Chapter 1

Gestural timing and contrast: an Irish case study

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Though a palatalized vs. velarized (*slender* vs. *broad*) contrast is fundamental to Goidelic languages of the Celtic family, contrasts involving either palatalization or velarization are typologically uncommon. Across languages, such contrasts are often dispreferred in onset compared to coda position, and in labial compared to coronal consonants. Previous phonetic research on both Russian and Irish has suggested that these asymmetries in contrast loss might be explained by, or at least correlated with, asymmetries in articulatory reduction and timing. We explore the timing of palatalization and velarization gestures in Irish stop consonants, and find differences between onset vs. coda position consistent with this general claim. However, we also find that gestural timing is structured in ways that allow for perceptual cues to the contrast to be recoverable, including in ways that might facilitate perception of the contrast in codas and (possibly) in labial consonants. Put simply, gestural timing in Irish may be optimized to support vulnerable contrasts.

1 Introduction

The living Celtic languages are divided into two groups, a Goidelic branch (including Irish and Scottish Gaelic) and a Brittonic branch (including Welsh and Breton).[1] In terms of phonological properties, an important feature distinguishing Goidelic languages from Brittonic ones is a phonemic contrast between palatalized and non-palatalized consonants, traditionally called *slender* and *broad* respectively. Compare for example the Irish minimal pair *brád* /bˠrˠɔːdˠ/ 'drizzle'

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[1] For a recent discussion of the classification of Celtic languages, see Eska (2017).

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and *bráid* /bˠrˠɔːdʲ/ ’neck, throat’; the two words differ only in whether the final consonant is palatalized or velarized. (These terms are explained below.) This palatalization contrast developed in Proto/Old Irish (Greene 1973, McCone 1996, Stifter 2017), and it occurs also in Scottish Gaelic (Ternes 2006, Nance & Ó Maolalaigh 2021) and Manx (Lewin 2019).

Many phonemic contrasts are allowed only in certain phonological environments. For example, though English distinguishes voiced obstruents from voiceless ones both word/syllable-initially and -finally (e.g. *back* vs. *pack* and *cab* vs. *cap*, Russian prohibits the contrast finally, neutralizing in favor of the voiceless series: compare [ˈlˠugˠə] ‘meadow (GEN.)’ and [ˈlˠukˠə] ‘onion (GEN.)’ (from /lˠugˠ-a/ and /lˠukˠ-a/ respectively) to [lˠukˠ] ‘meadow’ and [lˠukˠ] ‘onion’ (from /lˠugˠ/ and /lˠukˠ/ respectively.

It has long been understood that phonological alternations, including those leading to the positional neutralization of contrast, might have historical origins in phonetic processes, a hypothesis pursued most notably by Ohala (e.g. Ohala 1981, 1993b), but since explored by many. One way to test a hypothesis about the phonetic origins of positional contrast and neutralization is to examine a language that does *not* neutralize the relevant contrast, and look for potential phonetic seeds of neutralization there. Indeed, we have done this for Irish (see discussion further on). However, there is also much work showing that languages can be structured in ways that militate *against* contrast loss, a view most notably pursued by Lindblom (Lindblom 1986, 1990), but again explored since then by many.

In this paper we explore details of the timing of palatalization and velarization gestures in Irish stop consonants, as a function of prosodic position (word/syllable-initial vs. -final) and place of articulation (labial, coronal, dorsal). We find that timing patterns vary more in word/syllable-final position, a fact that may help explain the vulnerability of this contrast to loss in that position. However, we also find evidence that timing in that position can be structured in ways that may *facilitate* perception of the palatalization contrast. As for place of articulation, we find that patterns of timing in labial consonants, which are also vulnerable to loss of a palatalization contrast are more consistent than for other places of articulation; this may likewise facilitate perception of the palatalization contrast, though here the facts are less conclusive. Overall our results suggest that gestural timing in Irish may be optimized to support contrasts that are vulnerable.

2 Irish and the typology of contrastive palatalization

2.1 Palatalization and velarization

Palatalized (slender) consonants [Cʲ] are produced with a secondary high-front tongue constriction, akin to the constriction for a palatal vowel [i] or glide [j], which is roughly simultaneous with the primary constriction for that consonant.[2] Velarized (broad) consonants [Cˠ] are produced with a secondary tongue body constriction which is high and back in the mouth, as for [ɯ u] or [ɰ w], or sometimes in the mid-back or uvular region, as for [ɤ o] (International Phonetic Association 1999, Kochetov 2002, Bennett et al. 2018, Shaw et al. 2021). In this article the term 'secondary articulation' encompasses palatalization and velarization as defined above.

2.2 The palatalization contrast in Irish

All consonants in Irish are contrastively palatalized or velarized. Table 1 illustrates these phonemic contrasts with the basic inventory of consonants in Connacht Irish (or more specifically Connemara Irish), which here represents the western dialect group (De Bhaldraithe 1975, Ó Siadhail 1991, Ní Chiosáin 1991, 1994, 1999, Ní Chiosáin & Padgett 2012). The specific phonetic form of palatalized and velarized consonants varies somewhat across dialects (e.g. Ní Chasaide 1995, Hickey 2011), but all varieties of Irish share fundamentally the same inventory of phonological contrasts illustrated in Tab. 1.

As illustrated in Tab. 1, /Cˠ Cʲ/ contrasts are maintained across all places of articulation in Irish. In addition, /Cʲ/ and /Cˠ/ can appear across all vowel contexts as well as word/syllable-initially and -finally (some examples given in Tab. 2, left). In the data analyzed in this paper, word-initial sounds are also syllable-initial (and vice-versa), and word-final sounds are also syllable-final (and vice versa). For ease of reference we will often use "onset" to refer the former and "coda" to refer to the latter.[3]

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[2] Since not all languages with a palatalization contrast are reported to oppose velarization to palatalization, we use '/C⁽ˠ⁾ Cʲ/' to refer to palatalization contrasts generally. We use capital 'C' to refer to any consonant, and capital 'P', 'T', 'K' to refer generically to labial, coronal, and dorsal consonants, respectively. Slash brackets '/ /' indicate abstract phonemes, while square brackets '[ ]' indicate surface phonetic forms. Transcriptions are broad: for example, coronal [dˠ dʲ] are phonetically closer to dentalized [d̪ˠ] and retracted [d̠ʲ] in e.g. Gaoth Dobhair Irish (Ní Chasaide 1995).

