glottal burst, with no evidence of aperiodicity in the waveform. Because these items were so infrequent, they are not analyzed separately from tokens with aperiodicity. Glottal stop preceding vowel initial words is most common in isolation (80%) and post-consonantal position (79%), and is relatively less frequent in post-vocalic position (57%).

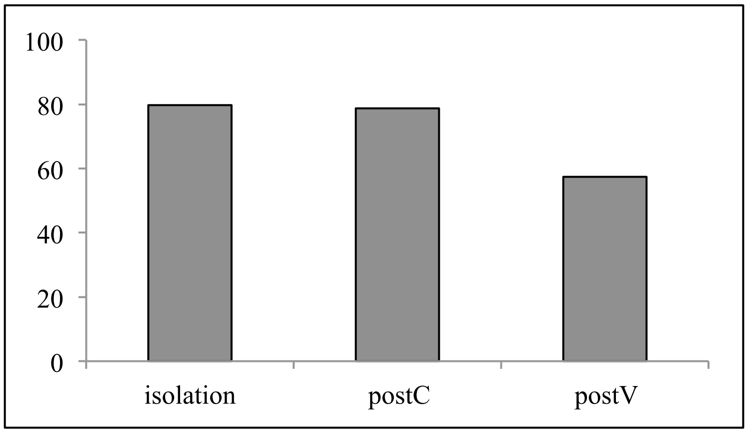

Figure 2: Proportion of vowel initial words produced with visual evidence of glottal closure.

To evaluate the differences in phonation types between contexts, a Mixed Logit Model (MLM) was fit using the *lmer* function in the LanguageR package (Bates et al. 2014) in R (R Core Development Team 2014, www.r-project.org). The dependent variable was presence vs. absence of visual cues to glottal closure. The model had a single predictor of context, with post-consonantal position set as the baseline, and a maximal random effects structure, with random intercepts for participant and item and random slopes by participant. The model finds that glottal closure is less common in post-vocalic position (β = 1.25, SE = 0.55, $z = 2.24$, $p < 0.03$), but that the difference between post-consonantal and isolation contexts is not significant (β = 0.01, SE = 0.50, $z = 0.01$, $p = 0.99$).

3.5.2 Voice quality measures

HNR in vowel initial words is shown in Figure 3, broken down by context and whether there was visual evidence of a preceding glottal closure. As can be seen, HNR values are much lower for vowels with aperiodicity in the waveform than in those without. Furthermore, this difference is more pronounced for vowels in post-vocalic or post-consonantal position than for those in isolation words, suggesting generally higher HNR in phrase medial position.

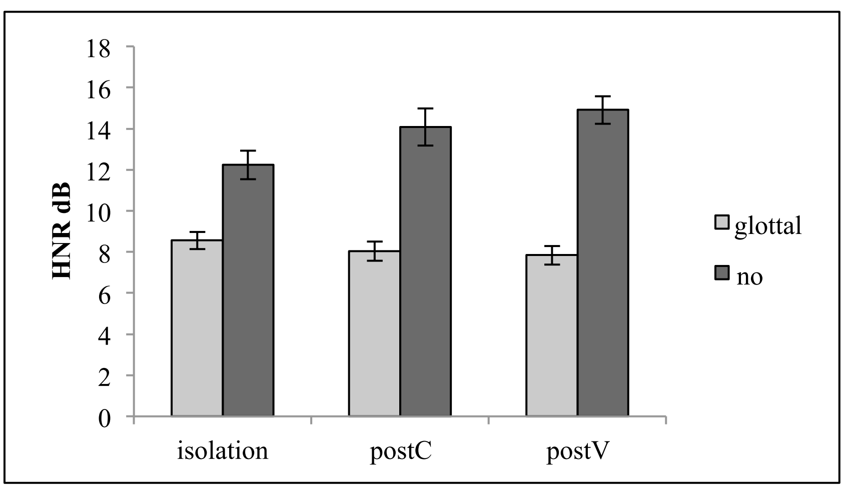

Figure 3: HNR in vowel initial words, by context and whether there was evidence in the waveform of a preceding glottal closure. Errors bars indicate the Standard Error Measure.

A Linear Mixed Model (LMM) was fit with a dependent variable of HNR, predictors of glottal closure, context and their interaction, as well as random intercepts by participant and item and random slopes by participant. The predictor of glottal closure was a two-level, contrast coded predictor comparing items with evidence of glottal closure to those without. The predictor of context was Helmert coded such that post-consonantal and post-vocalic contexts were compared to one another, and isolation context was compared to post-consonantal and post-vocalic contexts as a group. Following Gelman and Hill (2006), t values greater than ±2 are considered significant. The model finds a significant effect of glottal closure (β = 4.10, SE = -.78, t = 5.29): vowels with visual evidence of preceding glottal closure have a lower HNR than vowels with no such evidence. There is also a significant interaction of glottal closure and type (β = -3.29, SE = 1.33, t = -2.48): the effect of glottal closure on HNR is smaller in isolation context than in post-consonantal or post-vocalic contexts.

HNR was also compared between the three types of isolation words: vowel initial, plain stop initial and ejective initial. The results are shown in Figure 4. The purpose of this comparison is to determine whether vowel initial and ejective initial words have acoustic similarities that may suggest articulatory similarities and warrant grouping them as a class. Consequently, here all vowel initial tokens are grouped together, regardless of whether there was visual evidence of glottal closure or not. As expected, HNR is higher following plain stops than following ejectives or in vowel initial words.

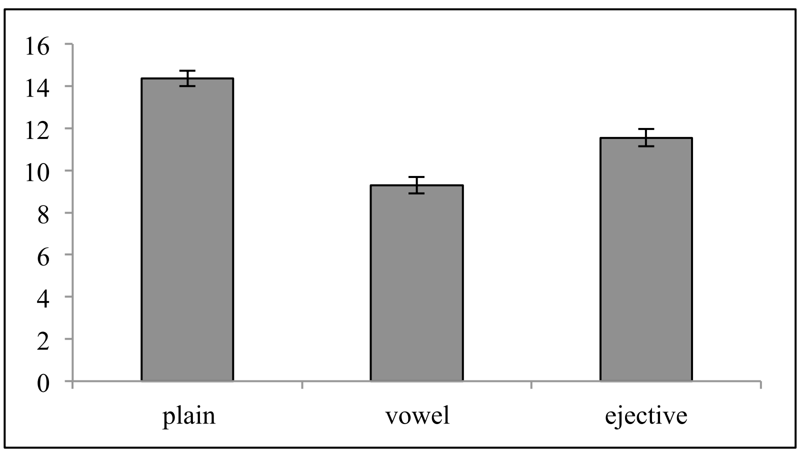

Figure 4: HNR in plain stop, ejective and vowel initial isolation words.

