An Ultrasound Study of Connemara Irish Palatalization and Velarization

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1. Introduction

Irish is well known for its use of contrastive secondary palatalization, as in *bán* [bɔːn] 'white' vs. *beann* [bʲɔːn] 'peak'. This distinction pervades virtually the entire consonant system; it is found in all word positions including word-finally, and it can have grammatical significance, as in *cat* [kat] 'cat (sg.)' vs. *cait* [katʲ] 'cat (pl.)'. As will be seen below, the non-palatalized consonants are often velarized.

Though secondary palatalization contrasts are well known, our understanding of the articulatory facts behind palatalization is limited. This is true even for better-studied languages with phonemic palatalization, such as Russian, where until recently articulatory data on a given sound was often limited to x-ray tracings of very few tokens produced by very few speakers (e.g., Fant 1960; Bolla 1981; see discussion in Proctor 2009:124-5). It is all the more true of Irish, for which there are only a few electropalatographic studies (e.g., Farnetani et al. 1991; Ní Chasaide & Fealy 1991).

In this paper we present the first ultrasound study of Irish, focusing on the realization of tongue body position in the secondary palatalization (and velarization) contrast. Unlike electropalatography, ultrasound imaging can provide direct information about tongue body shape and movement, crucial to an understanding of palatalization and velarization. Our data come from a variety of Connacht Irish spoken in Connemara, in the west of Ireland. It covers the articulatory realization of the palatalization contrast across place of articulation, manner (plosive vs. fricative) and vowel backness ([iː] vs. [uː]), for consonants in word-initial position.

Our results will thus facilitate a better descriptive understanding of Irish palatalization and velarization, and should be of interest to phonologists, phoneticians, dialectologists, and Irish language learners. Impressionistic descriptions of Irish palatalization can be imprecise or incorrect in certain regards, as will be seen. In addition, though our primary aim in this paper is descriptive, quantified articulatory data bear directly on theories of coarticulation, feature (in)variance, and contrast realization, among other areas.

Examination of our data leads to a number of general conclusions. First, tongue body position robustly distinguishes palatalized from non-palatalized consonants in our data, across place of articulation, manner, and vowel place contexts. Second, non-palatalized consonants are generally robustly velarized. These conclusions hold equally for labial consonants, contrary to some descriptive claims. Third, the systematic exceptions to the claim about velarization are the coronal consonants and [x], where velarization is present but consistently weaker. Finally, the tongue body realizations involved in the palatalization contrast are remarkably invariant across the place, manner, and vowel contexts we investigate (with the exceptions already mentioned), in spite of impressionistic differences in the realization of the contrast reported in the literature on Irish.

A primary result of our analyses are tongue surface outlines, estimated from several tokens, which represent the characteristic tongue body position for each speaker and each consonant (palatalized or velarized), broken down according to the factors of consonant place, manner, and vowel place. We provide representative diagrams where relevant in this paper. The rest of the tongue surface plots, and the processed raw data from which they are derived, can be found at [URL HERE].

2. Background
2.1 Irish

Irish (or Gaeilge) has a good deal of Irish state support. Nevertheless, Irish is a minority language in Ireland and could be regarded as highly endangered. According to a recent government strategy document, "Irish is the main community and household language of 3% of the country's population" (Government of Ireland 2006). This would put the number of such speakers at roughly 137,000, though many sources estimate fewer speakers. For example, Walsh (2011:29) cites census data in which only 1.8% of the population (roughly 72,000 speakers) reported speaking Irish daily outside of the education system.

On the other hand, a much larger proportion of the Irish population reports some fluency in the language. Indeed, there are many more people learning and speaking Irish as a second language than as a first language, in Ireland as well as elsewhere, and such learners may constitute the future of Irish (McCloskey 1997, 2001). Since the phonemic contrast between palatalized and velarized consonants characterizes most of the consonant inventory, it poses one of the fundamental challenges for second language learners of Irish. It should also be noted that the palatalization contrast is arguably itself endangered and waning in the speech of younger speakers, even in Irish speaking communities, because of the heavy influence of English (Ó Curnáin 2007). These observations underscore the importance of documentation of the contrast in the traditional dialects.

The shaded portions of Figure 1 show the Gaeltachtaí – areas where Irish is spoken as a community language – of the Republic of Ireland, based on census data of 2011. It is conventional to distinguish three major dialects of Irish, those of Ulster, Connacht, and Munster. Connemara is within the Connacht dialect area and lies to the west of the city of Galway. Our recordings for this dialect were made in Casla.

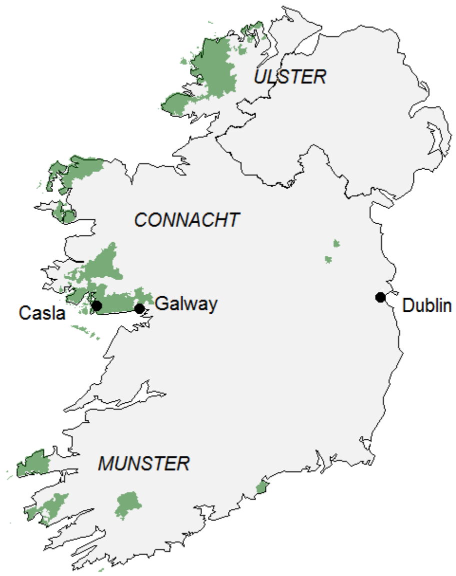

Figure 1: Gaeltachtaí (Irish speaking areas) of Ireland, following the 2011 Republic of Ireland census.

The consonant phoneme inventory of Connemara Irish is given below (de Bhaldraithe 1945; Ó Siadhail 1991; Ní Chiosáin & Padgett 2012). Palatalized consonants are marked with a superscript *j*. The Connemara vowel system can be roughly described as /i,e,a,o,u/, each occuring in long and short form.

(1) Connemara Irish phonemic consonant inventory[1]

	Labial		Coronal		Dorsal		Glottal	
Stop	p	p^j	t	t^j	k	k^j		
	b	b^j	d	d^j	g	g^j		
Fricative	f	f^j	s	s^j	x	x^j	h	(h^j)
	v	v^j			(ɣ)	($ɣ^j$)		
Nasal	m	m^j	n	n^j	ŋ	$ŋ^j$		
Liquid			l	l^j				
			r	r^j				

[1] See Ní Chiosáin and Padgett (2012) on the differences between this inventory and that of the Gaobh Dobhair, County Donegal dialect described in Ni Chasaide (1995). The sounds [h^j,ɣ,$ɣ^j$] appear only word-initially, and only as a result of grammatically conditioned lenition. The 'voiceless' and 'voiced' stops are generally realized as voiceless-aspirated and voiceless-unaspirated respectively, though we retain the usual transcriptions.

2.2 Palatalization and velarization
2.2.1 Introduction

We use the term '(secondary) palatalization' here to refer to a [j]- or [i]-like gesture accompanying a primary consonantal place gesture (International Phonetic Association 1999: 17). Velarization might likewise be described as a [ɰ]- or [ɯ]-like gesture accompanying the primary gesture (though we employ the conventional notation $C^{ɣ}$; see below for details on the articulatory realization of these sounds). As will be seen, the Irish non-palatalized consonants are velarized. The descriptive grammatical literature on Irish is consistent with this general understanding: 'slender' (palatalized) consonants are described as having a secondary articulation of the tongue resembling that of a high front vowel, 'broad' (velarized) consonants as having one resembling a high back vowel (de Bhaldraithe 1945; Breatnach 1947; Mhac an Fhailigh 1980).

Forms illustrating the palatalization contrast are given in (2). As the contrasts in (3) show, the presence or absence of palatalization can mark morpho-syntactic distinctions.

(2) Secondary palatalization in Cois Fharraige Irish

beann	[bʲɔːn]	'peak'	*bán*	[bɔːn]	'white'
peann	[pʲɔːn]	'pen'	*pán*	[pɔːn]	'pawnshop'
bráid	[brɔːdʲ]	'neck, throat'	*brád*	[brɔːd]	'drizzle'
scáil	[skɔːlʲ]	'shadow'	*scál*	[skɔːl]	'supernatural being'

(3) Palatalization encodes grammatical distinctions

cait	[katʲ]	'cat (pl.)'	*cat*	[kat]	'cat (sg.)'
báid	[bɔːdʲ]	'boat (nom.pl.)' (gen.sg.)	*bád*	[bɔːd]	'boat (nom.sg.)' (gen.pl.)

Compared to their non-palatalized counterparts, palatalized consonants have raised second formants (Ní Chasaide 1990; Ní Chiosáin & Padgett 2012). Palatalized plosives, particularly coronals when compared to labials, have releases that are louder, longer, and higher in spectral center of gravity (Ní Chiosáin & Padgett 2012). In both the articulatory and acoustic respects described above, Irish palatalized and velarized consonants resemble those of Russian. (See Kochetov 2006; Ní Chiosáin & Padgett 2012 and references therein.)

2.2.2 Previous articulatory studies of a palatalization contrast

There are a number of previous articulatory studies of palatalization in Russian. Since Russian has a palatalization contrast very much like that of Irish, these are relevant to the present paper.

Skalozub (1963) presents palatograms and x-ray tracings of four Russian speakers, including juxtapositions of palatalized and non-palatalized versions of the same sound. Skalozub's consonantal data are in the context of the vowel [a], usually [a__a]. There is a consistent and robust difference in tongue body backness between palatalized and non-palatalized versions of a sound, judging (for example) by the highest point of the tongue body. Skalozub concludes that palatalized sounds involve an active raising and fronting of the tongue body. For non-palatalized labials, she concludes (p.55) that there is active tongue backing – velarization; the back of the tongue is also high. (See also Kedrova et al. 2009.) She does not suggest active tongue backing in the case of non-palatalized coronals, and the tongue body is also less high for these sounds. Non-palatalized velars have a high, back tongue body, but it is not obvious how much of this can be attributed to an active velarization gesture rather than to the primary velar constriction itself. All of these observations seem true of Matusevich and Liubimova's (1963) x-ray data as well.[2]

Based on an EMMA analysis of several Russian speakers uttering nonsense words containing [p,p^j,t,t^j] in the context [a__a], Kochetov (2002) also concludes that palatalization involves active tongue body raising and fronting. He describes non-palatalized [p] as 'partially velarized', with active backing but not raising (p.72), but non-palatalized [t] as unspecified for any tongue body gesture. In fact, Kochetov finds that this sound is slightly fronted (still significantly backed compared to [t^j]); however, it should be borne in mind that this is in relation to the tongue body position for [a].

Proctor (2009) examines the tongue body properties of palatalized and non-palatalized [r,l,d] in Russian, based on ultrasound data for four speakers. Proctor's data are in the context of the vowels [u,a,e], using nonsense words. Proctor concludes that the tongue dorsum of non-palatalized [d] adopts the position of the neighboring vowel and that this sound therefore has no tongue body target, similarly to Kochetov. Proctor describes the tongue body gesture of non-palatalized [r] as "mid-central" and that of [l] as "mid-back".

Although most sources on the production of the Russian contrast define palatalization and velarization in terms of tongue body position, some instead suggest an understanding in terms of pharyngeal cavity width. Fant (1960:171) associates palatalization with a wide pharynx and velarization ("or rather...pharyngealization") with a constriction at the upper pharynx or uvula. We doubt that the Russian palatalization contrast should be identified primarily with pharyngeal width, since its most robust correlate is the second formant at

[2] Another source of x-ray tracing data on Russian palatalization is Bolla (1981). However, Bolla presents only one repetition of one speaker for each consonant type, and he does not control for adjacent vowel or position in the word.

the consonant-vowel transition (Jakobson et al. 1952; Halle 1959; Purcell 1979; Kochetov 2006), a property whose articulatory correlate (apart from the lips) is the location of the tongue body constriction in the oral cavity (see, e.g., Stevens 1998 on the articulatory correlates of the vowel formants). While palatalization does affect the first vowel formant, this effect is small in comparison to the effect on the second formant and can be explained by effects on the pharyngeal cavity of raising and fronting the tongue (Stevens 1998:263).

A persistent theme in the literature on Russian palatalization involves the prevalence or existence of velarization compared to palatalization (see discussion in Kochetov 2002:58-9; Proctor 2009:124-5). While palatalized sounds always involve tongue body raising and fronting, the tongue body realizations of non-palatalized sounds may be more variable (Kedrova et al. 2008). Labial consonants seem to have more robust velarization than coronals, as discussed above. In addition, velarization seems to depend on vowel context, and it is noteworthy that almost all of the studies cited above examine the contrast only in the context of [a]. While velarization may be weak (at least for some sounds) in that context, with the tongue body assuming something like the position of the vowel, this is clearly not the case before front vowels, where velarization of non-palatalized consonants is highly audible (Padgett 2001, 2010).