[3] Consonant clusters typically agree in their secondary articulations in Irish (Ní Chiosáin 1991, 1999). Such clusters may be palatalized (e.g. *coirpeach* [kˠirʲpʲəxˠ] 'criminal') or velarized (e.g. *léargas* [lʲeːrˠgˠəs] 'insight'). So while word-internal codas may not have *independent* /Cˠ Cʲ/

Table 1: Phonemic consonant inventory of Connemara Irish. Sounds in parentheses have highly restricted distributions.

	Labial	Coronal	Dorsal	Glottal
Stop	pˠ pʲ bˠ bʲ	tˠ tʲ dˠ dʲ	kˠ kʲ gˠ gʲ	
Fricative	fˠ fʲ vˠ vʲ	sˠ sʲ	xˠ xʲ (ɣˠ) (ɣʲ)	hˠ (hʲ)
Nasal	mˠ mʲ	nˠ nʲ	ŋˠ ŋʲ	
Liquid		lˠ lʲ rˠ rʲ		

Table 2: Words showing distribution of /Cˠ Cʲ/ (left) and minimal pairs (right).

caoin	[kˠiːnʲ]	‘lament’	*pán*	[pˠɔːnˠ]	‘pawnshop’
tiús	[tʲuːsˠ]	‘thickness’	*peann*	[pʲɔːnˠ]	‘pen’
láib	[lˠɔːbʲ]	‘mud, muck’	*cat*	[kˠatˠ]	‘cat (sg.)’
píob	[pʲiːbˠ]	‘pipe (gen.pl.)’	*cait*	[kˠatʲ]	‘cat (pl.)’

The wide distribution of the /Cˠ Cʲ/ contrast across all of these contexts allows for many minimal pairs (Tab. 2, right). It is also what makes the Irish language a useful and important testing ground for phonetically-oriented explanations of recurrent distributional restrictions on /C⁽ˠ⁾ Cʲ/ contrasts across languages.

2.3 Typological asymmetries in palatalization contrasts

Though allophonic secondary palatalization is found in many languages (Bateman 2011), its *contrastive* use, as in Irish /bˠrˠɔːdˠ/ vs. /bˠrˠɔːdʲ/, is relatively uncommon. Furthermore, among languages that do distinguish /C⁽ˠ⁾ Cʲ/, the contrast is not equally likely in all phonological environments (Takatori 1997, Kochetov 2002, Iskarous & Kavitskaya 2018). First, such contrasts tend to be neutralized or lost diachronically in codas, as in Bulgarian (e.g. Scatton 1993, Iskarous

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specifications, given that secondary articulations must assimilate in clusters, word-internal codas may be either palatalized or velarized, just like word-final codas. (Compounds and prefixes allow disagreeing clusters, e.g. *inphosta* [inʲ-fˠoːsˠtˠə] ‘marriable’, *fadtéarma* [fˠadˠ-tʲeːrˠmˠə] ‘longterm’; Ní Chiosáin 1991: Ch.2.)

The backness of short vowels is predictably determined by the secondary articulations of neighboring consonants, which is why we focus on long vowels in our discussion of vocalic contexts. See section 4.3 and Ní Chiosáin (1991), Ó Siadhail (1991) for details.

& Kavitskaya 2018) or Nenets (e.g. Kochetov 2002). As a result, the presence of a /C$^{(\text{ɣ})}$ C$^{\text{j}}$/contrast in coda position normally entails a corresponding contrast in onset position (but not vice-versa).[4] Second, /C$^{(\text{ɣ})}$ C$^{\text{j}}$/contrasts tend to be neutralized or lost diachronically in labial consonants compared to coronals. This pattern occurs for example in Czech (Short 1993, Iskarous & Kavitskaya 2018). These two restrictions may also interact, as in Belarusian, where palatalization is contrastive for both labials and coronals in syllable onsets, but palatalized labials do not occur in syllable codas (e.g. Bird & Litvin 2021).

Some signs of these asymmetries are evident within Celtic. Scottish Gaelic may have lost or be in the process of losing its palatalization contrast among labial consonants, with remnants in the form of /Pj/ (labial consonant - glide) sequences (Jackson 1967, De Búrca 1977, Ternes 2006, cf. Nance & Ó Maolalaigh 2021), as is true in some Polish dialects (Czaplicki 2010, Iskarous & Kavitskaya 2018). The same may have been true of Classical Manx (Lewin 2019). In Irish, there are many fewer words ending in palatalized labial stops compared to palatalized coronal stops, and the proportion of word-final labial stops that are palatalized is low compared to the proportion of word-final coronal stops that are palatalized, based on either a dictionary or corpus search of word types (Ní Chiosáin & Padgett 2012). As Kochetov (2002) notes, discussing similar facts for Russian, such asymmetries in frequency may reflect lexical attrition of contrasts in more vulnerable positions. They might in turn also enable further attrition of contrasts, possibly leading to neutralization, since language learners will have to learn the contrast based on fewer relevant lexical items.

In spite of such asymmetries in segment frequency, Irish still maintains the palatalization contrast in codas and in labials. For this reason, Irish is an ideal testing ground for hypotheses about the phonetic bases of contrast and contrast neutralization. For example, if contrasts are lost in certain contexts due to systematic phonetic asymmetries, then we might expect to find such phonetic asymmetries in Irish, even though it maintains the contrast. The hunt for phonetic precursors to neutralization of a /C$^{(\text{ɣ})}$ C$^{\text{j}}$/ contrast has precedents, including work of our own (Kochetov 2002, 2005, 2006, Ní Chiosáin & Padgett 2012, Stoll 2017, Padgett & Ní Chiosáin 2018, Iskarous & Kavitskaya 2018, Kirkham & Nance 2022, Padgett et al. 2023, Bennett et al. 2023). On the other hand, if languages are structured in ways that *support* contrast, then we might expect to find ways in which this is true

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[4] Marginal exceptions to this typological generalization include Estonian and Romanian, in which phonological palatalization only occurs word-finally or before a consonant (i.e. only in coda position). These unusual distributions owe to contextual palatalization before /i/, rendered opaque by historical or synchronic vowel deletion (Operstein 2010, Chitoran 2013, Malmi et al. 2023).

for the Irish palatalization contrast. The work presented here explores both of these possibilities, focusing on the timing of palatalization and velarization with respect to a primary place constriction. It develops ideas first presented by Padgett et al. (2023). Here we bring new analyses to bear, including analyses of the gestural trajectories of individual tokens and an exploration of individual subject behavior. We develop the idea of perceptual optimization, and we consider and reject an alternative understanding of gestural timing that relies on articulatory principles along the lines of Sproat & Fujimura (1993) and Krakow (1999).