To assess the differences in HNR between these three classes of words, a LMM was fit with a predictor of type with ejective initial words as the baseline. The model finds that vowels following plain stops have a significantly higher HNR than vowels following ejectives (β = 2.96, SE = 1.05, t = 2.83), and that vowels following ejectives in turn have a significantly higher HNR than word initial vowels (β = -2.43, SE = 1.15, t = -2.11).

The lower HNR in vowel initial isolation words than ejective initial isolation words is notable given that all vowel initial words are grouped together here, regardless of whether they showed evidence of glottal closure or not. Looking only at vowel initial isolation words without evidence of glottal closure, we find HNR values intermediate between those in vowels following ejectives and those following plain stops (ejective = 11.55 dB , non-glottalized vowel = 12.23 , plain = 14.36 dB). An additional LMM finds that non-glottalized, word initial vowels do not differ significantly in HNR from vowels following ejectives (β = -0.31, SE = 1.42, t = -0.22), nor from vowels following plain stops (β = -2.64, SE = 1.35, t = 1.96), though this latter difference is nearly significant. Even in vowels with no visual evidence of glottal closure, then, HNR measures suggest some irregularity associated with absolute utterance initial position.

3.6 Discussion

Glottal closure, as evidenced by both visual examination of the waveform and HNR measures, occurs preceding the majority of vowel initial words. The presence of glottal stop is variable: in 28% of tokens, there is no visual evidence of glottal closure. Glottal stop is also context dependent. While glottal closure is common across all contexts, it is relatively less frequent in post-vocalic position. This finding differs from what has been observed for English, in which non-contrastive glottal closure is more common in post-vocalic position, where it breaks up hiatus, than in post-consonantal position (Umeda 1978; Pierrehumbert 1995; Dilley et al. 1996; Mompeán & Gómez 2011; Garellek 2012, 2014; Davidson & Erker 2014).

The frequency of glottal closure in vowel initial words is consistent with these words being glottal stop initial at some level of representation, and in turn makes an OCP constraint on glottal stop and ejectives as [cg] segments plausible, though not certain. HNR is significantly lower in word-initial vowels than in vowels following ejectives, suggesting that the articulation of glottal closure differs between glottal stop and ejectives and that the voice quality correlates of this closure are substantially different. This difference may follow from differences in the alignment of the glottal constriction gesture with the following vowel (Lindau 1984; Kingston 1990) or from the strength or type of the glottal closure. More detailed instrumental work, for example electro-glottagraphy, is needed to ascertain the phonetic similarity between ejectives and glottal stop.

In sum, the results of the production task find that glottal closure is often present in vowel initial words, consistent with previous impressionistic descriptions. The phonological coherence of a natural class including ejectives and glottal stop, however, is still in question. The experiments reported in Section 4 take up this question by probing speakers' knowledge of phonotactic restrictions.

4 Nonce word studies: the phonological representation of laryngeal phonotactics

This section presents the results of two nonce word studies – a repetition task and a forced choice acceptability judgment task – aimed at assessing Quechua speakers' phonotactic knowledge. The goal of these studies is to determine whether speakers' treatment of nonce words is consistent with grammatical restrictions on [sg] and [cg] sound classes, and to assess the strength of restrictions on these classes relative to restrictions specific to ejectives and aspirates. Both experiments compared speakers' treatment of four types of phonotactically illegal nonce words. Words with two aspirates or two ejectives, e.g., *[k^{h}up^{h}i] *[k'up'i], violate a putative cooccurrence restriction on [sg] and [cg] by having two laryngeally marked stops, but also fall under the scope of a restriction on stops followed by ejectives or aspirates. Stimulus items of this type will be refered to as 'double' violations. Double violations were compared to 'glottal' violations, where one of the [sg] or [cg] specifications is associated with a glottal segment, e.g., *[hup^{h}u], *[ʔup’u]. All four types of phonotactically illegal nonce words are compared to phonotactically legal controls, e.g., [ʎup’u], [ʎip^{h}u].

Comparison of speakers’ treatment of double and glottal violations tests whether [sg] and [cg] are the natural classes relevant to cooccurrence restrictions, or whether aspirate and ejective stops are represented differently from their glottal counterparts. If [sg] and [cg] are the correct representational units, then double and glottal violations should be treated comparably. Comparison of the two types of glottal violations, [sg] and [cg], further serves to assess the representation of vowel initial roots as glottal stop initial. If such roots are phonologically glottal stop initial, than *[ʔup’u] and *[hup^{h}u] should be treated similarly. If such roots are instead phonologically vowel initial, then *[up’u] may be treated differently from *[hup^{h}u].

Any study that aims to investigate speakers’ knowledge of categorical phonotactic restrictions has to contend with the novelty of the stimuli that are presented to speakers. In addition to a hypothesized restriction on the stimulus in the phonotactic grammar, phonotactically illegal stimuli contain unattested structures that pose perceptual and articulatory challenges to speakers that may be independent of the grammar. The aim of using two substantially different tasks to assess speakers’ phonotactic knowledge of unattested structures is to abstract away at least partially from effects associated with a particular method of stimulus presentation or a particular type of response (e.g., production vs. a metalinguistic judgment).

4.1 Repetition

The first experiment compared speakers’ accuracy at repeating nonce words. Previous work has found that this task elicits errors on phonotactically illegal nonce roots violating the restriction on pairs of ejectives in Quechua (Author 2013, 2014). In these previous studies, nonce forms with pairs of ejectives, e.g., *[k’up’i], were found to be repeated by Quechua speakers as phonotactically legal forms with a single ejective, [k’upi], a significant portion of the time. Repetition errors are also found to occur at different rates for different types of illegal stimuli; forms with identical pairs of ejectives, e.g., *[k’uk’i], are found to be repeated more accurately than forms with two non-identical ejectives (Author 2014), as are forms with a plain stop-ejective pair, e.g., *[kup’i] (Author 2013). Repetition tasks have also been used to observe English speakers’ treatment of unattested onset clusters (Davidson 2010; Shaw & Davidson 2011; Wilson et al. 2015). In these consonant cluster studies, participants were also found to repair phonotactic violations, but do so in a way that closely tracks acoustic properties of the stimuli, e.g., the length of the release burst in a stop-stop cluster. Consonant clusters pose substantially different perceptual and articulatory challenges than the combinations of non-adjacent consonants that are the focus of the present study (Ussishkin & Wedel 2003).

4.1.1 Participants

Twenty-three native speakers of Quechua from the Cochabamba area of Bolivia completed the experiment. The participants were thirteen males and ten females, ages 21-47. All participants were fully bilingual in Spanish and had completed a university degree.