There are no previous articulatory studies of the Irish palatalization contrast that involve direct imaging of the tongue body, the articulator thought to be most relevant to the palatalization contrast, as discussed in the last section. However, using EPG, Farnetani et al. (1991) examined Irish [tˠ,tʲ,sˠ,sʲ,nˠ,nʲ,lˠ,lʲ,kˠ,kʲ] produced by one speaker in the context of [i,u,a]. The authors note that this speaker does not actually produce the palatalization contrast for the two sonorants, so only their findings regarding the obstruents are helpful for our purposes. Of these, the authors note that [sʲ,kʲ] involve tongue predorsum raising, and both show a good deal of tongue dorsum contact; [kʲ] is described as palatal. In addition, Farnetani et al.'s data suggest that some Irish consonants, especially [tʲ,kˠ,kʲ], resist coarticulation with a neigboring vowel compared to similar consonants in Catalan or Italian, and they relate this fact to the existence of contrastive palatalization in Irish. In a separate EPG study focusing on coarticulation, Ní Chasaide and Fealy (1991) examined /bˠ,bʲ,dˠ,dʲ,gˠ,gʲ/ of one speaker between long vowels and concluded that the consonants show less articulatory and acoustic coarticulation to vowels than similar consonants in French, Italian, and Swedish. (Their EPG data excluded the labials.) What little coarticulation there is is carryover and is stronger at the onset of the consonant than at the offset. The authors conclude that Irish supports the hypothesis that consonants resist coarticulation more when there are more consonantal contrasts.[3]

The purpose of our ultrasound study is to provide direct evidence about the behavior of the tongue body in the Irish palatalization contrast. We examine three places of articulation, including labials, which were not included in Farnetani et al.'s study. Our data relies on multiple speakers producing multiple repetitions in highly controlled contexts, and we quantify our results. Though we employ only two vowel contexts [iː,uː], these vowels

[3] We are aware of but have not had access to one more study (Ní Chasaide 1990).

represent the most extreme degrees of backness/frontness and so make good touchstones for gauging degrees of palatalization or velarization and degree of coarticulation between consonant and vowel. Finally, this study is part of a larger project gathering ultrasound data from all three major Irish dialects.

2.3 Goals of the study

Our ultrasound study focuses on what we take to be the primary articulatory correlate of secondary palatalization and velarization, the fronting vs. backing of the tongue body. It is a basic goal of this work to document the tongue body postures that realize the palatalization contrast. In addition, we address the following specific questions:

(4)

a. Does tongue body backness indeed consistently distinguish palatalized from non-palatalized consonants?
b. Do non-palatalized consonants involve an active secondary tongue body gesture; in particular, are they velarized?
c. Does the tongue body realization in these consonants depend on primary place of articulation or manner, or on a neighboring vowel's place? If so, how?

Question (4)c can be elaborated on in two ways. First, to what extent does tongue body position represent an invariant articulatory correlate of the Irish palatalization contrast? Based on impressionistic characterizations there seems to be a great deal of variation in the realization of Irish palatalization, a matter we return to in the discussion. Second, does degree of velarization vary depending on place of articulation, as it seems to in Russian?

3. Methods

3.1 Speakers

Our five speakers were all broadcasters for RTÉ Radió na Gaeltachta (the national broadcaster's Irish medium radio station), working in the station located in Casla, Connemara, where the recordings were made. In a sociolinguistic context in which the speaker base is rapidly declining, the speakers recorded are all considered exemplary speakers of their dialect. Because of their occupation, they are comfortable with sound technology and speaking while being recorded. They were two women (aged 46, 47) and three men (aged 35, 59, 60). They are all native speakers of Connemara Irish, and all of them use primarily Irish in their daily interactions. We provide more detail about their language backgrounds in the Appendix. None reported any difficulties in hearing, speaking, or reading.

3.2 Materials

The materials were designed to allow us to investigate the realization of palatalization as a function of consonantal place, manner (plosive vs. fricative) and vowel context ([iː] vs.

[uː]).[4] Speakers read a pseudorandomized list of 24 Irish words, with target consonants appearing word-initially in a CV(C) syllable. Target consonants were /p (b), pʲ (bʲ), f, fʲ, t, tʲ, s, sʲ, k, kʲ, x, xʲ/. The consonant /b/ was sometimes used instead of /p/ because word-initial /p/ has a limited occurrence in Irish for historical reasons.[5] Each consonant appeared before both /iː/ and /uː/. Words appeared in the carrier phrase *Scairt Aoife* _____ *Dé Céadaoin* [skartʲ iːfə _____ dʲeː kʲeːdiːnʲ] 'Aoife shouted ___ on Wednesday'. Tautosyllabic codas, if they occurred, were non-palatalized coronal consonants except in the case of [fiːʃ]. The full list of words used is given in Table 1. (Palatalized /s/ is realized as [ʃ] or [ɕ].)

	Plosive				Fricative			
	iː		uː		iː		uː	
	Vel	Pal	Vel	Pal	Vel	Pal	Vel	Pal
Labial	*buí* [biː] 'yellow'	*píosa* [pʲiːsə] 'piece'	*púca* [puːkə] 'ghost'	*b'fhiú* [bʲuː] 'it would be worth'	*faoi* [fiː] 'about'	*fís* [fʲiːʃ] 'vision'	*fút* [fuːt] 'about (2nd sg.)'	*fiú* [fʲuː] 'worth'
Coronal	*tuí* [tiː] 'straw'	*tígh* [tʲiː] 'house (gen.)'	*tús* [tuːs] 'beginning'	*tiús* [tʲuːs] 'thickness'	*suí* [siː] 'sitting'	*síos* [ʃiːs] 'downward'	*sú* [suː] 'juice'	*siúl* [ʃuːl] 'walking'
Dorsal	*caoi* [kiː] 'way, means'	*cíor* [kʲiːr] 'comb'	*cú* [kuː] 'hound'	*ciúnas* [kʲuːnəs] 'silence'	*chaoin* [xiːn] 'cried'	*chíor* [xʲiːr] 'combed'	*chúala* [xuːlə] 'heard'	*chiúnaí* [xʲuːniː] 'hushed'

Table 1: Word list

Speakers read through the list 6-8 times, for a total of 144-192 productions (between 4 and 8 useable repetitions, depending on speaker and item). No two successive stimuli began with a consonant of the same major place.

3.3 Procedure

Ultrasound data was collected using a Terason T3000 ultrasound system with a model 8MC3 probe. The ultrasound machine recorded video at a rate of 57 frames per second, giving one new image roughly every 17.5ms. The probe was mounted in an Articulate Instruments Ultrasound Stabilization Headset, which was worn by the speakers throughout the experiment. (See Scobbie et al. 2008 for validation of this headset for probe stabilization.) Acoustic data was collected simultaneously using a Shure WH20 dynamic cardioid microphone attached to the headset, recording directly to the ultrasound system (which includes a laptop computer).[6] Each recording session lasted about one hour.

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[4] The quality of short vowels is largely determined by neighboring palatalized consonants in Irish (Ó Siadhail 1991; Ní Chiosáin 1994), though we abstract away from this fact in our transcriptions. Using long [iː,uː] allows us to explore the effect of vowel quality on the realization of palatalization.

[5] Word-initial voiced stops are often realized as plain voiceless in Irish (see footnote 1). This should mitigate any possible deformation of the tongue dorsum caused by voicing during closure (Perkell 1969:21, 27).

[6] We also captured lip movement using video, though lip movement data are not analyzed here.

3.4 Data analysis
3.4.1 Data capture

For each token we used the release of a velar stop in the carrier phrase (the [k] in 'scairt' [skart^j]) to align the ultrasound video with its corresponding audio recording. (See discussion in Miller & Finch 2011:476.) Using EdgeTrak software (Li et al. 2005), the tongue surface shape was captured as 100 points at five instants in time for each token: consonantal onset minus 40 ms, consonantal onset, midway between consonantal onset and offset, offset, and offset plus 40ms. Consonantal onset and offset were judged using landmarks in the waveform and spectrogram of the audio signal.

Since the temporal dynamics of the palatalization contrast are not the focus of this paper, the analyses here are based primarily on one instant in time, and for this purpose we chose the consonantal onset. On the one hand, some prior research suggests that secondary palatalization and velarization gestures may peak at consonantal offset (e.g., Kochetov 2002), at least for consonants in word- or syllable-initial position, and this is a reason to focus primarily on the offset. On the other hand, there were several reasons to prefer the consonantal onset. First, we are interested in canonical postures for the palatalization contrast independent of vowel context; since our consonants are prevocalic, they show less influence of the vowel at the consonantal onset. Second, there is some concern about whether our offset data for stops capture the same point in the cycle of the secondary articulation compared to that of fricatives. This is because "offset" was defined for both sounds to coincide with the onset of periodic energy of a following vowel; but since voiceless stops in Irish are aspirated, this arguably locates the "offset" for stop consonants further into the vowel compared to that of fricatives. Finally, whether or not secondary palatalization and velarization gestures peak at consonantal offset, all previous research makes clear that they overlap the entire primary constriction, so we are unlikely to miss basic patterns in focusing on consonantal onset. Having said this, we do present a limited examination of consonantal onset vs. offset properties in Section 4.6, including the effect of vowel place in both onset and offset position.

The 4-8 tongue surface tracings acquired for each target word, for each speaker, were submitted to smoothing spline ANOVA (SSANOVA, Gu 2002; Davidson 2006) to find a best-fit curve. These best-fit curves can be interpreted as characteristic tongue shapes for a particular speaker's production of each consonant type. The final output of the SSANOVA algorithm is a surface consisting of a string of points separated by 0.01mm on the X-axis, with associated standard errors corresponding to y-axis variability at each point. We use these standard errors to estimate 95% Bayesian confidence intervals around each surface. Resulting plots can be seen in Figure 2, which shows Speaker 1's estimated tongue surfaces for palatalized vs. non-palatalized versions of every consonant in each vowel context (at consonant onset). In these figures, the front of the mouth is to the right. The dotted lines represent the 95% Bayesian confidence intervals around the tongue position. Where the confidence intervals of two lines do not overlap, we may assume that the tongue surfaces are significantly different. All SSANOVA curves were computed using the gss package (Gu 2013) in the R statistical software environment (R Development Core Team 2013).

3.4.2 Quantifying results

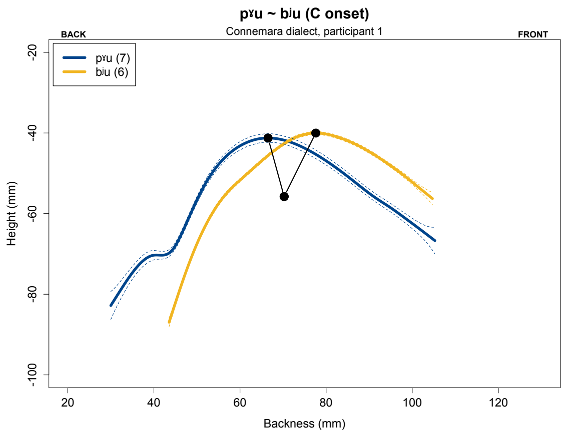
In order to produce replicable results, we must be able to quantify degree of palatalization or velarization. Some questions can be answered by directly comparing consonants of one type with those of another, a relative measure. For example, we might ask whether coronal consonants display weaker velarization than labials, and assess this possibility by comparing the tongue body shapes and positions for each consonant type. However, other questions presuppose a more 'absolute' measure. For example, we might hypothesize that certain non-palatalized consonants in Irish are actively velarized while others are not. Indeed, whether phonemically palatalized consonants are opposed to truly velarized consonants, or simply to plain consonants, may be a parameter of cross-linguistic variation (see, e.g., Toda & Honda 2003 for Japanese). In order to describe consonants as palatalized or velarized at all, or to talk about degrees of palatalization and velarization, we must rely on some stable landmark.

We follow Proctor (2009) in interpolating a hypothesized central 'schwa' point for this purpose.[7] We estimate the schwa points for each speaker by taking the (x,y) coordinates of every point on every SSANOVA surface we have for that speaker for all five timepoints, and including reference [k] tracings (see footnote 7). The x-axis and y-axis means are calculated from these points, along with standard deviations. X-axis and y-axis extremes are then determined by removing any points falling more than 2.25 standard deviations away from the mean along either axis. The schwa point is placed at the center of these adjusted x-axis and y-axis ranges. This point can be seen in all the plots of Figure 2.

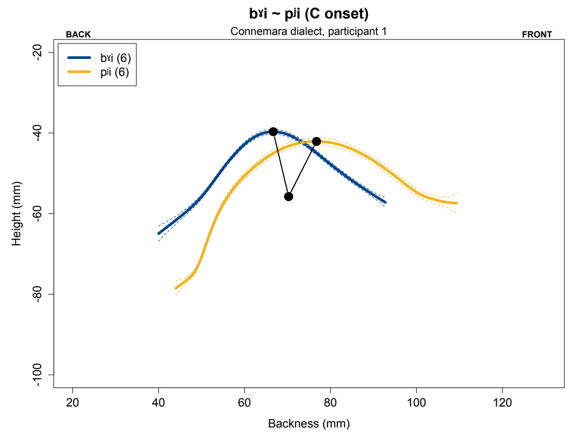
An independent question is what precise feature of the tongue curves we measure in order to determine degree of palatalization or velarization. As discussed in Section 2, we assume that tongue body position is the primary articulatory correlate of the contrast. As Proctor (2009) does, we therefore take the peak of the tongue body as a proxy measure. These tongue body peaks can also be seen in Figure 2.

[7] We explored an alternative, using the highest point of the tongue body for a reference [k] for each speaker (based on 30 repetitions), where "reference [k]" refers to the position of the tongue at the onset of the [k] in the word *scairt* [skart^j] of the carrier phrase. This approach gave very similar results.