3 Gestural timing and contrast

3.1 Gestural organization and perception

Perceptual studies on Irish and Russian have found that listeners have more difficulty identifying or distinguishing /Cˠ Cʲ/ in coda position compared to onset position, and for Russian, in labials compared to coronals. Kochetov (2002, 2004) found that Russian listeners misidentified /pˠ pʲ tˠ tʲ/ more often in word/syllable-final position than in initial position, even though the relevant consonant was intervocalic due to a following vowel-initial word.[5] In addition, listeners misidentified /pʲ/ more often than the other three consonants in coda position, most often confusing it with /pˠ/. Ní Chiosáin & Padgett (2012), Padgett & Ní Chiosáin (2018) found that Irish listeners discriminate /Cˠ Cʲ/ more poorly in coda position compared to onset position, for a number of stop and fricative consonants. (The codas in these stimuli were phrase-final.) As can be seen, these perceptual asymmetries mirror the typological ones discussed earlier, raising the possibility that the perceptual asymmetries *explain* the typology. In contexts where listeners cannot perceive the /Cˠ Cʲ/ contrast well, we might expect attrition and eventual loss of that contrast. We might also expect such perceptual asymmetries to have some basis in productions that are weaker, more variable, etc.

However, it's possible that languages are structured to be perceptually optimizing, in which case we might have a countervailing expectation: production of a /Cˠ Cʲ/ contrast might vary by position (initial or final) or by place (labial or coronal) in ways that *support* the contrast, specifically in vulnerable contexts. This idea and the previous are not contradictory; rather, there is strong reason

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[5] There is no evidence that consonants resyllabify across words in Russian. For example, word-final consonants devoice even when vowel-initial words follow (See discussion in Padgett & Myers 2014). See earlier discussion in 4.3.

to believe both. Which factor prevails in a given case, leading to loss or preservation of a contrast, depends on many factors that are generally beyond our power to predict.

The idea that languages might be structured in ways that facilitate the maintenance of phonological contrast goes back decades (e.g. Martinet 1952, 1964, Liljencrants & Lindblom 1972, Lindblom 1986, 1990). Most relevant here is work more specifically suggesting that *gestural timing* can be organized in ways that are perceptually optimizing. An important precedent is Kingston (1990), who argues that across languages glottal articulations are ‘bound’ in time most often to the release of stop consonants, because the burst characteristic of stops renders the glottal gesture most perceptually effective. Sonorant and fricative consonants lack bursts and so do not coordinate glottal articulations in the same way. Silverman (1997) argues in a similar way that laryngeal states creating phonation and tone contrasts in vowels are timed in nuanced ways that facilitate their perceptibility, and Wright (1996) argues that place gestures in consonant clusters are timed so as ensure recoverability of burst cues in consonants that lack internal place cues or formant transitions. More generally, Kingston & Diehl (1994) argue that speakers systematically control articulations in ways that support the perceptual distinctiveness of contrast, and there is a great deal of other evidence that phonetic targets are ultimately auditory, not gestural. (For an overview and arguments see Kingston 2019.)

The above observations do not necessarily imply that speakers *intentionally* structure their articulations to make their speech clear or intelligible for listeners. While that *could* be the case, it is also plausible that articulatory patterns which are easier to hear are also easier to learn, and therefore more likely to persist over time (e.g. Ohala 1993a). Articulatory patterns which produce less robust acoustic outcomes are more likely to be misheard by listeners: over time, such misperceptions can lead to sound changes involving the collapse of contrasts (e.g. Ohala 1981 and many others). In this way, perceptually-supportive articulatory strategies can emerge organically, without any intent on the part of speakers. That said, we remain open to the possibility that speakers do in fact strive to produce clear, intelligible speech in at least some circumstances. In either case, articulatory timing clearly plays an important role in the perceptibility of contrasts.

3.2 Gestural timing in palatalization contrasts

Previous work on the timing of secondary articulations in both Irish and Russian suggests that the tongue body gesture associated with palatalization reaches its target (or peaks) around the release of the primary place constriction for onset consonants (e.g. Ladefoged & Maddieson 1996: Ch.10, Kochetov 2002, 2006, Iskarous & Kavitskaya 2010, Bennett et al. 2018, Padgett et al. 2023). More specifically for Irish, Bennett et al. (2018) find that tongue body fronting for palatalized /C^j/ tends to peak at C release in both stops and fricatives. In contrast, velarized /C^ɣ/ does not show any clear, consistent asymmetries across timepoints: the magnitude of dorsal backing tends to be comparable at the beginning of C constriction, C midpoint, and C release.

Bennett et al. (2018) only examine consonants that are onsets (and prevocalic), and so do not address the timing of secondary dorsal constrictions in codas (or postvocalic position). However, based on an electromagnetic midsagittal articulometry (EMMA) study of four speakers, Kochetov (2006) found that Russian /p^j/ was produced differently in onset position compared to coda position. Kochetov measured the lag between the achievement of the secondary and primary articulations (defined in terms of velocity minima) of /p^j/, as well as the lag between the release of the two gestures. For all speakers, in onset position both the achievement and release of the palatalization gesture followed that of the labial constriction by 5-55 ms on average (depending on the speaker). This is consistent with our findings for Irish mentioned above. In coda position the relative timing of the palatalization gesture with respect to the labial one was found to be more variable by speaker, but it generally occurred earlier than in onset position. For example, the achievement of the palatalization gesture preceded that of the labial gesture by 5-25 ms for three of the speakers, but followed it for the fourth speaker. Biteeva (2021: 159-160) reports very similar findings for /t^j/, based on another EMMA study of nine speakers. Both studies characterize the relationship between primary and secondary articulations as sequential for onsets and more simultaneous for codas.

3.3 Gestural timing and perceptual consequences

It is worth considering the timing facts above in light of their effects on the production of cues to palatalization. As Kochetov (2006) points out, it is perceptually adaptive for the palatalization gesture of a stop to lag its primary place gesture in onset consonants. There are two major cues to the palatalization status of a stop: one is in the formant transitions between the consonant and a neighboring vowel (primarily the second formant) and the other is in the quality of the consonant burst, whose spectral properties are shaped by the presence of palatalization or velarization. In onset consonants these distinct cues more or less coincide in time at the release of the primary place gesture, indicated by the leftmost oval in Fig. 1.

Following the reasoning of Kingston (1990) for the timing of glottal articulations with respect to stop consonants (discussed earlier), coordinating palatalization to peak around this location maximizes its contrast potential. This fits well with the general finding that onset consonant-vowel transitions are perceptually robust (Fujimura et al. 1978, Ohala 1990, Steriade 2001, Wright 2004, Kochetov 2006).