4.1.2 Materials

The critical test stimuli were C_1VC_2V nonce words with an ejective or aspirate in C_2. The test stimuli fell into one of three types, depending on C_1. *Control* forms had a fricative or sonorant in C_1 and were phonotactically legal, e.g., [ʎup’u], [ʎip^{h}u]. *Double* forms had an ejective or aspirate in C_1 and were phonotactically illegal, e.g., *[k’up’i], *[k^{h}up^{h}i]. *Glottal* forms were either glottal stop or [h] initial and were phonotactically illegal, e.g., *[ʔup’u], *[hup^{h}u]. There were 6 items in each type, for a total of 36 stimulus items, given in Table 4.

	control	**double**	**glottal**
ejective	hak’i	k’up’i	ʔatʃ’i
	ʎitʃ’u	k’atʃ’u	ʔak’i
	ʎup’u	p’uk’a	ʔik’u
	mip’a	p’atʃ’i	ʔip’a
	ɲik’u	tʃ’ak’u	ʔutʃ’a
	satʃ’i	tʃ’up’i	ʔup’u
aspirate	juk^{h}i	k^{h}up^{h}i	hatʃ^{h}i
	jatʃ^{h}i	k^{h}itʃ^{h}a	hak^{h}i
	ʎip^{h}u	p^{h}ak^{h}i	hik^{h}u
	ɲak^{h}u	p^{h}utʃ^{h}a	hip^{h}a
	ɲutʃ^{h}i	tʃ^{h}ik^{h}u	hutʃ^{h}a
	sap^{h}u	tʃ^{h}up^{h}a	hup^{h}u

Table 4: Critical stimuli in the repetition experiment.

Each critical item was matched with a filler item with a plain stop in C_2, e.g., *ejective double filler* [k’upi] (cf. critical item [k’up’i]), *aspirate glottal filler* [hupu] (cf. critical item [hup^{h}u]), etc. Stops were drawn evenly from /p’ tʃ’ k’ p^h tʃ^h k^h p tʃ k/ and V_1 was drawn evenly from /a i u/. Fricatives and sonorants in the control stimuli and vowels in V_2 were selected as needed to make sure all items were nonce words. The stimuli were selected so that no item had a near neighbor that differed in only a change in laryngeal feature or glottal segment. For example, the stimulus [ʔup’u] is a nonce word, but so are [ʔupu], [ʔup^{h}u] and [hup’u].

The stimuli were made from recordings of a native speaker from Cochabamba reading phonotactically legal nonce words. All items were cross-spliced during the closure of the medial stop, e.g., [hupu] was made by cross-splicing [hupu] and [ʔupu] during the closure of [p]. Cross-splicing was used to avoid asking a native speaker to produce phonotactically illegal forms for use as stimuli. Intensity was scaled for each stimulus using the ‘Scale Intensity’ function in Praat (Boersma & Weenink 2014).

4.1.3 Procedure

The experiment was conducted partially at the Quechua Indigenous University of Bolivia (Universidad Indígena Boliviana Quechua) in Chimore, a town in the Cochabamba department of Bolivia, and partially in a hotel room in the city of Cochabamba. Participants were seated in front of a MacBook Air with Audio Technica headphones and an Audio Technica 831b lapel mic connected to a Marantz PMD560 digital recorder, at a sampling rate of 44kHz. Stimuli were presented aurally, in a unique random order, using the PsyScope X B77 software (Cohen et al. 1993). Each stimulus was presented two times with a 400 ms ISI. The full set of stimuli was presented twice, for a total of 144 items. The ejective and aspirate items were presented in separate blocks, balanced for order across participants.

Participants were told that the words they would hear would contain sounds that existed in Quechua, but that they had no meaning in Quechua or in any other language, and that they were to repeat what they heard as precisely as possible. The instructions were given orally in Spanish. Participants were allowed to practice for as long as they needed to become comfortable with the task, which took between 3 and 8 trials per participant. The experiment was self-paced, and participants pressed a key to move on to the next trial. The entire experiment took about 10 minutes.

4.1.4 Analysis

All responses were transcribed by two phonetically trained transcribers (the author and a graduate student research assistant). 29 tokens were removed because background noise made transcription impossible or because the response was disfluent or differed dramatically from the stimulus. In 76 cases, 5% of the data, the transcribers disagreed as to whether a given stop was ejective or plain. In these cases, the syllable on which the transcribers disagreed was spliced out of the response and presented to a native Quechua speaker to be classified as ejective or plain; the native speaker's judgment was then used as the transcription for that token. Once transcribed, responses were coded for accuracy and type of error. The main error type was de-ejectivization or de-aspiration of the medial stop, e.g., target *[k'up'i] produced as [k'upi], accounting for 97% of all errors. Additional errors (i) modified C_1, e.g., target *[ʔup'u] produced as [hup'u], (ii) changed an ejective to an aspirate or vice-versa, e.g., *[hup^{h}u] produced as [hup'u] or (iii) de-aspirated both stops, e.g., *[k^{h}up^{h}i] produced as [kupi]. Finally, 11 tokens were removed because they contained an error that did not repair the phonotactic violation, e.g, target *[k'up'i] produced as [kup'i], which is also phonotactically illegal.

4.1.5 Results

For both ejectives and aspirates, accuracy on double violations is much lower than control, while accuracy on glottal violations is only slightly lower than control. The results are shown in Figure 5.

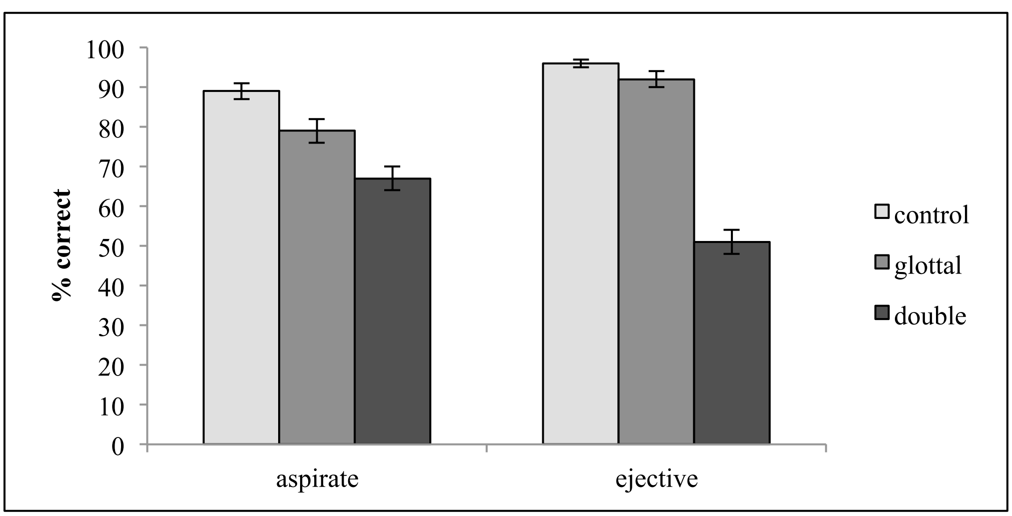

Figure 5: Accuracy on the repetition task, by laryngeal type and stimulus type. Error bars indicate Standard Error Measure.