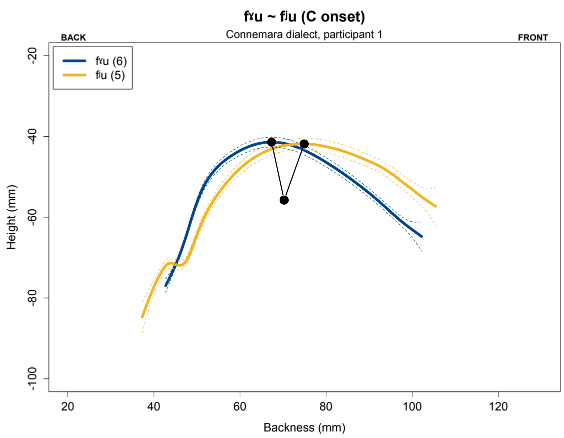
a.


pˠu ~ bʲu (C onset)
Connemara dialect, participant 1
BACK
FRONT
pˠu (7)
bʲu (6)
Height (mm)
Backness (mm)

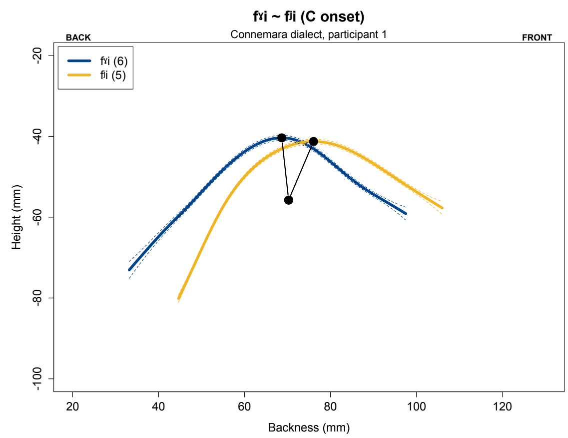
b.


bˠi ~ pʲi (C onset)
Connemara dialect, participant 1
BACK
FRONT
bˠi (6)
pʲi (6)
Height (mm)
Backness (mm)

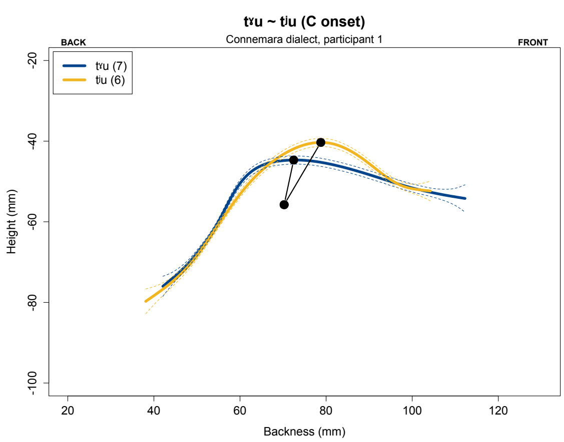
c.


fˠu ~ fʲu (C onset)
Connemara dialect, participant 1
BACK
FRONT
fˠu (6)
fʲu (5)
Height (mm)
Backness (mm)

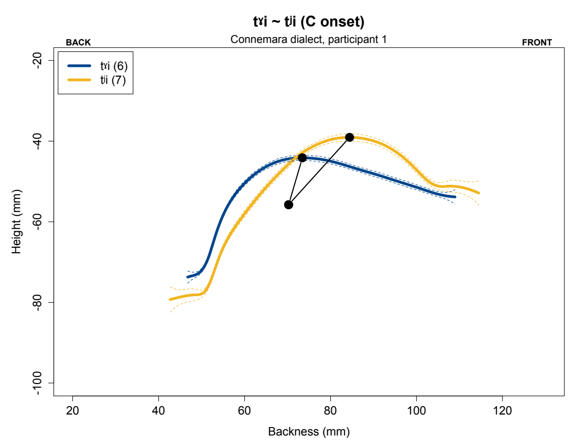
d.


fˠi ~ fʲi (C onset)
Connemara dialect, participant 1
BACK
FRONT
fˠi (6)
fʲi (5)
Height (mm)
Backness (mm)

e.


tˠu ~ tʲu (C onset)
Connemara dialect, participant 1
BACK
FRONT
tˠu (7)
tʲu (6)
Height (mm)
Backness (mm)

f.


tˠi ~ tʲi (C onset)
Connemara dialect, participant 1
BACK
FRONT
tˠi (6)
tʲi (7)
Height (mm)
Backness (mm)

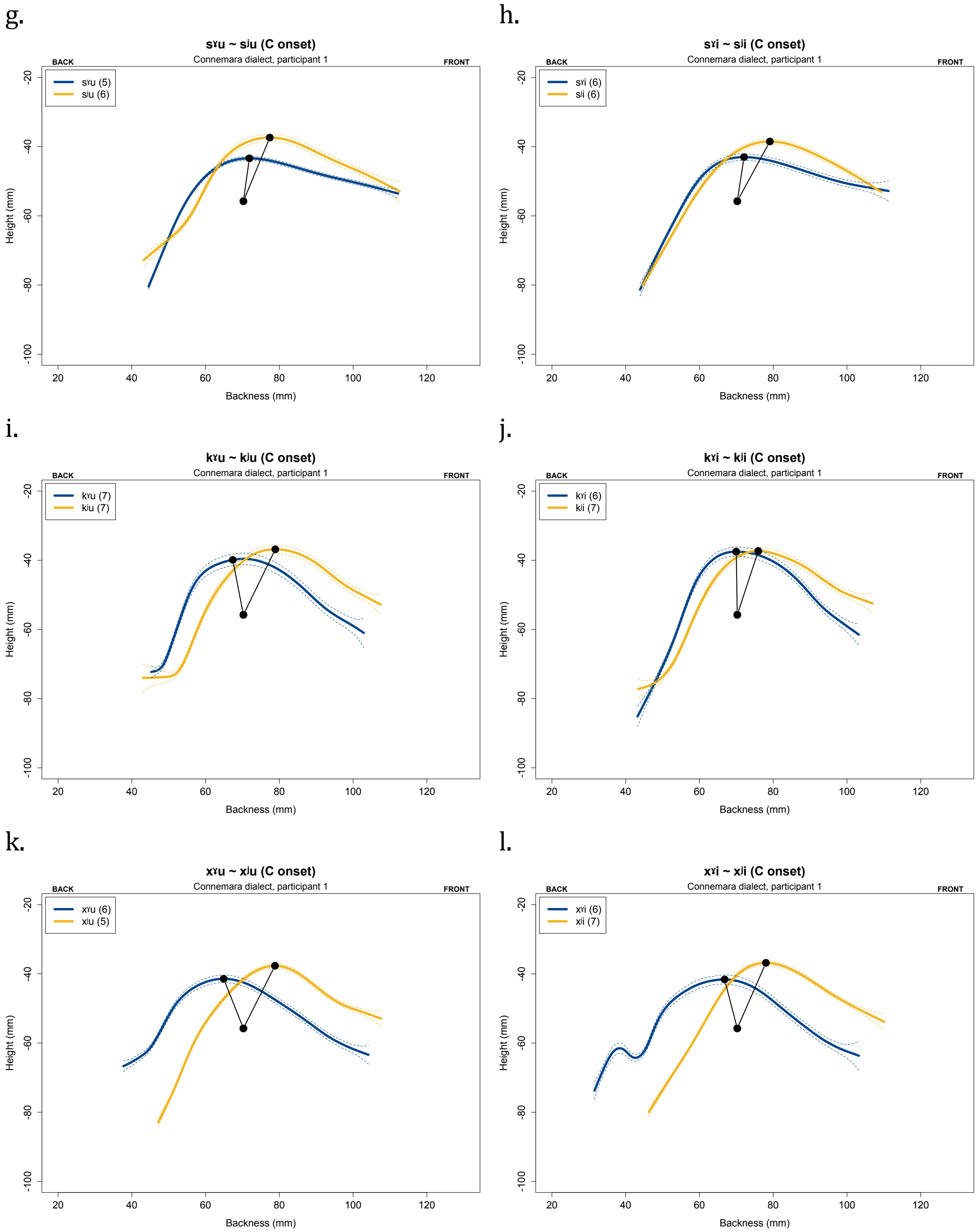


Figure 2: SSANOVA surfaces for palatalized (yellow) vs. non-palatalized (blue) consonants at consonantal onset before [uː] (left column) and [iː] (right column), Speaker 1. Labials (a-d), coronals (e-h), velars (i-l). Front of the mouth is to the right.

We employed an algorithm to locate these peaks. To find a point on the fitted SSANOVA surface that corresponds to the peak of the tongue dorsum, this algorithm seeks a relatively curved region of the tongue surface. Stone et al. (1987) find that the point of maximum curvature correlates well with the point of maximum dorsal displacement in vowels, though they use a different metric for curvature than the one used here. In our algorithm, curvature is calculated within a shifting window of analysis. At each point on the tongue surface, we calculate the curvature for a window centered on that point (using the circlefit function in the pracma package for R, Borchers 2013). This gives a curvature score for each point, providing an index of how curved the region around that point is. We use a window with a width equal to 20% of the length of the surface being analyzed.

We consider only regions of the surface that are concave-downward, i.e. flat or peak-like. (This is done by calculating second derivatives over the tongue surface). Within the concave-downward regions, we select the point with the highest curvature score. Finally, we consider the 20% window around this point of maximum curvature, and choose the highest point in that window as our inferred tongue dorsum peak. This is our measurement point. It will often, but not always be the highest point on the entire tongue surface.

The above algorithm is overly-sensitive to local 'wobbles' on the tongue surface, which occur especially in regions of the tongue that have a relatively variable shape. To filter out points that are not plausible dorsum peaks, we examine the region around each proposed measurement point. If the point is a true peak, the slopes of the surface surrounding it should be fairly small (close to flat). To assess this, we center a window on the point of interest (again 20% in size), calculate the magnitude of the surface's slope at each point in that window, and take the average. If this average slope magnitude is above a threshold (here .375), then our algorithm simply chooses the highest point on the tongue surface as the measurement point instead. For this data set, we visually inspected the measurement points chosen by this algorithm and found that they matched our own subjective judgments.

4. Results

We first discuss the palatalization contrast generally (Section 4.1). We then examine the realization of palatalization and velarization in more detail, beginning with the labial stop consonants (4.2). The following sections turn to the effects of place of articulation (4.3), manner (4.4), and vowel context (4.5).

4.1 The palatalization contrast

As can be seen in Figure 2, the tongue body positions differ significantly for all palatalized vs. non-palatalized consonants, in both vowel contexts, for Speaker 1. In particular, the tongue body is fronted in palatalized compared to non-palatalized consonants. (On tongue height facts see below.) This difference holds for every pair of palatalized vs. non-palatalized consonant matched for place, manner, and vowel context, for all five speakers. For example, Figure 3 shows the SSANOVA surfaces for palatalized vs. non-palatalized labial stops before the vowel [iː], for all 5 speakers.

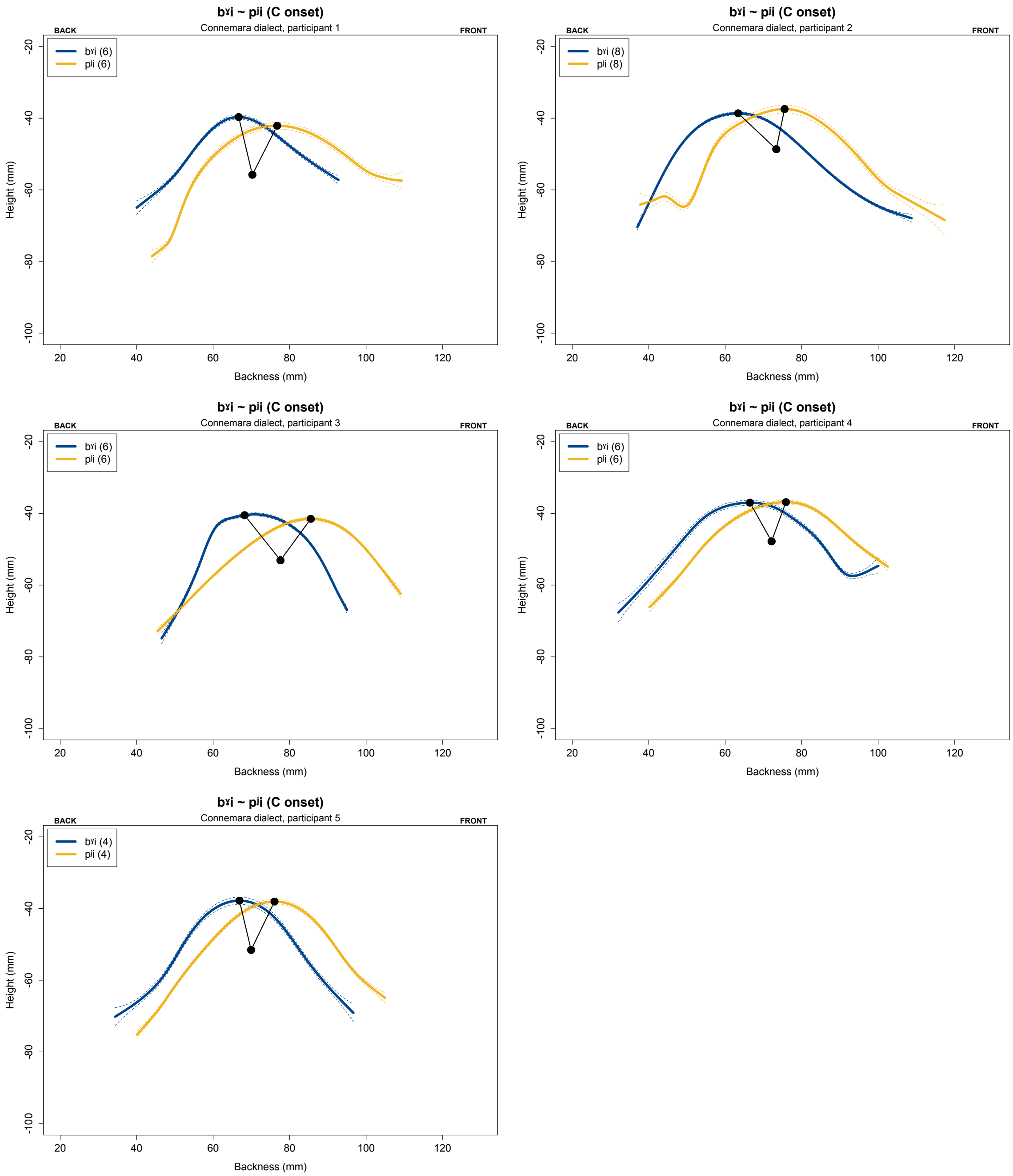


Figure 3: SSANOVA surfaces for palatalized (yellow) vs. non-palatalized (blue) [b/p] at consonantal onset before [iː], Speakers 1-5. Front of the mouth is to the right.