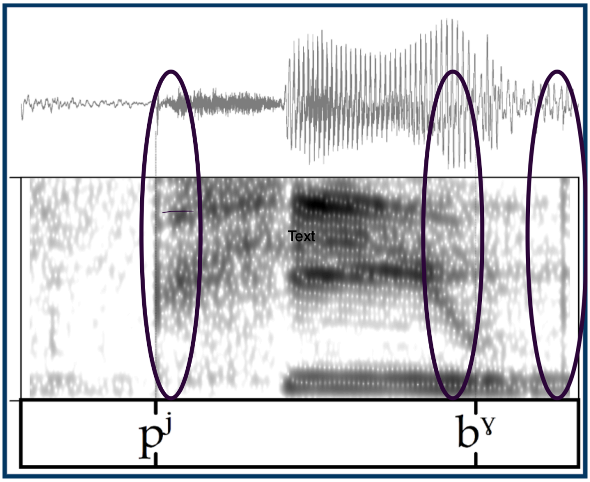

Figure 1: Waveform and spectrogram of the word *píob* /pʲiːbˠ/ (Connacht Speaker 1 repetition 1), showing location of major cues to Irish secondary articulations in onset (left oval) and coda (right two ovals) stops.

Things are different for coda stops, where the two major cues to palatalization are split in time, as shown on the right of Fig. 1. The formant transition cues to the contrast precede the stop closure (note the salient drop in the second formant for /bˠ/), while the burst cues lie at the release of the stop constriction (rightmost oval in the figure). If secondary articulations are timed to be perceptually optimizing, what should that entail for stops in final position? We do not know enough about the perception of palatalization cues to answer this question definitively. However, a reasonable first thought would be that gestures should be coordinated in a way that facilitates the perception of *both* formant transitions and burst properties. This would be true if the secondary articulation were to be achieved at, or slightly before, the onset of the primary articulation and be released at, or slight after, the release of the primary articulation. [6]

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[6] The discussion here is oversimplified, since it ignores the larger phrasal context of the word in Fig. 1. We return to this issue in the paper's discussion and conclusion.

As discussed in the last section, previous work on Russian has suggested that the primary and secondary articulations of coda palatalized stops can be roughly simultaneous, consistent with the above prediction, or that the palatalization gesture slightly precedes the primary one, perhaps favoring the formant transition cues. Roughly simultaneous coordination has also been found for Russian /lʲ/ (Kochetov 2005) and /sʲ/ (Kochetov 2009). In these studies, the sounds occurred word/syllable-finally before a vowel-initial word. As Kochetov (2005) notes for /lʲ/, these facts also seem consistent with the hypothesis about timing and perception: since these sounds have internal cues to palatalization (that is, the palatalized state of the consonant is audible during the steady state portion of its production), have no bursts, and would have formant transitions on both sides, we have no reason to expect timing of the palatalization gesture to be coordinated with either the beginning or end of the consonant in particular, regardless of syllable position (see also Gick et al. 2006).[7]

However, in the same phonetic context (coda before a vowel-initial word), Kochetov (2009) found that the palatalization gesture of /tʲ/ was timed to coincide more with the *release* of the primary coronal gesture. Assuming such a difference turned out to be systematic, it might suggest that gestural timing is sensitive not just to the presence but to the relative salience of phonetic cues. Ní Chiosáin & Padgett (2012) report that Irish /tʲ dʲ/ differ more from /tˠ dˠ/, respectively, in burst duration, intensity and center of gravity than /pʲ bʲ/ differ from /pˠ bˠ/. Indeed, in both Irish and Russian the release of /tʲ dʲ/ is very salient, even sounding somewhat affricated. In contrast, /pʲ bʲ/ differ *more* from /pˠ bˠ/, respectively, in second formant values than /tʲ dʲ/ differ from /tˠ dˠ/, in both Irish and Russian (Purcell 1979, Ní Chiosáin & Padgett 2012). These considerations might suggest that, if the timing of secondary articulation gestures in coda consonants is to favor either the beginning or end of the primary gesture, it would be more adaptive to favor the beginning in the case of labial stops and the end in the case of coronal stops. However, it should be noted that Kochetov (2009) found coordination with the end also in the case of Russian coda /nʲ/. This does not obviously sit well with the above reasoning, and overall this remains fairly speculative given the amount of available data.[8]

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[7] In this paper we may use the terms 'start' and 'beginning' interchangeably, both referring to the point in time when a stop closure is first achieved. The same is true of 'end' and 'release', but we often use 'release' when the focus is on the acoustic and perceptual consequences of the end of consonant closure.

[8] As noted above, Biteeva (2021) found roughly simultaneous coordination of primary and secondary articulation in /tʲ/, unlike Kochetov. In Biteeva's stimuli, the target coda preceded a word-initial coronal consonant, so that burst cues might have been less reliable, while in Ko-

3.4 Hypotheses

Though there is not a great deal of previous evidence to go on, what evidence there is suggests that the relative timing of primary and secondary articulation gestures in palatalization contrasts is more variable in the coda than in the onset, by (and possibly within) subject and consonant type. We would therefore expect to find such an onset-coda asymmetry in our Irish data.

If the guiding principle is that gestural timing is perceptually adaptive, then we expect both palatalization and velarization gestures to be aligned roughly with the release of onset stops in Irish, since that is where all cues to the contrast can be maximized. As noted above, previous work on Irish and Russian already leads us to expect this pattern for palatalized consonants. As for velarization, past work has *not* found any consistent tendency for /Cˠ/ gestures to align with consonant release in onset position, as observed for /Cʲ/. Regardless of syllabic position, velarization seems fairly static over the duration of the consonant. However, relevant data are limited.

In the case of coda stops, where cues to the palatalization contrast are split between the beginning and end of the primary place gesture, we have no general reason to expect alignment specifically with release. Assuming both formant transition and burst cues are important, we would expect primary and secondary articulation gestures to be roughly simultaneous. Put differently, we might expect secondary articulation gestures to be achieved by the beginning of the consonant and maintained through to the release.

However, as discussed earlier, perhaps not all cues are equal in every context. If formant transitions are more effective cues than burst properties are for labial stops, then we might expect alignment of secondary articulations with the beginning of coda labials, at the vowel-consonant transition. If the reverse is true for coronal stops, we might expect alignment with the coda consonant release instead. However, these latter predictions are somewhat speculative.