Two Mixed Logit Models were fit to analyze accuracy on the aspirate and ejective stimuli. Each model had a predictor of type with *control* as the baseline, and random intercepts by participant and item and random slopes by participant. The dependent variable was correct/incorrect. For both models, *double* did differ significantly from *control* (aspirate: $\beta = -1.64$, SE = 0.64, $z = -2.57$, $p < 0.02$, ejective: $\beta = -4.14$, SE = 0.92, $z = -34.5$, $p < 0.0001$), while *glottal* did not (aspirate: $\beta = -0.71$, SE = 0.65, $z = -1.09$, $p = 0.28$, ejective: $\beta = -0.45$, SE = 1.02, $z = -0.44$, $p = 0.66$).

As the control and glottal categories did not differ from one another, these were not subjected to any further analysis. The double category stimuli with ejectives and aspirates were directly compared to one another in a separate Mixed Logit Model, revealing that accuracy is significantly higher on aspirate double violations than on ejective double violations ($\beta = 0.92$, SE = 0.43, $z = 2.11$, $p < 0.04$).

4.1.6 Discussion

The results of the repetition task show evidence of a strong restriction against pairs of ejectives or aspirates, but do not show any evidence of a dispreference for [h]-aspirate or [ʔ]-ejective combinations. The large difference in treatment of double and glottal items in the experiment argues against a unified treatment of these restrictions, suggesting that [sg] and [cg] are not the natural classes over which phonotactic restrictions are stated. Instead, ejectives and aspirates appear to be treated quite differently from their glottal counterparts.

These results are not informative about the status of glottal stop in phonological representations. The absence of a difference between control and glottal items with ejectives suggests that the restriction on ejectives in glottal stop/vowel initial roots is very weak. Since control and glottal items with aspirates also do not differ, however, the absence of a control vs. glottal difference for ejectives is not interpretable. It could mean that Quechua has phonologically vowel initial roots, and the restriction *#V…[cg] is weak. Alternatively, Quechua may have phonologically glottal stop initial roots, and the restrictions on laryngeally marked stops and their glottal counterparts are stated differently from, and are weaker than, restrictions on pairs of stops (this is the conclusion from the experiments to follow in Section 4.2).

While the results of the repetition task are consistent with the phonotactic restrictions on pairs of ejectives and aspirates in the lexicon, it is possible that participants' performance is due to factors other than their phonotactic grammar. One possibility is that repetition errors are a result of the perceptual similarity of forms with two ejectives or aspirates and forms with a single ejective or aspirate, pairs like [k'up'i]-[k'upi] or [k^{h}up^{h}i]-[k^{h}upi]. Gallagher (2010) found that such pairs of forms were confusable for English speakers, suggesting that this contrast may be perceptually difficult independent of the grammar. It may be that participants' greater accuracy on glottal forms like *[ʔup'u] and *[hup^{h}u] relative to double forms like *[k'up'i] and [k^{h}up^{h}i] is not due to a weaker grammatical restriction on glottal forms, but rather is due to less perceptual uncertainty about the glottal forms. If true, this explanation still points to a strong distinction between ejective and aspirate stops on the one hand and [sg] and [cg] classes on the other: what is difficult is accurately perceiving multiple ejectives or aspirates, not multiple [sg] or [cg] segments.

4.2 Forced choice acceptability

In addition to the repetition task presented above, a forced choice acceptability task was also conducted to gauge the role of natural classes in the phonotactic grammar. In this task, participants were asked to make a metalinguistic judgment about which of two nonce forms is more wellformed.

A forced choice task was chosen instead of a rating task of individual stimuli because of the difficulty with presenting phonotactically illegal stimuli. When presented with a phonotactically illegal stimulus, listeners are likely to repair the stimulus to something legal. This effect can be seen in the repetition task above, where phonotactically illegal forms with two aspirates or two ejectives are systematically repaired to phonotactically legal forms, e.g., [k'up'i] repaired to [k'upi]. The ABX discrimination task reported in Author (2014) also shows that forms with two ejectives are not perceived veridically by Quechua speakers. The design of the current study addressed the issue of presenting phonotactically illegal stimuli in two ways. First, a minimal pair forced choice design was chosen to attract participants attention to the distinction between an illegal and legal stimulus. When presented with a minimal pair like *[k'amp'i]-[k'ampi], for example, participants attention is directed to the difference between these forms before making their judgment. If participants were instead presented with an illegal form like *[k'amp'i] in isolation, they may repair the stimulus to legal [k'ampi] and then make a judgment about this repaired form.[2] Second, stimuli were presented orthographically as well as aurally to aid participants in accurately perceiving the distinction between the minimal pairs.

Two forced choice studies were conducted, differing in the segments that contrasted in a minimal pair. Experiment a (Section 4.2.1) was run first, and Experiment b (Section 4.2.2) was run as a follow-up given the results of Experiment a.

4.2.1 Forced choice experiment a

4.2.1.1 Participants

Nineteen native speakers of Quechua from the Cochabamba area of Bolivia completed the experiment. The participants were nine males and ten females, ages 21-37. All participants were fully bilingual in Spanish and had completed a university degree, and all participants completed the repetition task prior to the forced choice task.

4.2.1.2 Materials

The stimuli were pairs of $C_1V(C)C_2V$ nonce words that minimally contrasted an ejective and a plain stop or an aspirate and a plain stop. There were three types of pairs. *Double* pairs contrasted a form with two ejectives or aspirates with a form with one ejective or aspirate, e.g., *[k'up'u] vs. [k'upu] and *[k^{h}up^{h}u] vs. [k^{h}upu]. *Glottal* pairs contrasted a form with a [ʔ]-ejective or [h]-aspirate combination with a [ʔ]-plain or [h]-plain combination, e.g., *[ʔup'u] vs. [ʔupu] and *[haʎp^{h}u] vs. [haʎpu]. *Control* forms contrasted an ejective or an aspirate with a plain

[2] In informal pilot studies, this effect was observed. Participants judged illegal forms with two ejectives *[k'up'i] or two aspirates *[k^{h}up^{h}i] as wellformed. When questioned about their responses, however, it was revealed that participants were judging a form with just one ejective [k'upi] or aspirate [k^{h}upi]. Participants often repeated the form to themselves before judging it, repairing the phonotactic violation. When corrected by the experimenter that the form in fact had two ejectives, the participants responded that such a form was impossible to say in Quechua, and that in Quechua it would have to be pronounced with a single ejective.

stop in phonotactically legal forms, e.g., [ʎup’i] vs. [ʎupi] and [ʎip^{h}u] vs. [ʎipu]. There were 12 pairs of each type, for a total of 72 trials, given in Table 5.