4.2 Palatalization and velarization in labial stops

In the plots in Figure 2 and Figure 3, our 'schwa' point tends to occupy a central position on the x-axis with respect to the tongue peaks for palatalized and non-palatalized consonants. This might suggest that consonants are indeed either palatalized or velarized, displaced in backness from a neutral position. However, we have no a priori guarantee that the 'schwa' position, which is based on the range of tongue imaging, actually approximates a neutral vocal tract position.

An examination of consonantal realizations across both vowel contexts provides independent support for both palatalization and velarization as active components of the Irish consonant articulations. It therefore also gives confidence in our interpolated ‘schwa’ as a relatively central position. Consider first the production of the palatalized labial stop before both [iː] and [uː], as shown in Figure 4. We can assume that the tongue body in *píosa* [pʲiːsə] ‘piece’ is raised and fronted: if this were not true due to palatalization, it would be true given the cross-linguistic ubiquity of consonant-to-vowel coarticulation (Recasens 1999).[8] As Figure 4 shows, the tongue body position before [uː] is very similar to that before [iː] (if anything it is more fronted), implying that the tongue body is also raised and fronted in the case of *b’fhiú* [bʲuː] ‘it is worth’. In fact, this palatalization before [uː] is very audible, given the difference in backness between the palatalized consonant (high second formant) and a high back vowel (low second formant).[9] A plot showing formant transitions (over 7 repetitions with Loess smoothing lines), for Speaker 1’s productions of [bʲuː], is given in Figure 5 (left). The overall F2 transition seen likewise supports a raised and fronted tongue body for the palatalized labial stop.

Since all of our consonants were produced before a high vowel (either [iː] or [uː]), we might expect [p/b] to evince high tongue body positions simply due to consonant-to-vowel coarticulation.[10] What we can safely conclude from our data so far is that palatalized labial stops have fronted tongue body targets.

As for the non-palatalized labial stops, Figure 3 shows that their tongue body is equally high, though further back. This relatively back position before [iː] might imply active velarization. Consider now Figure 6, which shows non-palatalized [p/b] before both [iː] and [uː]. We can assume that the tongue body in *púca* [puːkə] ‘ghost’ is raised and backed, if not due to velarization then due to coarticulation with [uː]. Figure 6 shows that the tongue body is equally high and back in *buí* [bˠiː] ‘yellow’, confirming velarization (which we henceforth transcribe). This velarization before [iː] is highly audible, given the transition in F2 from a velarized consonant (low F2) to a high front vowel (high F2). The plot on the right in Figure 5 shows this transition for non-palatalized [b]. Again given the high vowel context, what we can safely conclude is that non-palatalized [p/b] have back tongue body targets.

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[8] We conclude later that Irish consonants do *not* coarticulate with a following vowel that differs in backness specification, as in *b’fhiú* [bʲuː]. This could mean there is no coarticulation when backness values are the same, as in *píosa* [pʲiːsə], but in principle it is difficult to say.

[9] For readers interested in hearing the pronunciations of these and other forms, selected sound files can be found at [URL HERE].

[10] Of course, a raised tongue body before mid and low vowels would show that palatalized and velarized consonants have inherently higher tongue body targets.

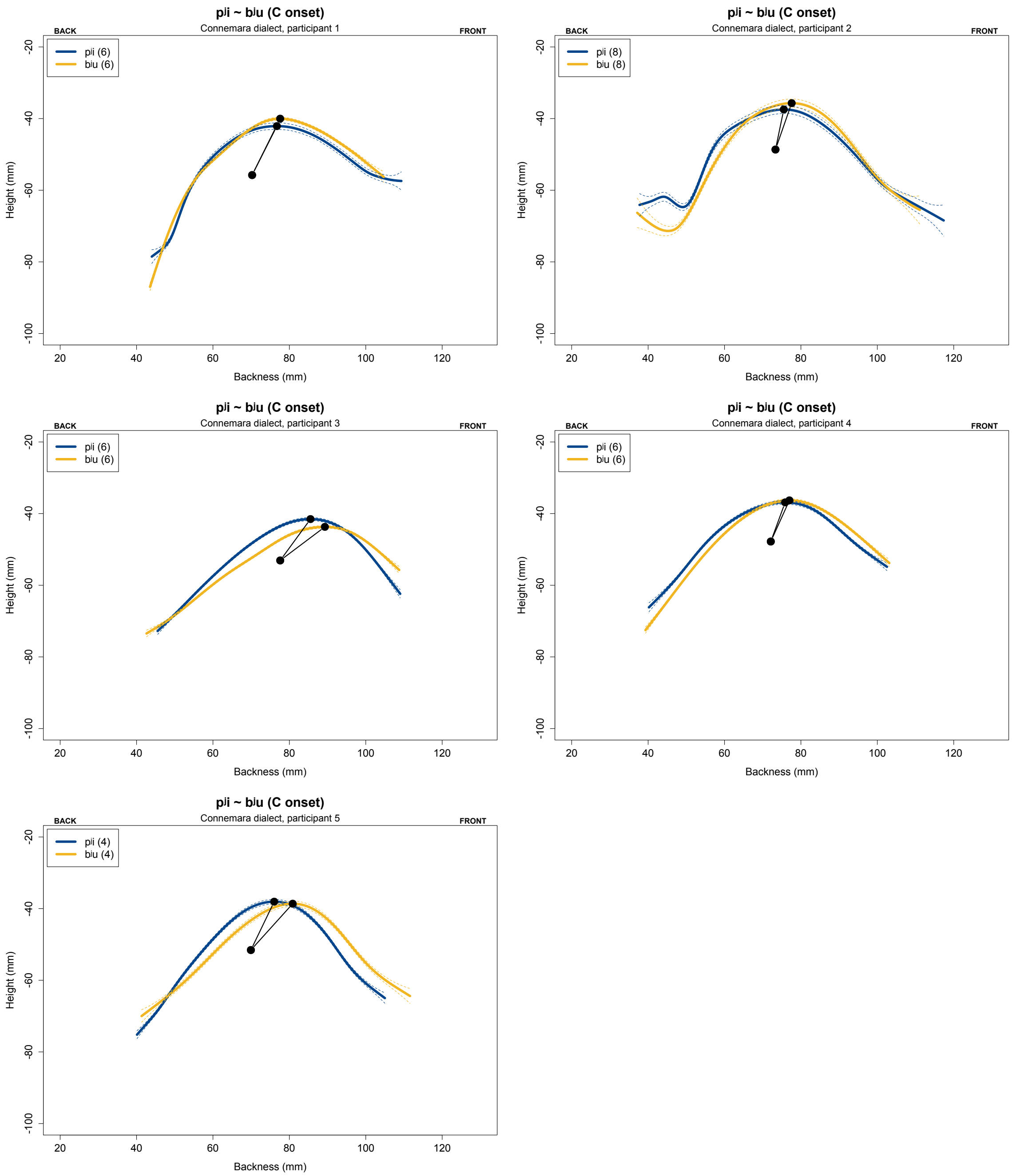

Figure 4: SSANOVA surfaces for palatalized [p/b] before [iː] (blue) vs. [uː] (yellow) at consonantal onset. Speakers 1-5.

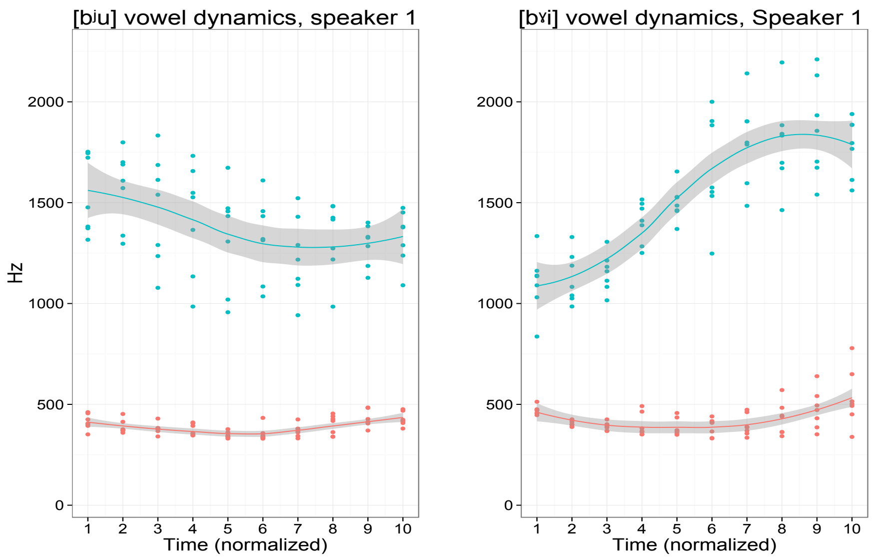

Figure 5: Plots of F1 and F2 trajectories, with Loess smoothing lines, for [bʲu:] (left) and [bˠi:] (right), Speaker 1

4.3 Effects of place of articulation

The lips and tongue are articulatorily independent; hence our results concerning palatalization and velarization in labials should reflect no articulatory constraints imposed by the primary place of articulation. We might therefore take these results to form a baseline by which we discuss tongue body realization for other places of articulation. Since it would take up too much space here to present the relevant figures for all five speakers, for the rest of the paper we present figures only for Speaker 1. However, we substantiate our general conclusions by means of statistics for all of the speakers. For readers interested in more detail, SSANOVA curves for all speakers by place, manner, vowel context, and time point can be found [URL HERE].

As noted earlier, the tongue body is fronted in C^j (any palatalized consonant) compared to C^{γ} (any velarized one) not only for [p/b] but for all consonants matched for place, manner, and vowel context, for all speakers. Figure 7 summarizes tongue body backness for all speakers and consonants, collapsed over vowel context. (We justify collapsing over vowel context in Section 4.5.) Each symbol in this figure represents the horizontal distance between the tongue body peak and our 'schwa' point, for one speaker and consonant, based on that speaker's SSANOVA plots.[11]

[11] The x-axis distances in this scatterplot were normalized for each speaker before plotting. This was done by dividing them by 20% of the standard deviation of the x-axis values for that speaker's tongue surface tracings (see Section 3.4.2 for related discussion). We normalized the y-axis values seen in Figure 9 analogously.