4 Ultrasound study

4.1 Methods

4.2 Participants

We recorded 7 native Irish speakers, whose language background corresponded to each of the three major Irish dialect groups (Fig. 2). The shaded portions of

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chetov's it was prevocalic. An interesting question for future work is whether such differences are systematic.

Figure 2 show the Gaeltachtaí -- areas where Irish is spoken as a community language. It is conventional to distinguish three major dialect areas for Irish, that of Ulster in the northwest, Connacht in the west, and Munster in the southwest. Our study includes speakers from all three dialect areas, and we use these terms, but it should be noted that there is dialectal diversity within each dialect area.

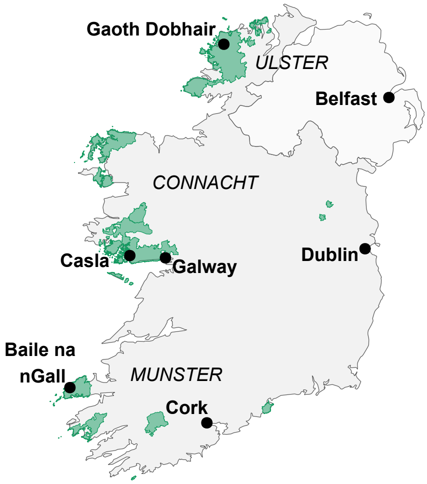

Figure 2: Officially recognized *gaeltachtaí* (Irish-speaking areas) in the Republic of Ireland, shaded in green (*gaeltachtaí* map data provided by `https://data-osi.opendata.arcgis.com/`, under CC by 4.0 license, `https://creativecommons.org/licenses/by/4.0/`).

We recorded two speakers of Ulster Irish (U1, 24, M; U2, 40, M), three of Connacht Irish (C1, 42, F; C2, 50, F; C3, 43, F), and two of Munster Irish (M1, 34, M; M2, 56, M). (Mean age = 41, median = 43.) Recordings took place in Gaoth Dobhair, Casla, and Baile na nGall, indicated on the map.

All of our speakers were professional Irish-language broadcasters, working for RTÉ Raidió na Gaeltachta, the Irish-language radio network of Raidió Teilifís Éireann, Ireland's national public service media system. Their jobs required them to speak and read Irish throughout the workday. All were native speakers of their respective dialects who were raised and currently live in the relevant dialect area. Their parents were native speakers who spoke Irish to them, except that one speaker's father (C3) was a native English speaker who spoke both English and Irish to her, and another's (M1) mother was a native English speaker who spoke Irish to him. They attended primary and secondary school through Irish in their respective dialect areas, though C1-3 and M1 used both English and Irish in secondary school. All speakers attended third level colleges. All reported reading Irish on a daily basis. None reported any difficulties in hearing, speaking, or reading.

As in Bennett et al. (2018), we chose to work with Irish-language broadcasters for several reasons. First, even in traditional Irish-speaking communities (*gaeltachtaí*), English has grown increasingly dominant, particularly among younger speakers, as noted earlier. In this fragile sociolinguistic context, native speakers may avoid interactions — such as experimental phonetic studies — in which they perceive that their Irish is being evaluated. The speakers for this study represent relatively traditional varieties of Irish, are comfortable with audio recording technology, and are accustomed to speaking while being recorded.

Given the number of speakers of each dialect area, we cannot infer anything firm about dialect differences based on our study, though the speakers clearly showed expected properties of their dialects. (For example, the Ulster speakers pronounced /tʲ dʲ/ as [t͡ɕ d͡ʑ] respectively.) A tentative investigation of inter-speaker differences is provided in section 7.

4.3 Items

The materials were (mostly) monosyllabic words with a target stop consonant controlled for secondary articulation (/Cʲ/ or /Cˠ/), place of articulation (labial, coronal, dorsal), position (word-initial or -final) and adjacent vowel /iː uː ɔː/ (= 2 × 3 × 2 × 3 = 36 total conditions). There was one word per condition. The words used are given in Tables 8 and 9 in the Appendix.

We used long /iː uː ɔː/ for the vowel contexts because these vowels vary in both backness — which is key to /Cˠ Cʲ/ contrasts in Irish — as well as height. Short vowels cannot be used for this purpose, because non-low short vowels take on the backness of a following consonant (Ní Chiosáin 1991, Ó Siadhail 1991): they are predictably front before palatalized consonants (e.g. *min* [mʲ**i̠**nʲ] ‘grain’) and back before velarized consonants (e.g. [mʲ**u̠**nˠ] ‘small’).

In using all three of /iː uː ɔː/, this study expands on Bennett et al. (2018), who only considered onset consonants preceding /iː uː/. Having said this, we found substantial variation in the pronunciation of /ɔː/ depending on dialect, speaker, context and word, particularly for the Ulster speakers, who had qualities including [ɔ a ɑ ʌ ɛ]. The high vowels were more consistent, though we saw some variation in the backness of /uː/ depending on the speaker and word. Due to these and other unanticipated variations in vowel production, the conclusions we can draw about vowel context effects are limited.[9]

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[9] In two forms the vowel context differed from the expected because of diphthongized pronunciations: [iːədˠ] for *iad* ‘them’ and [bˠuːɨkʲ] or [bˠuːɪkʲ] for *buaic* ‘pinnacle’.

Since perfect control of materials would have made it impossible to use actual words, the target stops in our word list were either voiceless or voiced as needed (e.g. *tuí* /**t**ˠiː/ ‘straw’ vs. *díon* /**d**ʲiːnˠ/ ‘roof’). For similar reasons, three of our forms are disyllabic instead of monosyllabic, though in all cases the target consonant was an onset/word-initial one in the stressed (initial) syllable (these are *píosa* /**p**ʲiːsˠə/ ‘piece’, *púca* /**p**ˠuːkˠə/ ‘ghost’, and *ciúnas* /**k**ʲuːnˠəsˠ/ ‘quiet (noun)’). For one word, /bʲeːkʲ/ ‘shout’, with a final /kʲ/ target consonant, the vowel context was /eː/ instead of /iː/. In the case of onset/word-initial consonants, the nearest consonant (after the following vowel), if there was one, was a velarized coronal (e.g. /dʲiːnˠ/ ‘roof’), except in the case of /pˠuːkˠə/ ‘ghost’. In the case of coda/word-final target consonants, the nearest consonant (before the preceding vowel) was more varied (see Table 9 in the Appendix), again to ensure that actual words were used.