	control	double	glottal
ejective	hap’u - hapu	tʃ’ak’u - tʃ’aku	ʔatʃ’a - ʔatʃa
	hitʃ’u - hitʃu	tʃ’aʎp’u - tʃ’aʎpu	ʔak’i - ʔaki
	huk’a - huka	tʃ’ik’u - tʃ’iku	ʔaʎp’u - ʔaʎpu
	ʎatʃ’u - ʎatʃu	k’amp’i - k’ampi	ʔamp’a - ʔampa
	ʎuk’a - ʎuka	k’iʎp’u - k’iʎpu	ʔik’a - ʔika
	ʎup’i - ʎupi	k’untʃ’a - k’untʃa	ʔik’u - ʔiku
	ɲak’u - ɲaku	k’up’u - k’upu	ʔiʎp’u - ʔiʎpu
	ɲutʃ’i - ɲutʃi	p’ach’u - p’achu	ʔintʃ’a - ʔintʃa
	ɲup’a - ɲupa	p’ik’u - p’iku	ʔutʃ’i - ʔutʃi
	sap’i - sapi	p’intʃ’a - p’intʃa	ʔuk’i - ʔuki
	sitʃ’a - sitʃa	p’utʃ’i - p’utʃi	ʔuntʃ’a - ʔuntʃa
	suk’i - suki	p’uk’i - p’uki	ʔup’u - ʔupu
aspirate	ʎatʃ^{h}u - ʎatʃu	tʃ^{h}ak^{h}i - tʃ^{h}aki	hatʃ^{h}a - hatʃa
	ʎip^{h}u - ʎipu	tʃ^{h}aʎp^{h}u - tʃ^{h}aʎpu	hak^{h}i - haki
	ʎuk^{h}a - ʎuka	tʃ^{h}ik^{h}u - tʃ^{h}iku	haʎp^{h}u - haʎpu
	ɲak^{h}u - ɲaku	k^{h}amp^{h}i - k^{h}ampi	hamp^{h}a - hampa
	ɲutʃ^{h}i - ɲutʃi	k^{h}iʎp^{h}u - k^{h}iʎpu	hik^{h}a - hika
	ɲup^{h}a - ɲupa	k^{h}untʃ^{h}a - k^{h}untʃa	hiʎp^{h}a - hiʎpa
	sap^{h}u - sapu	k^{h}up^{h}u - k^{h}upu	hintʃ^{h}i - hintʃi
	sitʃ^{h}a - sitʃa	p^{h}atʃ^{h}u - p^{h}atʃu	hink^{h}u - hinku
	suk^{h}i - suki	p^{h}ik^{h}u - p^{h}iku	hutʃ^{h}i - hutʃi
	jatʃ^{h}i - jatʃi	p^{h}intʃ^{h}a - p^{h}intʃa	huk^{h}a - huka
	jap^{h}i - japi	p^{h}utʃ^{h}i - p^{h}utʃi	huntʃ^{h}a – huntʃa
	juk^{h}i - juki	p^{h}uk^{h}i - p^{h}uki	hup^{h}u - hupu

Table 5: Stimulus pairs in forced choice experiment a.

As for the repetition task, and all stimuli were cross-spliced and normalized for intensity.

In addition to the contrast between phonotactically legal and illegal stimuli in the double and glottal pairs, all pairs of stimuli differed in phonotactic probability. In medial position, plain stops are much more frequent (42% of all medial consonants) than ejectives (12%) or aspirates (5%). Due to this frequency difference, a general preference is expected for stimuli with medial plain stops. The question, then, is whether this preference is stronger in the double and glottal pairs, where it is consistent with a phonotactic restriction, than in the control forms, where no phonotactic restrictions apply to either form.

4.2.1.3 Procedure

The experiment was conducted in a hotel room in the city of Cochabamba. Participants were seated in front of a MacBook Air with Audio Technica headphones. Stimuli were presented aurally and orthographically, in a unique random order, using the PsyScope X (B77) software (Cohen et al. 1993). Ejectives are represented with an apostrophe following the stop, and aspirates with a <h> following the stop, e.g., [k’ampi] <k’ampi> and [p^{h}iku] <phiku>. The orthographic representation of the stimulus followed the aural presentation by 50 ms, and there was a 500 ms interval between the two stimuli in a trial. The order in which the words were presented was randomized by participant. For example, the pair *[k'amp'i]-[k'ampi] was presented as *[k'amp'i]-[k'ampi] to some participants and as [k'ampi]-*[k'amp'i] to others. All trials were randomized and presented to participants in a single block.

Participants were told that they would hear words that contained sounds from Quechua, but didn't mean anything. The instructions, given orally in Spanish, were to listen to both words and to choose the word that sounded most natural as a word of Quechua. Participants pressed the "1" key to select the first word, on the left side of the screen, and the "0" (marked with a "2" label) to select the second word, on the right side of the screen. Participants practiced with 3-6 trials until they were comfortable with the format of the experiment. The experiment was self-paced and took about 5 minutes.

4.2.1.4 Results

Responses were coded for whether the stimulus with the plain medial stop was chosen or not. As can be seen in Figure 6, there is a dispreference for stimuli with plain stops in the control and glottal pairs, but a strong preference for stimuli with plain stops in double pairs.

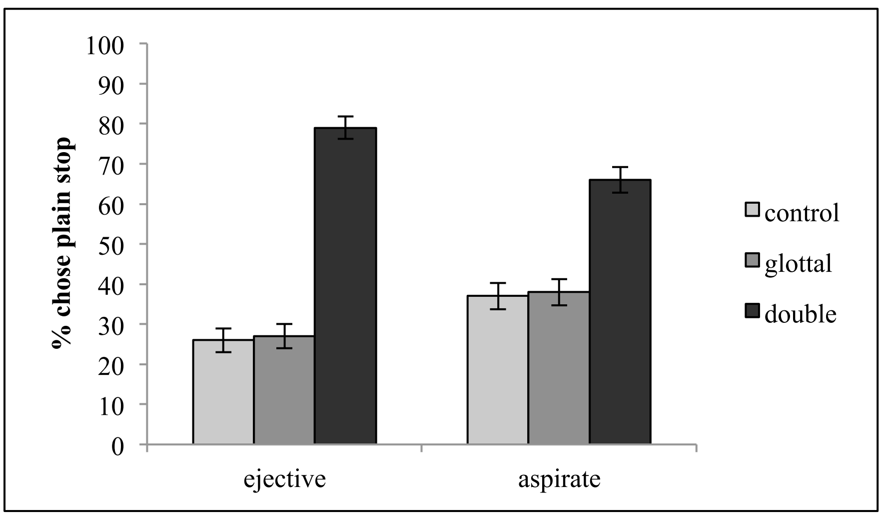

Figure 6: Proportion of stimuli with medial plain stops chosen, by trial type. Errors bars indicate Standard Error.