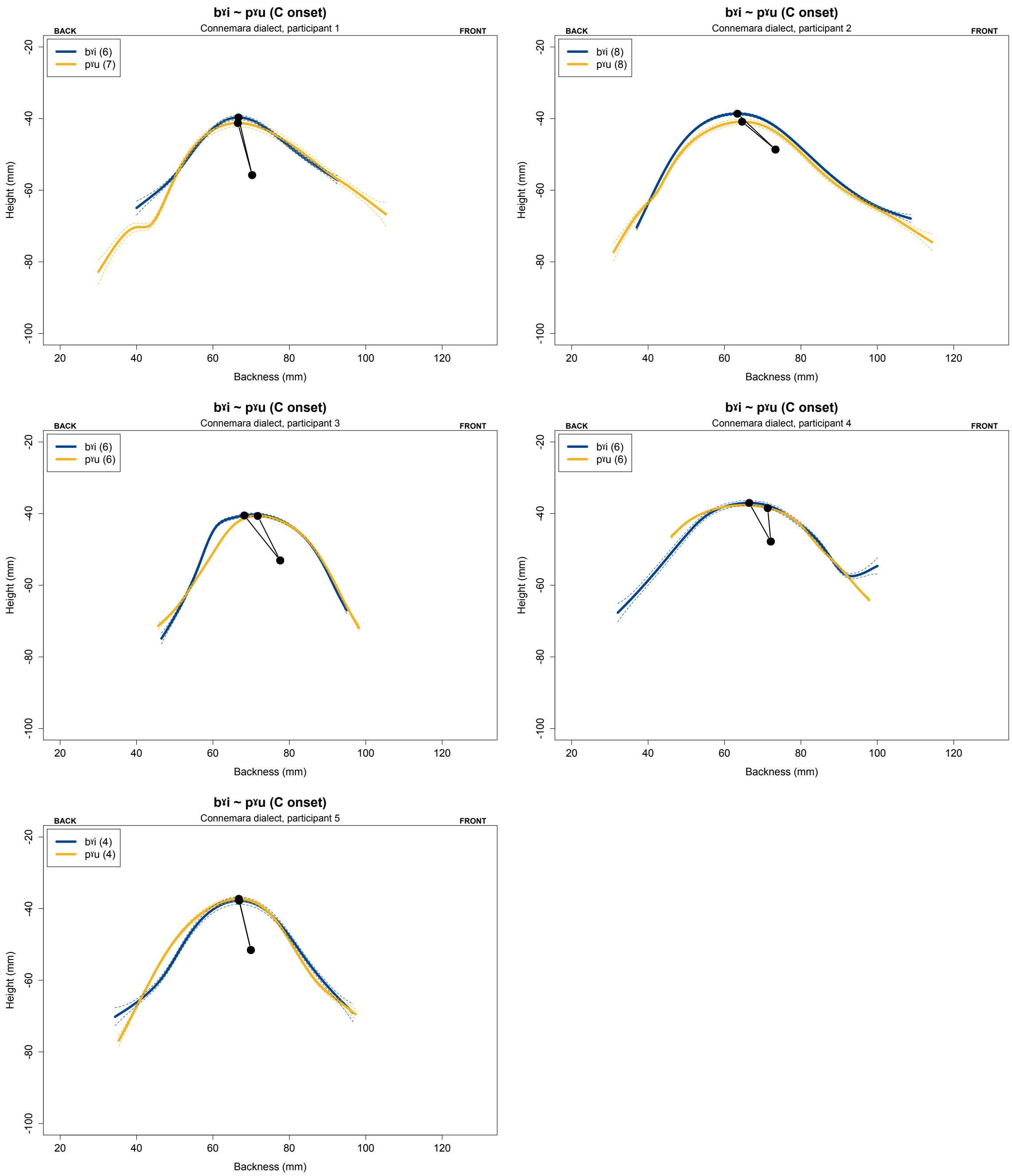

Figure 6: SSANOVA surfaces for non-palatalized [p/b] before [i:] (blue) vs. [u:] (yellow) at consonantal onset. Speakers 1-5.

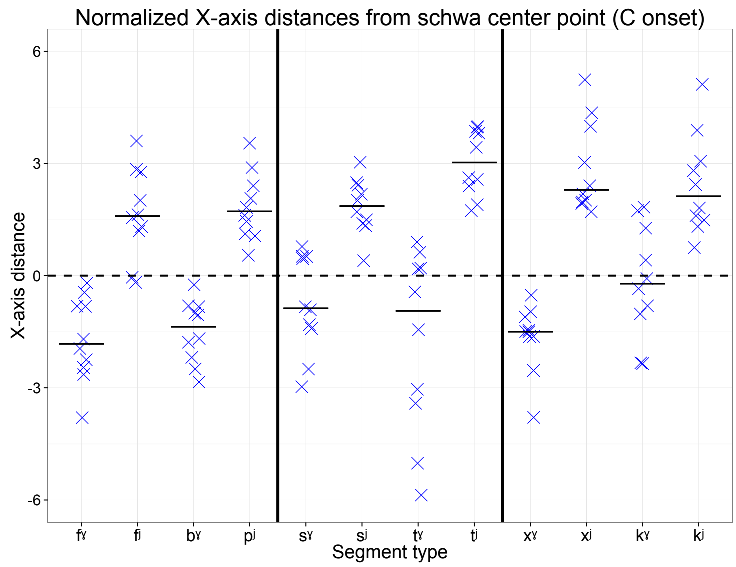

Figure 7: Tongue body backness (w.r.t. 'schwa', in normalized units) by consonant, at consonantal onset. Each symbol represents one speaker. Median values are highlighted.

The consistent separation in backness of $C^{ɣ}$ from corresponding C^{j} is evident in this figure, and indeed the backness distinction seems to depend very little on primary place of articulation. However, palatalized [t^{j}, k^{j}, x^{j}] are somewhat further fronted as a group than are [p^{j}/b^{j}, f^{j}, s^{j}] (W=233, p<.01).[12] Among the non-palatalized sounds, [$k^{ɣ}$] is less backed than the rest taken together (W=368, p<.05).

There are more striking effects of place of articulation on tongue body height. For example, coronal [$t^{ɣ}$] and [$s^{ɣ}$] have tongue bodies that are both backed and **lowered** compared to those of [t^{j}] and [s^{j}] respectively, something visible in Figure 2(e-h). A more direct comparison by place of articulation can be had in Figure 8, which shows SSANOVA surfaces for Speaker 1's palatalized (top row) vs. velarized (bottom row) stop consonants before both [uː] (left) and [iː] (right), this time grouped by place of articulation. The tongue body is highest for the velar stop (perhaps not surprisingly, since [k] involves a complete dorsal constriction). What stands out otherwise is the notably lower tongue body for [$t^{ɣ}$] compared to [$p^{ɣ}$] and [$k^{ɣ}$]. The fricative [$s^{ɣ}$] patterns analogously.

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[12] For this and the following comparisons, we ran Wilcoxon rank-sum and signed-rank tests. We opted for non-parametric tests because the distributions we compare are not always normal. In general, the *p*-values we report are larger (more conservative) than the *p*-values returned by parametric *t*-tests over the same comparisons. If we apply the Holm-Bonferroni correction to our tests, since we are doing multiple comparisons, all the significant findings in this section remain.

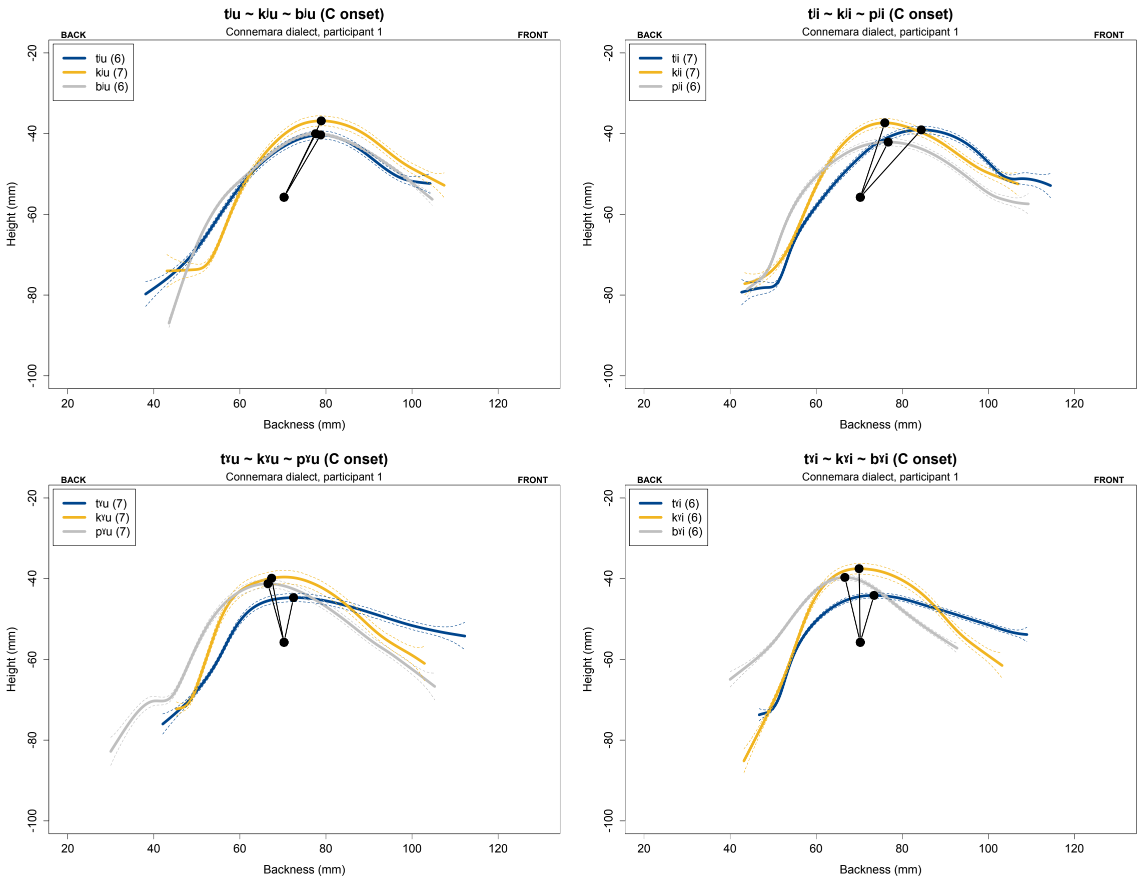

Figure 8: SSANOVA surfaces for palatalized (top row) and non-palatalized (bottom row) stops before [u:] (left) and [i:] (right), at consonantal onset. Speaker 1. Labial = gray, coronal = blue, velar = yellow.

For a more detailed examination of the facts, Figure 9 summarizes tongue body height for all speakers and consonants, collapsed over vowel context. This figure shows, first, that labial consonants occupy an intermediate position in terms of tongue height, with no difference between palatalized and velarized labials (V=110, p=0.87).[13] In contrast, the palatalized and velarized coronals differ significantly from each other (V=210, p<.001). In addition, the height of [tˠ, sˠ] is significantly lower than that of [pˠ/bˠ, fˠ] (W=345, p<.001), while that of [tʲ, sʲ] is significantly *higher* than that of [pʲ/bʲ, fʲ] (W=53, p<.001). In terms of tongue height at least, coronals seem to be weakly velarized.[14]

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13 Wilcoxon signed-rank tests (signified here with the 'V' statistic) are paired non-parametric tests, analogous to paired t-tests. The rank-sum test ('W' statistic) is an unpaired non-parametric test.

14 The sound [tˠ] seems unusually variable in its backness realization, see Figure 7. This may also be indicative of weaker velarization in this sound. The sound [sˠ] does not behave analogously, but this could be a reflection of the higher control thought to be necessary for fricatives (Recasens 1999:91), and especially sibilants (Iskarous et al. 2011), apart from any question of velarization.

Turning to the velars, [kˠ, kʲ, xʲ] have even higher tongue bodies than [tʲ, sʲ] (W=571, p<.001). But the tongue body of [xˠ] is strikingly low compared to that of [xʲ] (V=55, p<.01), a point to which we return in the next section.

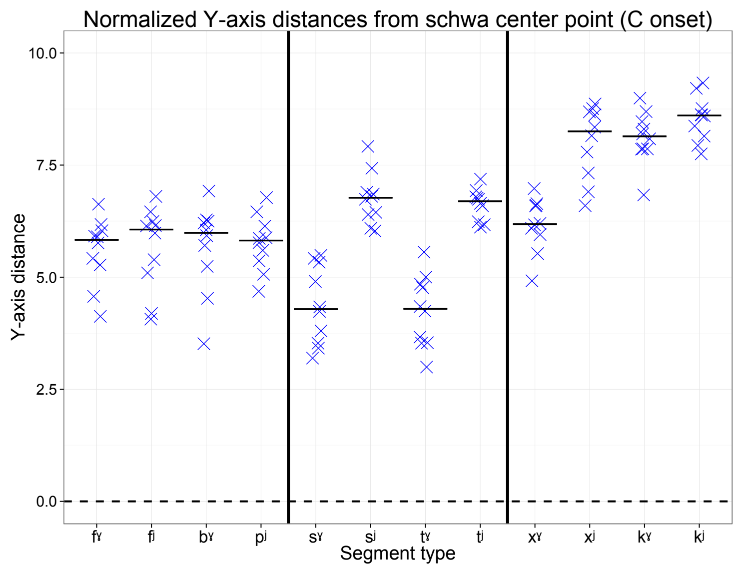


Figure 9: Tongue body height (w.r.t. 'schwa', in normalized units) by consonant, at consonantal onset. Each symbol represents one speaker. Median values are highlighted.

The effects of place of articulation on tongue body height in the Irish palatalization contrast can be summed up as follows. Among palatalized sounds, the tongue body is on average highest for velars, less high for coronals, and even less high (though still raised) for labials. The tongue body height of velarized labials is essentially equal to that of palatalized labials. However, [tˠ, sˠ] have relatively low tongue bodies. The tongue body of [kˠ] is high, though that of [xˠ] is not.

4.4 Effects of manner (and place)

Figure 2(c-d) and (k-l) show Speaker 1's characteristic tongue body positions for palatalized vs. velarized [f] and [x]. The labial fricative seems to pattern just as the labial stop does, but [xˠ] has a tongue body that is notably lowered compared to [xʲ], as seen above. These differences by manner can be seen more directly in Figure 10, which shows Speaker 1's SSANOVA surfaces for [pˠ/bˠ] vs. [fˠ] and [kˠ] vs. [xˠ] before both vowels.