Items were recorded in the context of the carrier sentence [ˈdˠuːrʲtʲ ˈiːfʲə ___-əˈnˠʊrˠə] ‘Aoife said ___ last year’. This means that word-final target consonants were positioned before a vowel-initial word, something that made segmentation and labeling based on the acoustic signal easier. However it does raise the question whether the relevant target consonants are actually syllable-final in these sentences, as we assume they are. We do not believe that Irish has resyllabification between lexical words: we refer the reader to arguments in Green (2001) that resyllabification in Irish is possible only in the case of certain proclitics.[10] Note also that Kochetov (2006)’s finding of different timing for word-final labials compared to word-initial ones, discussed in section 3.2, was also based on items placed in a carrier sentence before a vowel. As we will see, our own timing results also show that final stops do not behave like initial ones.

4.4 Recording procedure

Recordings were done in RTÉ Raidió na Gaeltachta studios in Gaoth Dobhair (Gweedore, Ulster), Casla (Costelloe, Connacht) and Baile na nGall (unofficially Ballydavid, Munster). Speakers repeated the 36 experimental items five times each in the frame sentence described above. All speakers read the words in the same pseudo-random order.

4.4.1 Ultrasound and audio recording

We recorded midsagittal images of the tongue surface using a portable Terason T3000 ultrasound system and model 8MC3 3-8MHz probe with a 90° field of

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[10] For discussion of Irish syllabification in general, see Ní Chiosáin (To appear).

view (using a depth setting of 10 and focal setting of 8, giving ≈ 46 fps, or 1 frame every 22 ms), using the Ultraspeech software package (Hueber et al. 2008), which automatically aligned the audio and video recordings. The probe was stabilized and held in place with an Articulate Instruments ultrasound stabilization headset (Wrench 2008, Scobbie et al. 2008). Simultaneous audio was recorded using a Shure WH20 dynamic cardioid microphone attached to the headset, recording directly to the ultrasound system (which included a laptop computer) at a 44.1 kHz sampling rate.[11]

4.5 Data annotation

4.5.1 Landmark identification and frame

Temporal landmarks for each consonant were annotated in Praat (Boersma & Weenink 2020), on the basis of acoustic information present in the waveform and spectrogram of the audio signal (see Turk et al. 2006). The beginning of C closure was primarily identified by a drop in amplitude from the preceding vowel. For onset stops, this vowel belonged to the preceding word in the frame sentence (the proper name *Aoife* [ˈiːfˠə]). For coda stops, the preceding vowel belonged to the same target word. Stop offsets were marked at the beginning of the stop release burst. In cases of uncertainty the choice was generally made to err in the direction of smaller consonant duration so as to minimize the possibility of including vocalic information as part of the consonant.

We extracted ultrasound frames for analysis at three different landmarks: stop onset, stop release, and the midpoint between them. (These correspond to the terms ‘C start’, ‘C end’, and ‘C midpoint’ used below.) These landmarks were determined as described above (see also Fig. 1). Analyzing secondary articulations at each of these three landmarks should provide us with at least a rough measure of how those secondary articulations are timed relative to major articulatory events in the corresponding primary articulations of the same consonant.

4.5.2 Contour tracing

Mid-sagittal ultrasound images were traced using EdgeTrak software (Li et al. 2005). EdgeTrak produces contours consisting of 100 points per traced tongue surface (Fig. 3), each with (X,Y) coordinates in Cartesian space.

Some mid-sagittal images could not be traced due to issues with image quality. This led to imbalances in the number of tokens across speakers and places

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[11] The microphone failed for the Connacht recordings, and the laptop’s built-in microphone had to be used instead.

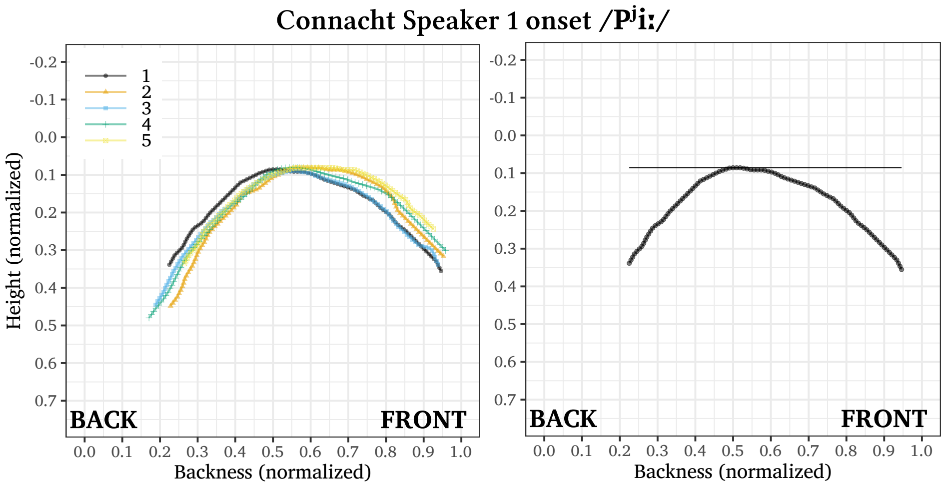

Figure 3: Left: sample EdgeTrack tracings for 5 tokens of onset /Pʲiː/ at C end, Connacht Speaker 1. Right: example identification of dorsal peak for one EdgeTrak tracing in this set (repetition 1).

of articulation. For some speakers, all tokens at a particular place of articulation could not be traced reliably, usually because the tongue surface for that consonant type consistently moved outside of the region in which the tongue body could be confidently identified (i.e. outside of the field of view and/or depth of the image produced by our ultrasound probe). This most often occurred for dorsal stops, and sometimes for coronal stops. More detailed information about the number of tokens traced per speaker are provided in Table 10 in the Appendix.

4.6 Quantitative analysis

4.6.1 Normalization

In order to ensure that contour tracings were comparable across speakers, all tracings were range-normalized on a by-speaker basis. The X-coordinates were rescaled to the interval [0,1], and Y-coordinates were rescaled by the same proportion and similarly shifted to have a minimum value of 0 (see Fig. 3).

4.6.2 Dorsal peak backness

To assess the degree of velarization (= tongue body backing) and palatalization (= tongue body fronting) across contexts, we identified the X coordinate of the highest point of the tongue body in each contour (Fig. 3). The position of this X coordinate can then be used as a measure of the degree of fronting or backing of the tongue body in a given context.

In some tokens there was a plateau rather than a unique highest point for the traced contour. In such cases the center of the plateau was selected as the ‘peak’ of the tongue body, and the X coordinate of that center point used as our measure of tongue body fronting/backing.