A Mixed Logit Model was fit with a ternary predictor of type (with control as the baseline) and a binary predictor of condition (ejective or aspirate) and their interaction. The dependent variable was whether the form with a plain stop was chosen or not. The model had random intercepts by item and participant and random slopes by participant. In the full model, there is a significant interaction between type:double and condition ($\beta = 2.59$, SE = 0.71, $z = 3.65$, $p < 0.001$). To determine the source of this interaction, two additional models were fit comparing control pairs and double pairs between the ejective and aspirate conditions. In control pairs, plain stops were chosen significantly less often in the ejective condition than in the aspirate condition ($\beta = -1.20$, SE = 0.43, $z = -2.82$, $p < 0.01$); in double pairs, plain stops were chosen significant more often in the ejective condition than in the aspirate condition ($\beta = 1.31$, SE = 0.38, $z = 3.43$, $p < 0.001$). The significant interaction term thus indicates a stronger effect of type (control or double) in the ejective condition than the aspirate condition. A third model was fit with a predictor of condition and a binary predictor of type (glottal or control) to assess any differences between glottal and control pairs. This model returned a significant effect of condition, indicating that plain stops were disprefered in the ejective condition (β = -1.16, SE = 0.40, z = -2.93, p < 0.01), but no effect of type or interaction between type and condition.

4.2.1.5 Discussion

The forced choice task finds a strong preference for medial ejective and aspirate stops in control and glottal pairs, and a strong dispreference for medial ejective and aspirate stops in double pairs. The preference for ejectives and aspirates in control and glottal pairs is the opposite of what would be expected based on frequency (plain stops are more frequent) and phonotactics (ejectives and aspirates are restricted in glottal forms). This unexpected preference for ejectives and aspirates is likely reflects participants' knowledge that ejectives and aspirates are found in Quechua but not in Spanish, and hence make a word particularly "like Quechua".

Despite this overall preference for ejectives and aspirates, a comparison between glottal and double pairs is still informative. Glottal pairs are treated identically to controls, indicating that the phonotactic restriction contributes nothing to participants judgments. For double pairs, however, the phonotactic restriction does seem to contribute and overrides the general preference for ejectives and aspirates. In double pairs, plain stops are prefered, as is expected based on both frequency and phonotactics.

The results of the forced choice task, like the repetition task, show strong evidence for a restriction against pairs of ejective or aspirates, but do not show any evidence of a restriction on [h]-aspirate or [ʔ]-ejective combinations. The results again suggest phonotactic restrictions over ejective and aspirate classes, as opposed to [sg] and [cg] classes.

The lack of support for restrictions on [h]-aspirate or [ʔ]-ejective combinations could mean that these combinations are not actually restricted in speakers' grammars, or it could be that the two tasks run so far are not sensitive enough to detect a relatively weak restriction. There may be restrictions on [h]-aspirate and [ʔ]-ejective combinations, but these restrictions are not strong enough to cause repetition errors or to override the preference for ejectives and aspirates in the forced choice task. A second forced choice task was run to pursue this possibility by presenting participants with minimal pairs that contrasted [h] and [ʔ], as opposed to an ejective or aspirate and a plain stop, e.g., *[ʔak'i] was compared to [hak'i] and [ʔak^{h}i] to *[hak^{h}i].

4.2.2 Forced choice experiment b

4.2.2.1 Participants

Nineteen native speakers of Quechua from the Cochabamba area of Bolivia completed the experiment. The participants were six males and thirteen females, ages 20-37. All participants were fully bilingual in Spanish and had completed a university degree. None of the participants had participated in any of the experiments presented so far.

4.2.2.3 Materials

The stimuli were pairs of $C_1V(C)C_2V$ nonce words that minimally contrasted an initial [h] and [ʔ]. There were three types of pairs depending on C_2. In *aspirate* and *ejective* pairs, C_2 was an aspirate or an ejective and the pair contrasted a legal and an illegal form, e.g., [hak^{h}i] vs. [ʔak^{h}i] and [hak'i] vs. [ʔak'i]. In *plain* pairs, C2 was a plain stop and the pair contrasted two legal forms, e.g., [haki] vs. [ʔaki]. There 10 pairs in each type, shown in Table 6. There were also 30 fillers (contrasting legal forms with ejectives, aspirates and plain stops) for a total of 60 items. All stimuli were cross-spliced and normalized for intensity.

control	ejective	aspirate
haki - ʔaki	hak'i - ʔak'i	hak^{h}i - ʔak^{h}i
haʎpu - ʔaʎpu	hamp'a - ʔamp'a	haʎp^{h}u - ʔaʎp^{h}u
hampa - ʔampa	hatʃ'a - ʔatʃ'a	hamp^{h}a - ʔamp^{h}a
hatʃa - ʔatʃa	hik'a - ʔik'a	hatʃ^{h}a - ʔatʃ^{h}a
hika - ʔika	hik'u - ʔik'u	hik^{h}a - ʔik^{h}a
hiku - ʔiku	hiʎp'u - ʔiʎp'u	hink^{h}u - ʔink^{h}u
hinku - ʔinku	huk'i - ʔuk'i	hintʃ^{h}i - ʔintʃ^{h}i
huka - ʔuka	huntʃ'a - ʔuntʃ'a	huk^{h}a - ʔuk^{h}a
huki - ʔuki	hup'u - ʔup'u	hup^{h}u - ʔup^{h}u
huntʃa - ʔuntʃa	hutʃ'i - ʔutʃ'i	hutʃ^{h}i - ʔutʃ^{h}i

Table 6: Stimulus pairs in forced choice experiment b.

As in forced choice experiment a, the pairs in experiment b differ in phonotactic probability. If glottal stop initial words are truly glottal stop initial, then they are more frequent (12% of all initial segments) than [h] initial words (6%), and a general preference for [ʔ] initial forms should be observed in the control condition. If instead words may be vowel initial, then [h] and [a] (6%) are equally frequent, and [h] is more frequent than any of the three initial vowels [a] (5.9%), [i] (2%) or [u] (4%), and a general preference for [h] initial forms should be observed in the control condition. In either case, ejective and aspirate pairs can be compared to control forms to assess deviations from the general preference when no phonotactic violation is involved.

4.2.2.4 Procedure

The procedure was the same as for forced choice experiment a.

4.2.2.5 Results

Responses were coded for whether the stimulus with initial [h] was chosen or not. As can be seen in Figure 7, there is a preference of [h] initial stimuli in across all three types of pairs. This preference is slightly weaker in aspirate pairs than in control pairs, and stronger in ejective pairs, consistent with the phonotactic restrictions.

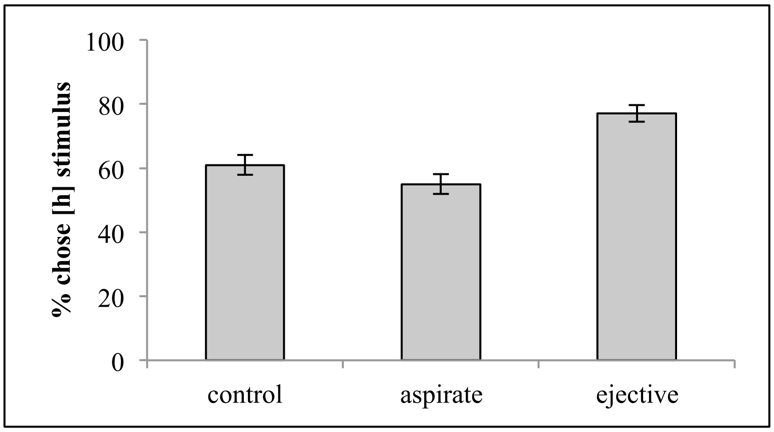

Figure 7: Proportion of stimuli with initial [h] chosen, by trial type. Errors bars indicate Standard Error.