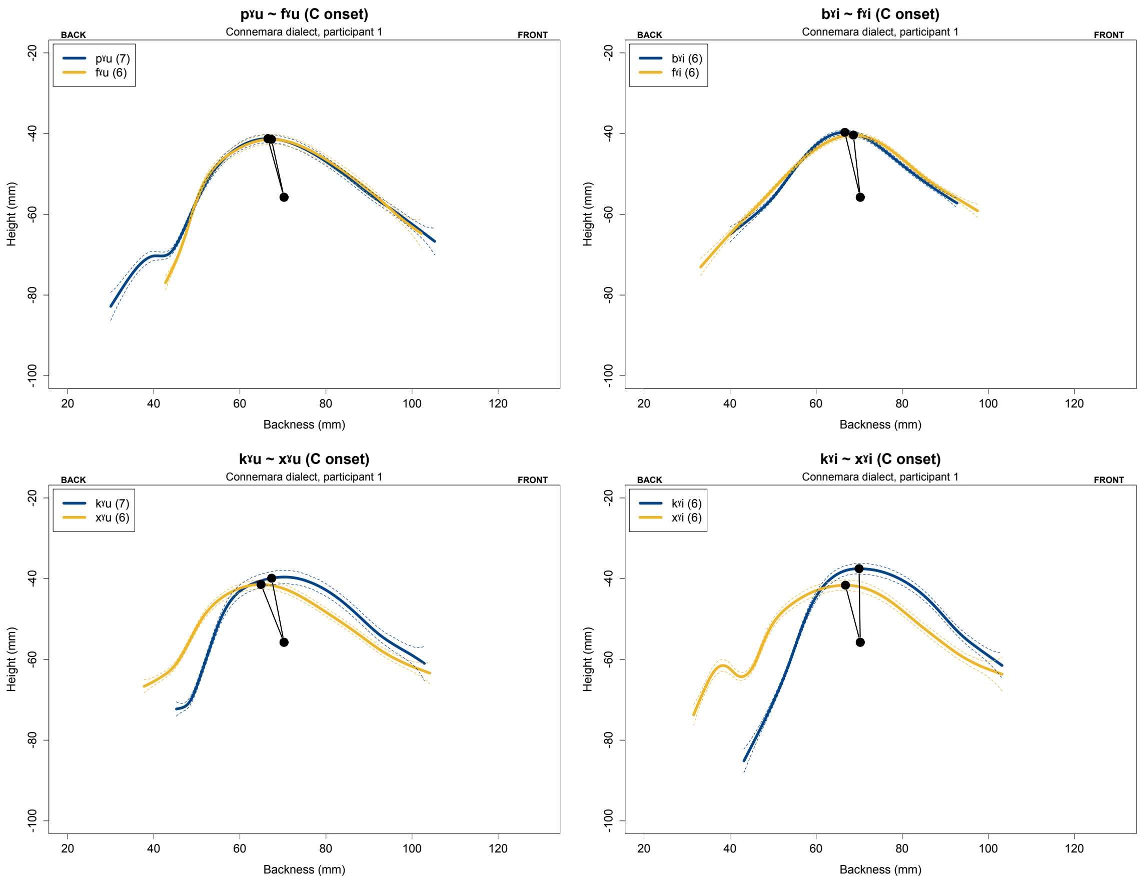


Figure 10: SSANOVA surfaces for for non-palatalized fricative (yellow) vs. stop (blue) labials (top) and velars (bottom), before [u:] (left) and [i:] (right), at consonantal onset, Speaker 2.

In general manner interacts very little with the palatalization contrast: most stop-fricative pairs behave as the labials in Figure 10 do, whether they are palatalized or velarized. The clear exception is [xˠ]. The difference between [xˠ] and [kˠ] is not merely because [xˠ] is less constricted (since it's a fricative); again, note the difference between [xˠ] and [xʲ] in Figure 2(k-l) and in Figure 9.

4.5 Effects of vowel context

Figure 11 shows Speaker 1's SSANOVA surfaces for palatalized and non-palatalized [t] and [k] across the [iː] vs. [uː] context. Analogous images for [p/b] appear in Figure 4 and Figure 6.

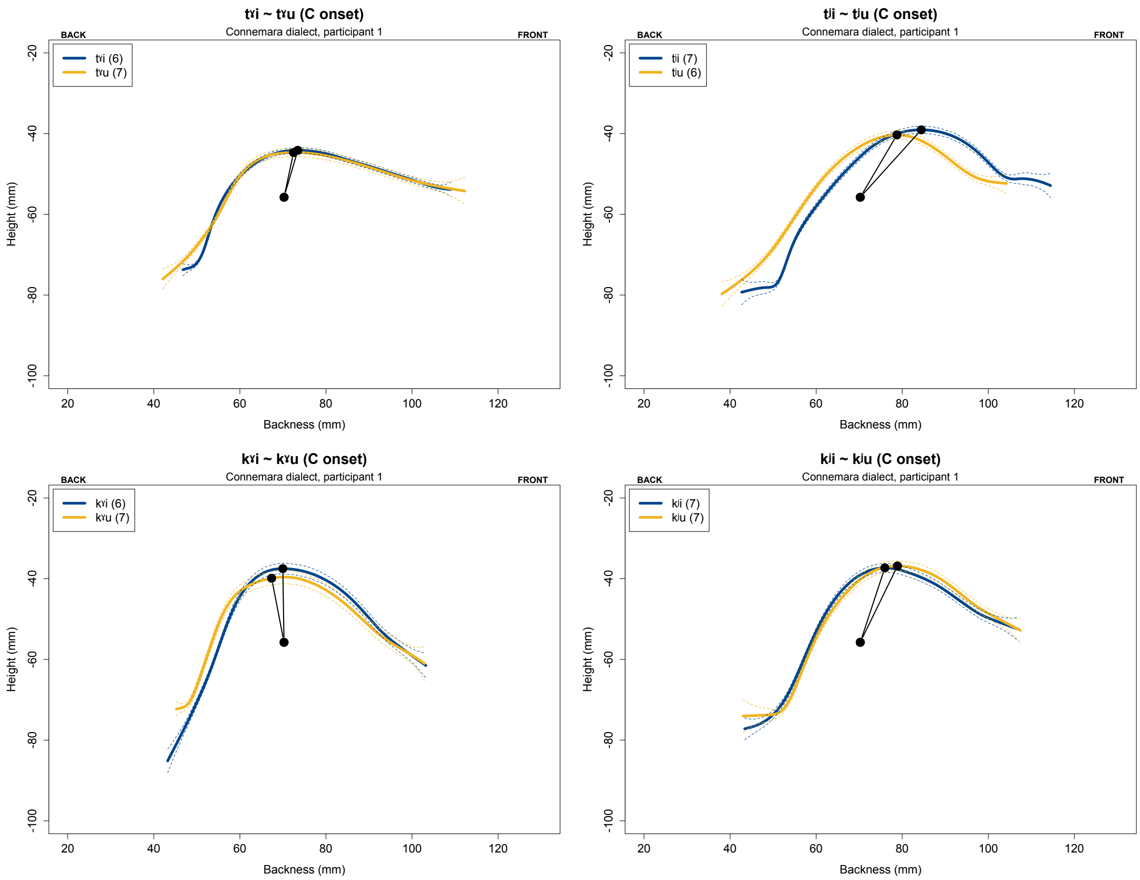


Figure 11: SSANOVA surfaces for for non-palatalized (left) and palatalized (right) coronal (top) and velar (bottom) stops before [u:] (left) and [i:] (right), at consonantal onset, Speaker 1.

What is striking about these figures is the overall absence of influence of the vowel. Though Speaker 1's [t^j] might suggest otherwise, across all speakers the vowel context has very little effect on tongue position for these Irish consonants, as can be seen in Figure 12 and Figure 13, which are like Figure 9 and Figure 7 but with information now broken down by vowel as well. Most telling given the [i:] vs. [u:] context are the consonant backness results in Figure 13. The possibility of coarticulation would lead us to expect consonants that are relatively backed before [u:] and fronted before [i:]. Though we might discern this possibility in two or three cases (e.g., [$f^ɣ$], [s^j]), the trend is absent or even reversed in other cases (e.g., [$p^ɣ$/$b^ɣ$], [p^j/b^j]), and overall there is no effect (W=1790, p=0.96). Nor is there any effect of vowel backness **within** palatalized (W=427, p=0.74) or velarized (W=462, p=0.87) sounds.

4.6 Consonantal onset vs. offset

The generalizations so far have concerned patterns at the time of consonantal onset. We have reasons to prefer analyzing this timepoint, as discussed in Section 3.4.1, but here we present some comparisons between consonantal onset and offset. As discussed earlier also, our offset data for stops may actually reflect a point well into the following vowel. For this reason we focus here only on the fricatives.

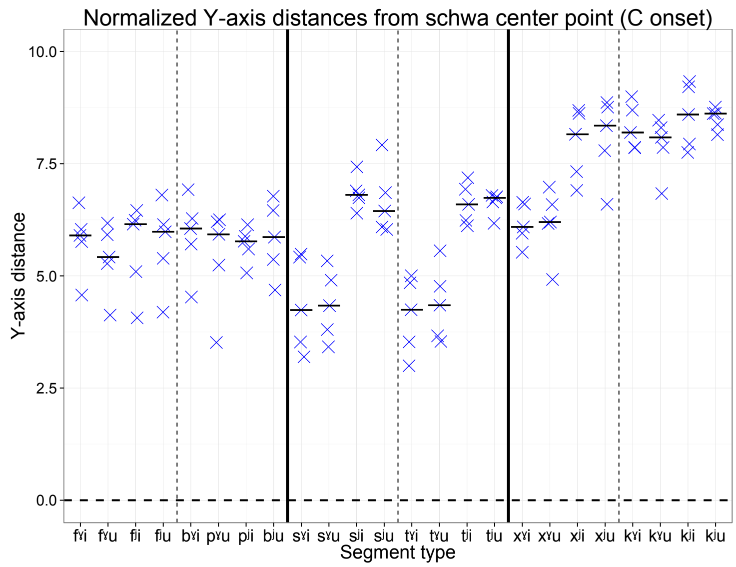


Figure 12: Tongue body height (w.r.t. 'schwa', in normalized units) by consonant and vowel, at C onset. Median values are highlighted.

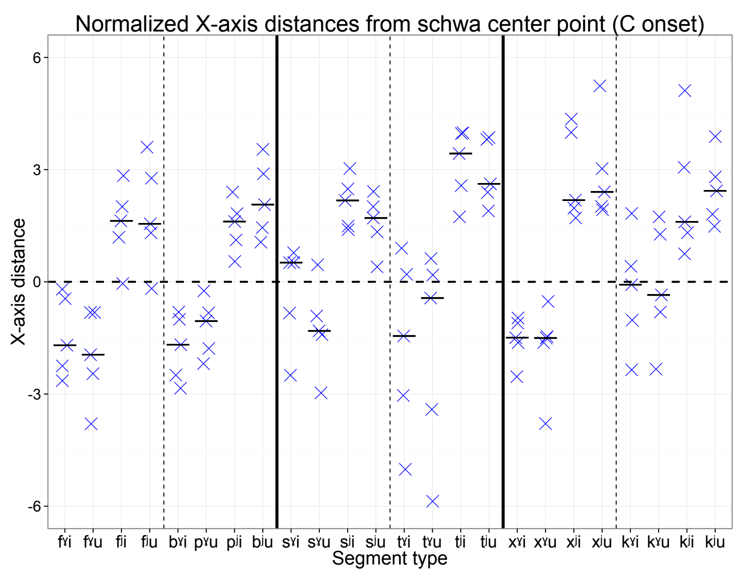
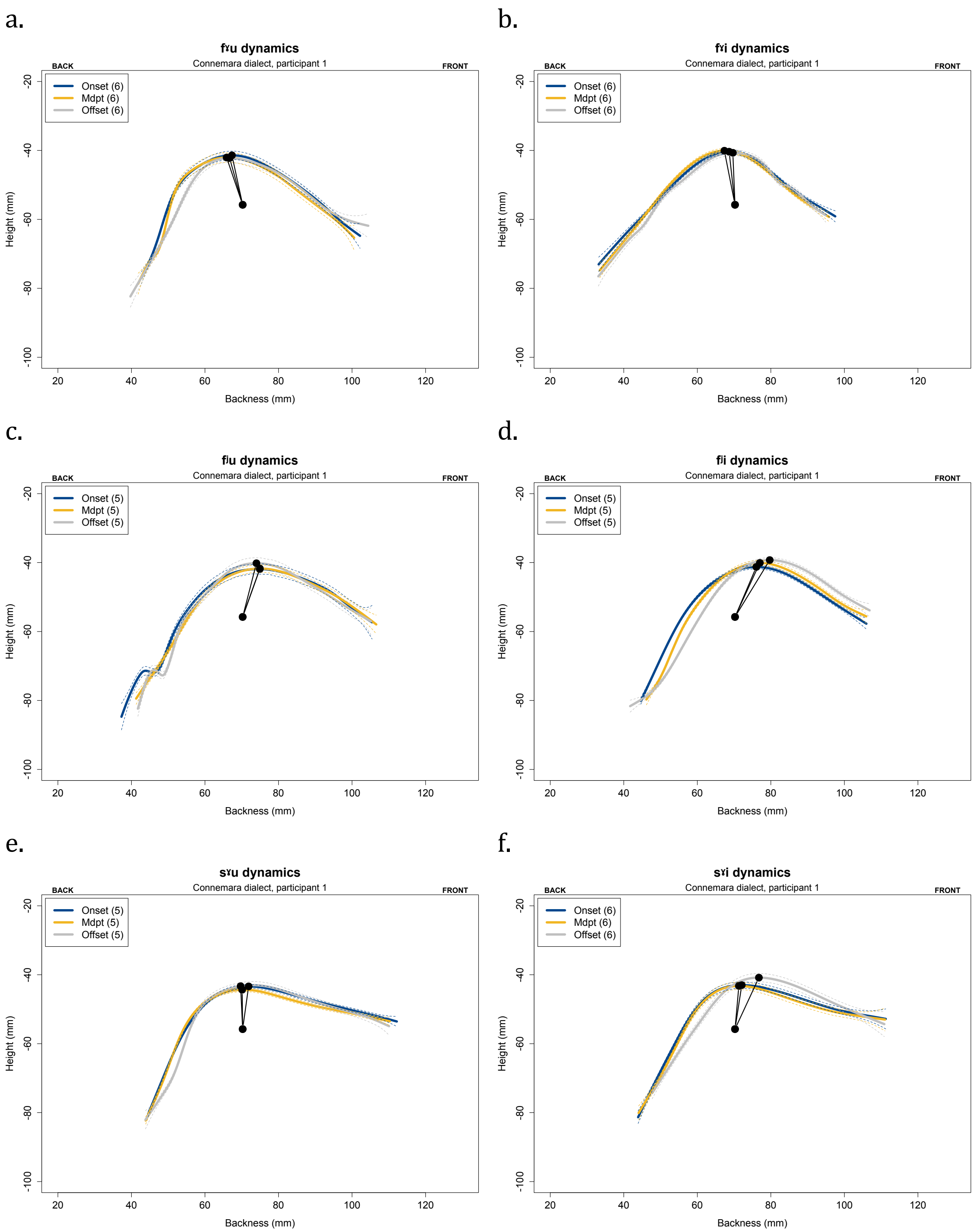


Figure 13: Tongue body backness (w.r.t. 'schwa', in normalized units) by consonant and vowel, at C onset. Median values are highlighted.