We visually inspected each raw tracing to ensure that the highest point of the tongue contour was in a region which plausibly corresponded to the tongue body. For one speaker’s coronal data (M2), the highest point of the tongue surface fell on the tongue blade or tip, and not the tongue body; this data has been excluded from the analysis of dorsal backness.

Overall we examined the X position of the dorsal peak for 782 tokens in our data. The data and R scripts used to carry out this analysis are available at https://github.com/rbennett24/articles/tree/master/Irish_pal_timing_syll_FACL.

4.6.3 Dependent measure: change in backness over time

Our primary research questions concern the timing of secondary articulations in Irish. In our statistical analysis, we investigated differences in dorsal backness at C end vs. C start, for each token in our data. To do this, we subtracted the dorsal backness value at C start for each token from the corresponding value at C end. This difference – dorsal backness at C end relative to C start, in each token – is the dependent variable for our analysis. Values which are different from zero indicate a difference in the magnitude of dorsal backing/fronting across timepoints; if consistent across tokens, this would suggest that the secondary articulation gestures for /$C^ɣ$ C^j/ peak at either C end or at C start, in a given condition.

Such skews can be taken as evidence for a particular pattern of gestural alignment between primary and secondary articulations. For example, if dorsal fronting peaks at C end (= release) for /C^j/, we expect values of C end - C start to be positive for tokens of /C^j/, because the tongue should move forward over time. If dorsal backing for /$C^ɣ$/ also peaks at C release, we expect values of C end - C start to be *negative* for /$C^ɣ$/, since velarization involves backing the tongue body rather than fronting it.

Somewhat more succinctly: positive numbers mean the tongue body moves forward over time during the consonant, while negative numbers mean it moves backward. Consistent patterns of either type can be used as evidence for timing relationships between primary and secondary articulations.

5 Results

Fig. 4 shows dorsal backness trajectories, from C start to C midpoint to C end, for each token in our data. Certain tendencies are already apparent. For example, the position of the tongue dorsum appears to be further front at C release, compared to C start, for onset /Pʲ Tʲ Kʲ/, suggesting gestural alignment between the secondary /Cʲ/ articulation and stop release. Similarly, the tongue dorsum is further *back* at C release compared to C start for onset /Pˠ/. We also observe a certain amount of variability in timing patterns across tokens in the same condition. Some of this variability may owe to the influence of vowel context (e.g. Bennett et al. 2023). Below we focus on other sources of variability.[12]

To help interpret the values presented in Fig. 4 and subsequent figures, Tables 3 and 4 provide some summary statistics about the distribution of dorsal backness values in our data. For example, a difference of 0.11 between start and end position in Fig 4 would correspond to a difference of about one standard deviation for the full set of backness values in our data (across all three of C start, midpoint and end), or about 1/6 of the overall range of these values (Table 3). It would also be about the same size as the difference in mean dorsal backness between velar /Kʲ/ vs. /Kˠ/ in onset position at C end in our data (Table 4). Figs. 3 and 5 are also useful for visualizing these differences; see Table 5 for related statistical analysis.

Table 3: Summary statistics for distributions of dorsal backness values in our data. sd = standard deviation, IQ range = inter-quartile range, Δ(X) = size of range for X.

Mean	Median	Range	Δ(Range)	sd	IQ range	Δ(IQ range)
0.5020	0.5080	[0.1356,0.7789]	0.643	0.108	[0.4266,0.5952]	0.173

We statistically analyzed values of tongue body backness at C end (relative to C start) using linear mixed-effects modeling in R (R Development Core Team 2020) with the lmerTest package (Kuznetsova et al. 2020; see also e.g. Pinheiro & Bates 2000, Gelman & Hill 2006, Baayen et al. 2008, Bolker et al. 2009, Barr et al. 2013, Matuschek et al. 2017, Tomaschek et al. 2018, Oberpriller et al. 2022). The predictors Consonant Place, Secondary Articulation, Syllable Position, and Vowel Context were sum-coded in order to reduce collinearity between

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[12] A point of clarification: for each token, the value at C end is relative to C start. As a consequence, the values at C end should *not* be interpreted as reflecting the overall degree of palatalization (fronting) or velarization (backing) in a given token. Instead, values at C end should be interpreted as reflecting *change in backness over time.* (The same goes for values at C midpoint, of course, though we do not analyze that data here.) See Bennett et al. (2023) for an analysis of the strength of palatalization/velarization in this data.

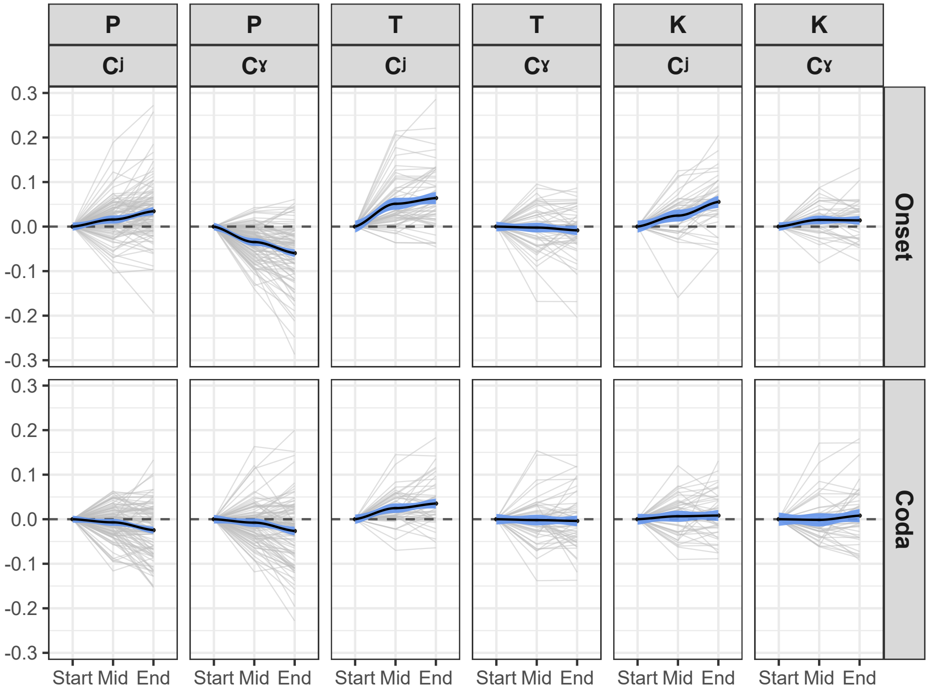

Figure 4: Trajectories for backness of dorsal peak over C start, midpoint, end timepoints, relative to values at C start. Grey lines represent trajectories for individual tokens, black lines represent loess-smoothed regressions over pooled values, with overlaid ribbon in blue showing confidence intervals around estimates of the mean.