A Mixed Logit Model was fit with a ternary predictor of type (with control as the baseline) and a dependent variable of whether the [h] initial form was chosen or not. The model had random intercepts by item and participant and random slopes by participant. The model finds that the preference for [h]-initial forms is significantly higher in ejective pairs than in control pairs (β = 0.83, SE = 0.28, z = 2.97, $p < 0.01$), but did not differ between aspirate pairs and control pairs.

To understand why the somewhat surprising finding of a significant effect for ejective pairs but not aspirate pairs, the data was explored in some more detail. For aspirate pairs, pairs with medial affricates were found to pattern quite differently from pairs with medial stops, as shown in Figure 8. The preference for [h] initial forms is much weaker for aspirate pairs than control pairs when there is a medial stop, but not when it is a medial affricate.

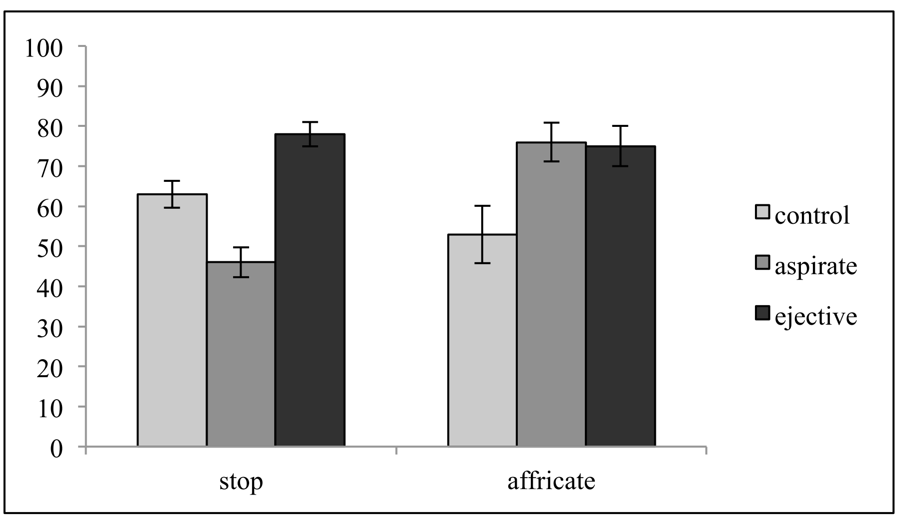

Figure 8: Proportion of stimuli with initial [h] chosen, by trial type and manner of medial consonant. Errors bars indicate Standard Error.

A second Mixed Logit Model was fit adding a predictor of manner. This model found a significant interaction between aspirate type pairs and manner (β = -1.78, SE = 0.57, z = -3.14, $p < 0.01$). Two follow-up models were fit separately for stops and affricates. For stops, [h] initial forms were chosen significantly more often in ejective pairs than in control pairs ($\beta = 0.80$, SE = 0.31, $z = 2.54$, $p < 0.02$), and significantly less often in aspirate pairs than in control pairs ($\beta = -0.84$, SE = 0.31, $z = -2.72$, $p < 0.01$). For affricates, [h] initial forms are chosen significantly more often in both ejective ($\beta = 1.03$, SE = 0.43, $z = 2.41$, $p < 0.02$) and aspirate ($\beta = 1.02$, SE = 0.40, $z = 2.57$, $p < 0.02$) pairs than in control pairs. It is not entirely clear why stimuli with aspirated affricates would pattern so differently from stimuli with affricated stops, but this pattern may be related to the infrequency of aspirated affricates in in medial position (.5% of all medial consonants as opposed to 1.3% for [pʰ] and 1.6% for [kʰ]).

4.2.2.6 Discussion

The main result of forced choice experiment b is that an an effect of a phonotactic restriction on both [ʔ]-ejective and [h]-aspirate combinations was found, unlike in forced choice experiment a or in the repetition task. Participants chose [h] initial forms more often when the alternative was a form with a [ʔ]-ejective pair, e.g., [hak’i] is chosen over *[ʔak’i] more often than [haki] is chosen over [ʔaki], and less often when the [h] initial form contained an aspirate, e.g., *[hakʰi] is chosen over [ʔakʰi] less often than [haki] is chosen of [ʔaki]. This effect for [h]-aspirate combinations is only found when for aspirated stops [pʰ] or [kʰ], as opposed to the affricate [tʃʰ].

Restrictions on [h]-aspirate and [ʔ]-ejective forms yeilded significant effects in opposite directions; the magnitude of these effects, however, was comparable, as indicated by the β coefficients (for forms with medial stops): 0.80 for ejectives, -0.84 for aspirates. This pattern is consistent with [ʔ] being present phonologically. Contradictorily, then, a preference for [h] initial forms was also found in control pairs ($p < 0.0001$), which is surprising given that [ʔ] initial roots are more frequent than [h] initial roots. More work is needed to determine if a factor other than simple positional frequency could lead speakers to prefer [h] initial forms.

4.3 Summary

The results presented in this section reveal clear effects of restrictions on pairs of aspirate and ejective stops that influence both linguistic performance, in the form of the repetition task, and metalingusitic judgments, in the form of the forced choice task. The results also support restrictions on [h]-aspirate and [ʔ]-ejective pairs, though these effects are found only in one of the two forced choice tasks. This pattern is consistent with strong phonotactic restrictions stated over features that uniquely pick out aspirate and ejective stops, and relatively weaker restrictions on [sg] and [cg], which group aspirates and ejectives with their glottal counterparts.

5 General discussion

The main finding in this paper is that stronger phonotactic constraints target the classes of aspirate and ejective stops independently from their glottal counterparts. The classes of [sg] and [cg] segments are also supported by one of the three experiments, suggesting relatively weaker restrictions on these classes. Two hypotheses were outlined earlier for how ejectives and aspirates may be represented as distinct from their glottal counterparts, either as a single class picked out by [long VOT], or as independent classes [aspirate] and [ejective]. The experimental results support the second hypothesis with two distinct class [aspirate] and [ejective] because aspirates and ejectives were treated differently on both the repetition task and the forced choice task. In both cases, a restriction on pairs of ejectives had a significantly stronger effect on participants' performance than a restriction on pairs of aspirates; this difference is unexpected if ejectives and aspirates make up a single natural class.