First, even at consonantal offset position there is generally little influence of the following vowel. Figure 14 shows for Speaker 1 how the tongue body changes from consonantal onset to midpoint to offset, for all fricatives before both [iː] and [uː]. If coarticulation with a following vowel increased through these timepoints, then we would expect to see progressive backing of the tongue body before [uː] in, e.g. Figure 14(a) and progressive fronting before [iː] in, e.g. Figure 14(b). In fact there is strikingly little change for most consonants. There are exceptions to be discussed below, however, and there is a good deal of variability among participants.



a.
fˠu dynamics
Connemara dialect, participant 1
BACK
FRONT
Onset (6)
Mdpt (6)
Offset (6)
Height (mm)
Backness (mm)
b.
fˠi dynamics
Connemara dialect, participant 1
BACK
FRONT
Onset (6)
Mdpt (6)
Offset (6)
Height (mm)
Backness (mm)
c.
fʲu dynamics
Connemara dialect, participant 1
BACK
FRONT
Onset (5)
Mdpt (5)
Offset (5)
Height (mm)
Backness (mm)
d.
fʲi dynamics
Connemara dialect, participant 1
BACK
FRONT
Onset (5)
Mdpt (5)
Offset (5)
Height (mm)
Backness (mm)
e.
sˠu dynamics
Connemara dialect, participant 1
BACK
FRONT
Onset (5)
Mdpt (5)
Offset (5)
Height (mm)
Backness (mm)
f.
sˠi dynamics
Connemara dialect, participant 1
BACK
FRONT
Onset (6)
Mdpt (6)
Offset (6)
Height (mm)
Backness (mm)

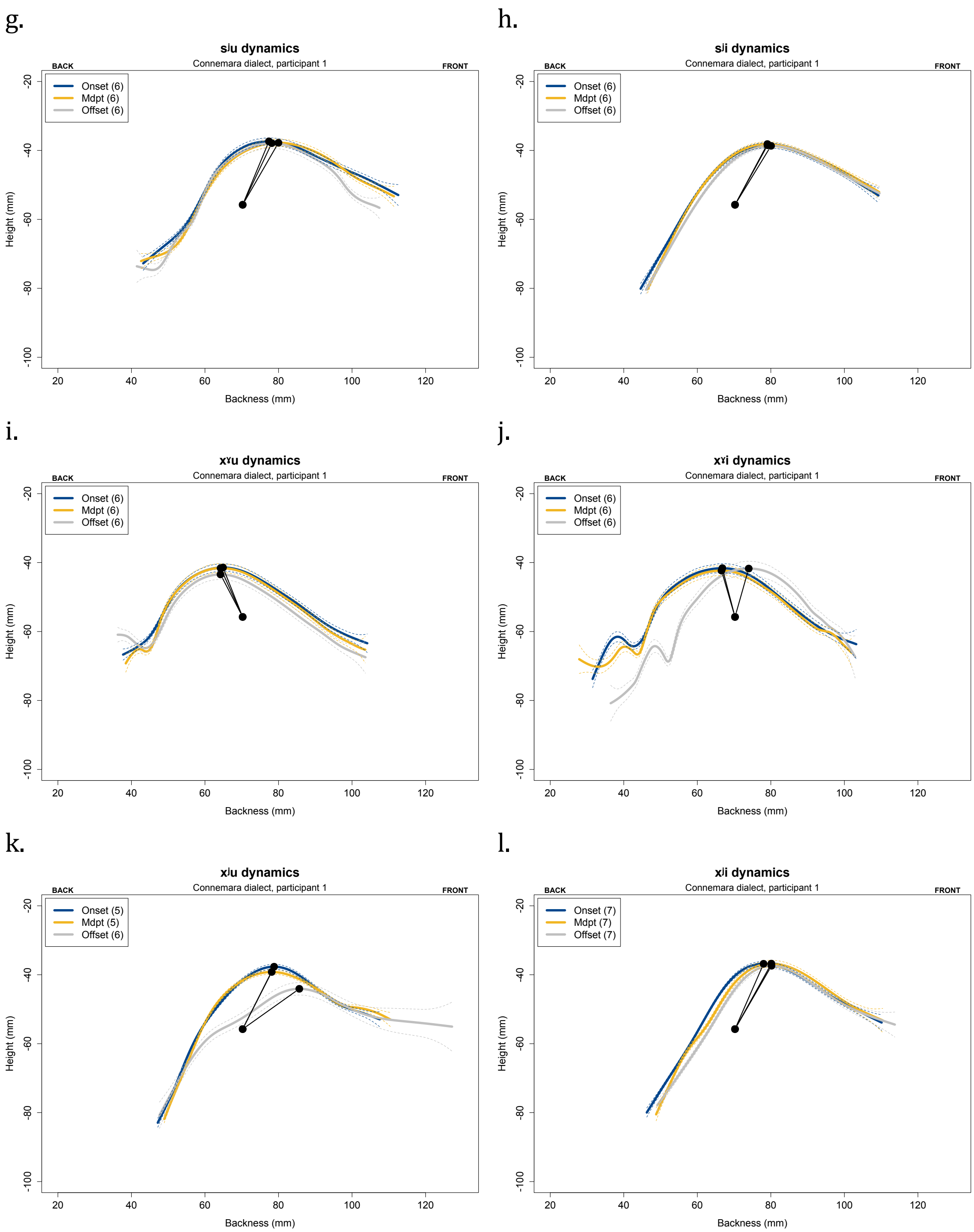


Figure 14: SSANOVA surfaces at consonantal onset (blue), midpoint (yellow), and offset (grey) for for non-palatalized (top) and palatalized (bottom) fricatives before [uː] (left) and [iː] (right), Speaker 1. [f] (a-d), [s] (e-h), [x] (i-l).

Figure 15 and Figure 16 are analogous to Figure 12 and Figure 13 respectively. Though we focus on results for fricatives, the stops are shown in these figures as well. Continuing the discussion of coarticulation and backness (Figure 16), a comparison of corresponding velarized fricatives before [iː] vs. [uː] does suggest a small effect of the vowel for the participants overall. The tongue body of velarized fricatives is fronted before [iː] compared to before [uː] (W=187, p<.01), by about 1.9 normalized units, roughly 16% of the backness scale shown. By the standards of consonant-to-vowel coarticulation in languages where it has been studied, this is a very modest effect. There is no significant difference at all in the case of the palatalized fricatives (W=147, p=0.16), though their means are slightly fronted before [iː] compared to [uː], by about 0.5 normalized units.

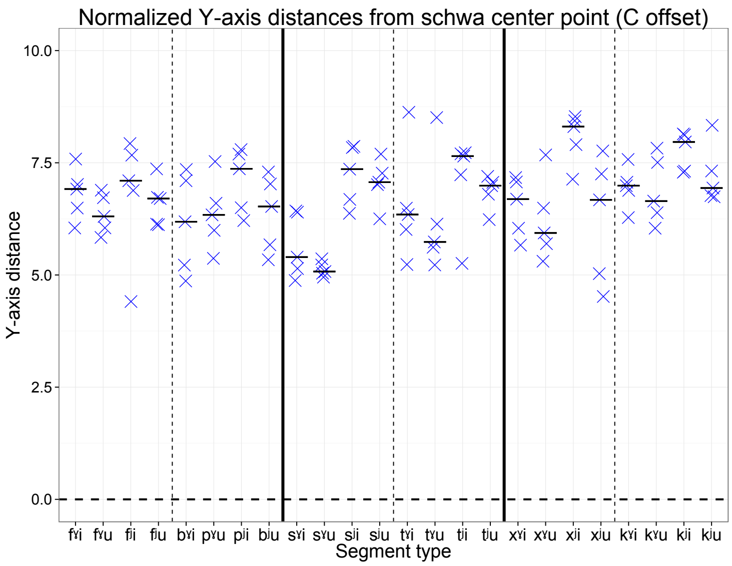


Figure 15: Tongue body height (w.r.t. 'schwa', in normalized units) by consonant and vowel, at consonantal offset. Median values are highlighted.

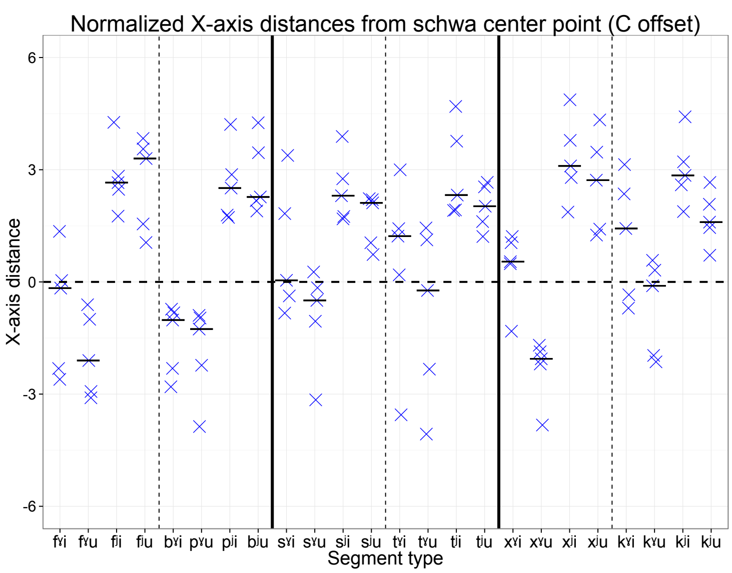


Figure 16: Tongue body backness (w.r.t. 'schwa', in normalized units) by consonant and vowel, at consonantal offset. Median values are highlighted.

Figure 15 and Figure 16 show data for all participants but give no indication of variability within a participant. Figure 17 instead shows for each participant and all fricative-vowel sequences how the tongue body peak moves from consonantal onset, through the midpoint, to offset.