Table 4: Differences between mean backness values of /Cʲ/ - mean backness values of /Cˠ/ at C end, across places of articulation and syllable positions

Syllable position	/Pʲ/ - /Pˠ/	/Tʲ/ - /Tˠ/	/Kʲ/ - /Kˠ/	Overall
Onset	0.166	0.206	0.100	0.163
Coda	0.132	0.190	0.079	0.134

simple predictors and higher-order interactions, and to help with model interpretability. All two-way interactions between these predictors were included in the initial model; we also included a three-way interaction between Consonant Place, Secondary Articulation, and Syllable Position. The reference level for Consonant Place was Labial; for Vowel Context it was /iː/; for Syllable Position it was Onset; and for Secondary Articulation it was /Cʲ/.

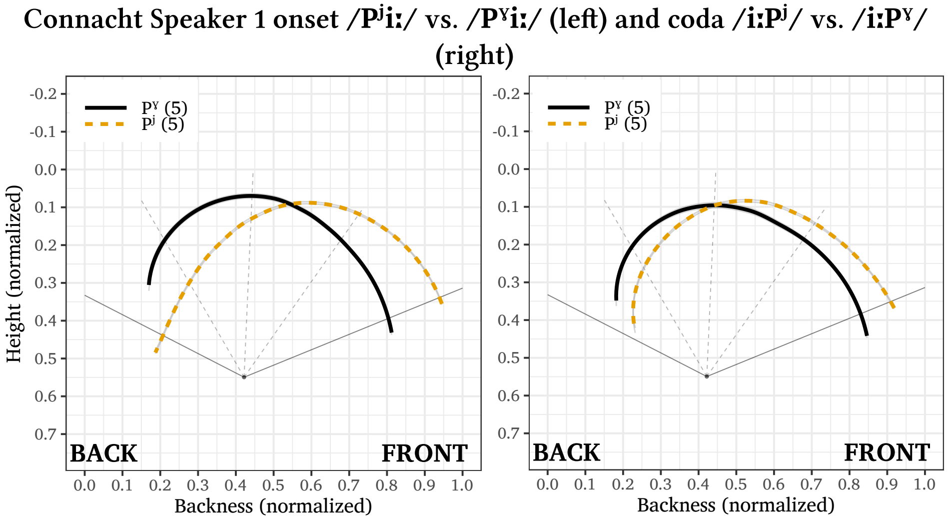
Connacht Speaker 1 onset /Pʲiː/ vs. /Pˠiː/ (left) and coda /iːPʲ/ vs. /iːPˠ/ (right)

Figure 5: Loess-smoothed curves for /Pʲ/ vs. /Pˠ/ in the context of /iː/, in both onset (left) and coda (right) position. Connacht Speaker 1 (see Fig. 3)

A random effect for Speaker was included, along with by-speaker random slopes for Syllable Position. Models with additional by-speaker random slopes failed to converge, in part because of the unbalanced nature of our data (see Appendix). We did not include a random effect of Word because we only had one word per condition of interest. The specifications for the model are provided in (1).

(1) Linear mixed-effects model specifications:
Dependent variable: Backness of dorsal peak at C end - C start ~
Three-way (1):
C Place × Secondary Articulation + Secondary Articulation +
Two-way (6):
C Place × Syllable Position + C Place × V Context + C Place × Secondary Articulation + V Context × Syllable Position + V Context × Secondary Articulation + Secondary Articulation × Syllable Position +
Simple (4):
C Place + Syllable Position + V Context + Secondary Articulation +
Random effects:
(1+Syllable Position|Speaker)

This model was fit with the parameter REML = False so that we could use the log-likelihood test to carry out model criticism and simplification. However, model criticism did not lead to the exclusion of any fixed-effect predictors (with $\alpha = .05$), starting with the highest-order (three-way) interaction term, and retaining all simple predictors participating in interactions. As such, our final model was the same as our initial model (1). The residuals appeared approximately normally-distributed in the model. This model has only limited collinearity: the maximum variance inflation factor (VIF) was 1.34, as reported by the `check_collinearity()` function in the PERFORMANCE package (Lüdecke et al. 2021). VIF values below 5 are generally accepted to signal fairly low collinearity (e.g. Tomaschek et al. 2018).

The model results are provided in Table 5. The *p*-values we report were estimated by the LMERTEST package. We have enclosed certain significant (or near-significant) predictors in boxes to highlight their relevance for the hypotheses we consider here: namely, that the timing of secondary palatalization and/or velarization gestures may be less stable in codas than in onsets, and less stable in labials than in consonants at other places of articulation (especially coronals).

Table 5: Linear mixed-effects model parameters for analysis of dorsal backness trajectories (values at C end, relative to C start).

Predictor	Estimate	SE	*p*
(Intercept)	0.0054	0.0049	.31
C place			< .001*
Coronal	0.0099	0.0031	< .01*
Dorsal	0.0144	0.0034	< .001*
Syllable position			< .46
Coda	-0.0051	0.0065	.46
Secondary articulation			< .001*
/Cˠ/	-0.0207	0.0020	< .001*
V context			< .001*
/uː/	0.0023	0.0028	.43
/ɔː/	0.0150	0.0028	< .001*
C place × Syllable position			< .075
Coronal:Coda	0.0072	0.0032	< .05*
Dorsal:Coda	-0.0058	0.0034	.09
Secondary articulation × C place			< .01*
/Cˠ/:Coronal	-0.0067	0.0029	< .05*
/Cˠ/:Dorsal	0.0099	0.0031	< .01*
Secondary articulation × Syllable position			< .001*
/Cˠ/:Coda	0.0141	0.0020	< .001*
C place × V context			< .001*
Coronal:/uː/	-0.0138	0.0041	< .001*
Dorsal:/uː/	-0.0018	0.0044	.69
Coronal:/ɔː/	0.0078	0.0040	.05
Dorsal:/ɔː/	0.0062	0.0043	.15
V context × Syllable position			< .001*
/uː/:Coda	0.0012	0.0027	.64
/ɔː/:Coda	0.0234	0.0026	< .001*
Secondary Articulation × V context			< .01*
/Cˠ/:/uː/	0.0009	0.0026	.74
/Cˠ/:/ɔː/	0.0067	0.0026	< .05*
Secondary articulation × C place × Syllable Position			< .01*
/Cˠ/:