The presence of the smaller classes of aspirates and ejectives in addition to the larger classes [sg] and [cg] may arise because they refer to more phonetically salient properties of the relevant segments. Both ejectives and aspirates have a long voice onset time (VOT), and ejectives additionally have a high amplitude burst. The varied acoustic profile of ejective and aspirate stops – a closure, burst and VOT portion – gives ejective and aspirate stops a high degree of distinctness in amplitude and spectral properties relative to surrounding sounds, increasing their perceptual salience (Ohala & Kawasaki-Fukimori 1997; Henke et al. 2012). Articulatorily, ejectives and aspirates differ from their glottal counterparts in involving the coordination of both an oral and a laryngeal gesture. Coordination of multiple gestures, and the acoustic consequences of varying coordination, has been argued to be a core property of the representation of laryngeally marked stops (Kingston 1990; Steriade 1997) and a main contributor to articulatory complexity (Goldstein et al. 2007).

The importance of different types of phonetic similarity in determining natural classes and the strength of phonotactic restrictions on those classes could be tested through work with other languages whose phonologies target phonetically disparate classes. In Hausa, for example, mentioned earlier in Section 2, a cooccurrence restriction targets the series of [cg] segments, which includes ejectives, implosives and [ʔ]. Based on the data here, it would be expected that Hausa speakers would treat pairs of ejectives as more illformed than ejective-implosive or [ʔ]-ejective pairs. If this is not the case, additional, specific properties of the phonetics or phonology of Quechua may be responsible for the importance of [aspirate] and [ejective] classes.

Given the classes [aspirate] and [ejective], speakers' behavior on the experiment tasks may be seen to reflect a phonotactic grammar like that in Table 7. OCP constraints target the features [aspirate] ([asp]) and [ejective] ([ej]), penalizing pairs of aspirates and pairs of ejectives. OCP constraints also target [sg] and [cg] classes, penalizing pairs of aspirates and pairs of ejectives as well as [h]-aspirate and [ʔ]-ejective pairs. The stronger and more persistent effect of constraints on [ej] and [asp] on participants' behavior is indicated here with a solid line, representing a higher weighting of these constraints in the phonotactic grammar.

	*[ej][ej]	*[asp][asp]	*[cg][cg]	*[sg][sg]
*[k'up'i]	*		*	
*[k^{h}up^{h}i]		*		*
*[ʔup'i]			*	
*[hup^{h}i]				*

Table 7: Constraint violations for stimulus types include in the experiments.

To account for the full range of unattested consonant combinations in Quechua, additional constraints are necessary that rule out medial ejectives and aspirates in roots with initial plain stops (*[kup'i], *[kup^{h}i]) or combinations of ejectives and aspirates within a root (*[k'up^{h}i], *[k^{h}up'i]). These illformed combinations can be ruled out with two additional constraints that penalize a stop followed by an ejective or aspirate later in the root: *[-cont, -son][aspirate] and *[-cont, -son][ejective]. These constraints will also penalize pairs of two ejectives or two aspirates, duplicating the work of *[ej][ej] and *[asp][asp]. The argument that both sets of constraints are necessary comes from previous studies comparing forms with two ejectives and forms with a plain stop-ejective pair, e.g., *[k'ap'u] and *[kap'u] (Author 2013). Forms with two ejectives were subject to a greater repair rate than forms with a plain stop ejective combination, suggesting that the grammar penalizes ejective pairs more heavily. This result argues in favor of a strong OCP restriction penalizing ejective-ejective pairs, in addition to the violations incurred for *[-cont, -son][ej]. The full phonotactic grammar for laryngeal features is shown in Table 8. Wellformed combinations of [ʔ]-aspirate or [h]-ejective do not violate any constraints, as these pairs of segments do not fall into a natural class.[3]

	*[ej][ej]	*[asp][asp]	*[-cont, -son][ej]	*[-cont, -son][asp]	*[cg][cg]	*[sg][sg]
*[k'up'i]	*		*		*	
*[k^hup^hi]		*		*		*
*[ʔup'i]					*	
*[hup^hi]						*
*[kup'i]			*			
*[$k^hup'i$]			*			
*[kup^hi]				*		
*[$k'up^hi$]				*		
[$ʔup^hi$]						
[hup'i]						

Table 8: Constraint violations of all unattested forms with a laryngeally marked segment, as well as attested combinations of [ʔ]-aspirate and [h]-ejective.

With this set of constraints, forms with two ejectives or two aspirates violate both sets of OCP constraints as well as the constraints on ejectives and aspirates following any kind of stop. In models of gradient wellformedness, grammaticality is correlated with both the number of violations incurred and the weighting or ranking of the violated constraints (Coetzee & Pater 2008; Hayes & Wilson 2008). The multiple constraint violations incurred by pairs of ejectives and pairs of aspirates also contribute to the illformedness of these forms, though the experimental results suggest that *[cg][cg] and *[sg][sg] may not be strong enough to have an impact on all tasks.

6 Conclusion

This paper has shown that phonotactic restrictions in Quechua target aspirate and ejective stops to the exclusion of their glottal counterparts, supporting the natural classes [aspirate] and [ejective] in addition to [sg] and [cg]. While the laryngeal phonotactics of Quechua can be described with constraints on [sg] and [cg] alone (Parker & Weber 1996; MacEachern 1999; Mackenzie 2013), Quechua speakers' experimental behavior reflects restrictions on aspirate and ejective stops specifically, and only weakly shows evidence for restrictions on the [sg] and [cg] classes. It is proposed that the particularly salient acoustic properties of aspirate and ejective

[3] The assumption here is that [ʔ] is not truly a stop (Garellek 2014).

stops relative to their glottal counterparts is responsible for the use of these classes in the phonological grammar.

While the results here provide support for the activity of aspirate and ejective classes, the results also reflect restrictions on [sg] and [cg]. Roots with [h]-aspirate and [ʔ]-ejective combinations are unattested, and a dispreference for roots with these combinations is found on one of the three behavioral tasks. Indeed, it would be quite surprising if Quechua speakers' had no representation of this restriction, as much previous work has found evidence for speaker knowledge of very fine grained phonotactic patterns (Vitevitch & Luce 1999; Bailey & Hahn 2001; Kessler & Treiman 1997; Frisch et al. 2001; Vitevitch & Luce 2005; Daland et al. 2011). The repetition task and forced choice experiment may have found no effect of restrictions on [sg] and [cg] because the restriction is relatively weak and doesn't cause the same perceptual and production difficulties that restrictions on aspirates and ejectives do. Alternatively, it may be that these restrictions only show up on specific tasks because they are represented differently than restrictions on aspirates and ejectives. If the dispreference for [h]-aspirate and [ʔ]-ejective combinations is due to a relatively weak phonotactic restriction on [sg] and [cg], then these structures should be treated as more illformed than other non-existent structures that would traditionally be analyzed as accidental gaps, e.g., there are no [j]-ejective combinations in Quechua, [ɲ]-[p^h] is an unattested onset combination, etc. Future work will aim to further understand the role of the [sg] and [cg] natural classes in Quechua by exploring these comparisons.

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