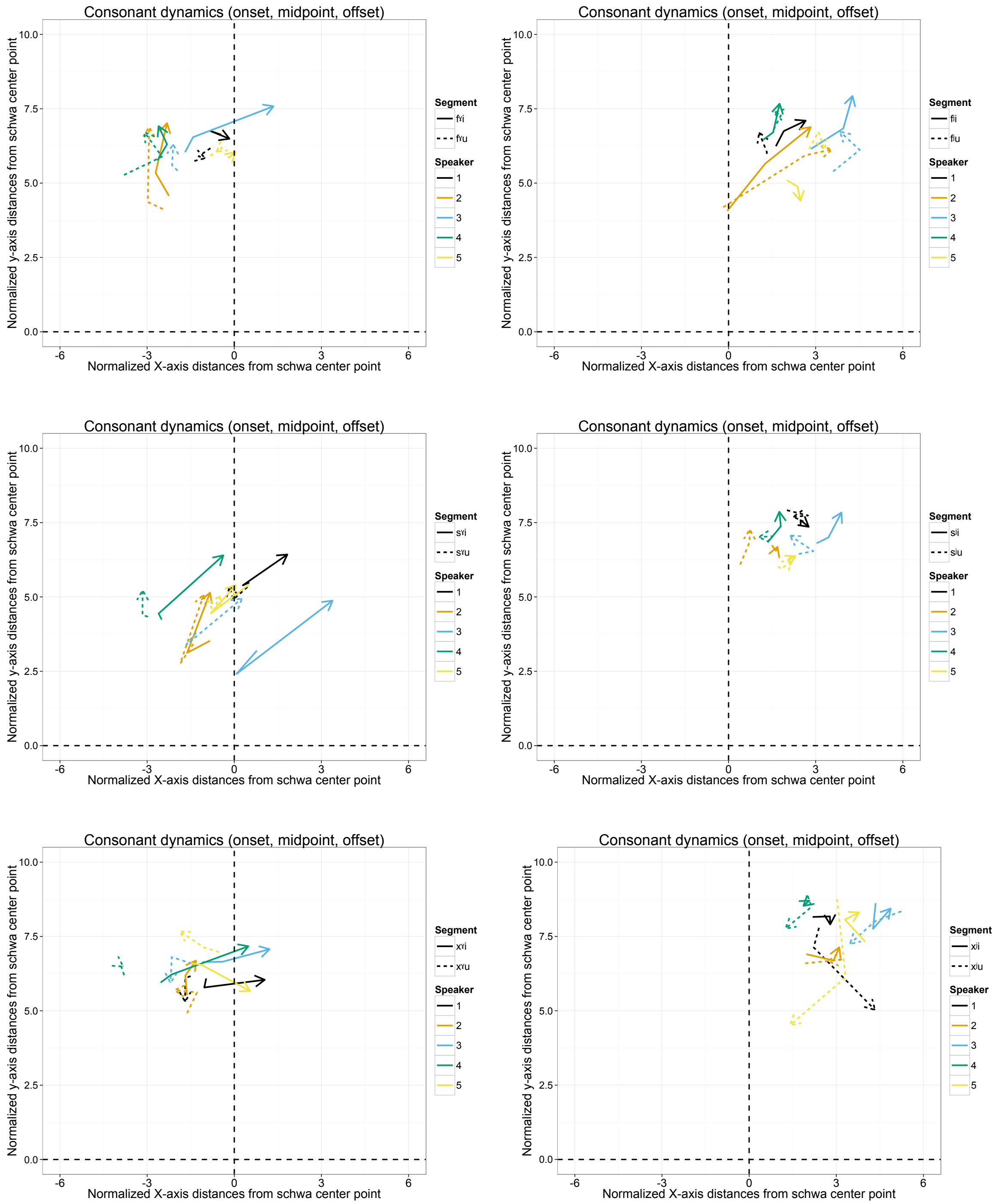


Figure 17: Tongue body trajectories from consonantal onset, through midpoint, to offset for each participant, for velarized (left row) and palatalized (right row) fricatives before [i:] (solid line) and [u:] (dashed line).

Inspection of this figure makes clear that there is no very general tendency for the vowel to increasingly exert its influence over the time course of a consonant and that there is a great deal of variability among participants. One exception may be the robust tongue fronting seen for all five participants during [sˠiː] and for four during [xˠiː]. This difference in backness at onset vs. offset for [sˠiː] and [xˠiː] is significant (V=3, p<.01, roughly 1.5 normalized units difference).[15] Note, however, that two subjects also show fronting in [sˠuː], suggesting that not all of the fronting in [sˠ] can be attributed to the vowel. Palatalized fricatives overall do not show any tendency to back before [uː] (V=51, p=0.64), though two or three participants show backing in [xʲuː]. The figure also makes clear that there is no general backing of velarized fricatives before [uː], though this might be less surprising. There is some fronting of palatalized fricatives for [iː], particular for [fʲ], but again note the similar fronting in [fʲuː], suggesting that it is the dynamics of palatalization itself and not the vowel that causes fronting.

We cannot easily judge coarticulatory effects based on tongue body height, since the tongue body is high in [iː,uː], in palatalized consonants, and in some velarized consonants, but we can note what dynamic tendencies do exist. The tongue body tends to raise over time for both [fˠ,fʲ] in both vowel environments (V=16, p<.001), an overall difference of roughly 1 normalized unit on our height scale of 10 shown. There is a good deal of participant variability, however, as can be seen in Figure 17. The velarized segments [sˠ,xˠ], excluding [xˠuː], also show raising over time (V=30, p<.001), for a difference of roughly 0.9 units overall. In contrast, [sʲ,xʲ] do not significantly change in height overall (V=110, p=0.87), but note the lowering that occurs in [xʲuː] for 4 subjects. Finally, the small trajectories for [sʲ] (realized as [ʃ] or [ɕ]) suggest that this sibilant has a relatively constrained tongue body position.

5. Discussion
5.1 Palatalization and velarization

Our ultrasound results show, first, that tongue body backness very reliably distinguishes palatalized from non-palatalized consonants, at least for the range of consonants and vowel contexts explored here. Furthermore, non-palatalized consonants involve active tongue backing – that is, they are velarized.

The finding of active velarization and even palatalization for labial consonants is interesting, since traditional dialect descriptions leave room for doubt on this point. Across dialects, many descriptions have little to say about the position of the tongue body during the production of labials (e.g., Quiggin 1906; Breatnach 1947; de Búrca 1958; Stockman 1974). Sommerfelt (1922:31-2), commenting on a different dialect of Donegal, does suggest that the tongue body is further back for [bˠ] than for [bʲ], but he also claims that the dorsum is in a "neutral position" for [bʲ], rather than fronted. In fact, secondary articulations in the case of labial consonants are sometimes characterized in terms of differences in *lip rounding* (Breatnach 1947; Ó Siadhail 1991; Ní Chasaide 1995). For example, Ó Siadhail (1991:83) states that "…slender [palatalized] labials are hardly ever phonetically

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[15] If we apply the Holm-Bonferroni correction to the tests in this and the previous section, since we are doing multiple comparisons, this comparison falls slighly below significance.

palatalized", and Breatnach (1991) writes "…in forming the [palatalized bilabial] stop the lips are rather spread, and are kept close to the teeth". Ó Cuív (1944), Mhac an Fhailigh (1980), and de Bhaldraithe (1945) all suggest that palatalized and non-palatalized labials combine a distinction in lip-rounding with the same dorsal movements found at other places of articulation (at least in the south and west Gaeltacht areas).

Though we find that labials pattern as other places of articulation do in showing consistent palatalization and velarization, the traditional descriptions may find some validation in our results. The tongue body is not as high or fronted in palatalized labials as it is in other palatalized consonants. For some of our speakers, palatalization in labials before [uː] does sound slight; before [iː], which is already high and fronted, it is indiscernible. (See discussion below.)

5.2 Variability

It is a long-standing question in phonetics and phonology to what extent there is invariance in feature realization (e.g., Cooper et al. 1952; Stevens & Blumstein 1981; Perkell & Klatt 1986). While acoustic invariance for some contrasts seems elusive, some have placed their hopes in the area of production (e.g., Liberman & Mattingly 1985; Browman & Goldstein 1986 et seq.) In some respects our results suggest a good deal of consistency in the realization of the palatalization contrast across place, manner, and vowel context.

As seen above, consonant manner (stop vs. fricative) in general has no effect on tongue body realization in the palatalization contrast. The obvious exception is [x$^{\gamma}$], to which we return later. More strikingly, the vowel context ([iː] vs. [uː]) also has very little effect. At consonantal onset there is no sign of the consonant-to-vowel coarticulation seen in most languages; even at consonantal offset the effects seen are modest overall and simply absent for some consonants and speakers. It is not hard to imagine why this might be; presumably the inherent secondary palatalization and velarization specifications of Irish consonants override any such coarticulation with following vowels. Farnetani et al. (1991) and Ní Chasaide and Fealy (1991) also find resistance to coarticulation for Irish consonants, and the effect is well documented for Russian (Öhman 1966 ; Purcell 1979; Choi & Keating 1991; see discussion in Recasens et al. 1997; Manuel 1999; Recasens 1999).

Our tongue body data allow us to see past some impressionistic variability in the realization of Irish palatalization. For example, the Irish contrast has been described as one of palatalized vs. plain consonants before back vowels, e.g., *beo* [b^{j}oː] 'alive' vs. *bó* [boː] (rather than [b$^{\gamma}$oː]) 'cow', but of *plain* vs. *velarized* consonants, respectively, before front vowels, e.g. *bí* [biː] (rather than [b^{j}iː]) 'be (imp.)' vs. [b$^{\gamma}$iː] 'yellow' (Ní Chiosáin & Padgett 2001, 2012). That is, at least for labials palatalization is no more evident before front vowels than velarization is before vowels like [uː]. (Palatalization seems more auditorily salient in coronals and velars, as opposed to labials, because it is often accompanied by some degree of affrication.) This apparent shift in the realization of the contrast is only an artifact of the vocalic context, however. As seen above (especially Figure 4 and Figure 6), the tongue body is in the same position in *píosa* [p^{j}iːsə] 'piece', impressionistically [piːsə], as it is in *b'fhiú* [b^{j}uː] 'it is worth', just as it is in the same position in *púca* [puːkə] 'ghost' as it is in *buí* [bˠiː] 'yellow'. While the transition from *Cˠ* to [i/e] or from *Cʲ* to [u/o] is highly audible, there is effectively *no* transition in tongue body position from *Cˠ* to [u/o] or from *Cʲ* to [i/e]. Hence the impressionistic variability in the realization of the palatalization contrast follows from relative articulatory *invariance* in a variable vocalic context.

5.3 Velarization in coronals and [x]

Though there is a great deal of consistency in the realization of the tongue body in the Irish palatalization contrast, there are systematic exceptions involving the velarized coronals and [xˠ].

As seen above, the tongue body is surprisingly low and back in [xˠ] compared to [kˠ]. Manner (stop vs. fricative) otherwise seems to have little bearing on the palatalization contrast. It has been claimed that some Connemara speakers optionally pronounce non-palatalized [x] as uvular [χ] (Ó Curnáin 2007:171).[16] Our tongue body results for [xˠ] might suggest such a uvular realization.

As for [tˠ] and [sˠ], they are more weakly velarized than other non-palatalized sounds in Irish, though only in terms of tongue height. (The results of Sections 4.3 and 4.6 also suggest greater variability of tongue body realization for these sounds.) It is worth pointing out that their weaker velarization is audible. For our speakers the [tˠ] and [sˠ] of *tuí* [tˠiː] 'straw' and *suí* [sˠiː] 'sit' ranged impressionistically from very velarized to not velarized at all. This difference for coronals mirrors what has been found for Russian (see Section 2.2), suggesting that there might be a general explanation for this pattern. Such an explanation could lie in production. For example, it is conceivable that constraints on producing coronals like [t] or [s], together with the coupling between the tongue body and blade/tip, inhibit full velarization in coronals.[17] An alternative explanation relies on the idea of cue trade-off: [tʲ] and [sʲ] have robust cues to their palatalization apart from the second formant displacement associated with tongue body production. The sound [tʲ] is frequently affricated; this, and the quality of the noise in [sʲ] and in the release of [tʲ] are potential cues to palatalization (Ní Chiosáin & Padgett 2012). It is possible that velarization is weaker in [tˠ, sˠ] because velarization in these sounds trades off with these 'secondary' cues to palatalization in [tʲ, sʲ], thereby reducing the functional importance of the F2 transition associated with tongue body backing for [tˠ, sˠ].

6. Conclusion

This paper, together with the related archive of images, data, and recordings at [URL here], should be of interest to anyone concerned with understanding the Irish palatalization

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[16] Quiggen (1906) and Ní Chasaide (1995) state that /xˠ/ debuccalizes to [h] in northern dialects; perhaps [χ] is a stage intermediate between [xˠ] and loss of place.

[17] However, Iskarous et al. (2011) find that American English /s/ allows relatively free movement of the tongue dorsum in the y-axis dimension. This may suggest that the lowered dorsum observed for velarized /sˠ/ in our data is not a simple consequence of articulatory coupling.

contrast, one that has never before been documented in any tongue body imaging study. Apart from its descriptive interest, the data here bear on theories of coarticulation, featural invariance, and contrast realization, among other areas.

One limitation of this study is its focus on data from only one of the three major dialect areas, Connacht Irish. We have obtained analogous data representing the two other major dialect areas, Munster and Ulster Irish, which we intend to present in future work. We also intend to analyze lip capture data from the same ultrasound sessions. This study is also limited in the range of consonants and contexts explored. In future work we plan to explore other consonant types and to examine consonants in a wider range of contexts, including in word-final position and adjacent to a broader range of vowels.

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Appendix: speaker background

All speakers live in Connemara. Speaker 1 (male, 60) and Speaker 3 (female, 46) grew up and live in An Cheathrú Rua. Speaker 4 (female, 47) grew up in Cor na Rón Lár, and now lives in Doire Bhanbh. Speaker 5 (male, 59) grew up and lives in Na hAille. Speaker 2 (male, 35) spent years 1-5 in London, and afterwards grew up in Béal an Daingín, where he now lives.

Both parents of all but Speaker 2 are/were native speakers of Connemara Irish. Speaker 2's father is/was a native speaker of Connemara Irish, and his mother is/was a native English speaker.

Speakers 1,3,4,5 all report speaking Irish with their parents and other caregivers, grandparents, siblings, spouse, children, and (where possible) friends and community. Speaker 5's spouse is a native English speaker, but he reports speaking Irish with her. Speaker 2 reports speaking English with his parents, Irish with his siblings about half the time, and Irish with his friends; his spouse is a native English speaker with whom he speaks Irish.

With the exception of Speaker 1, all speakers' schooling (primary and secondary) was through the medium of Irish. Speaker 1 attended an Irish medium primary school and an English medium secondary school. All speakers attended third level colleges. All read Irish on a daily basis.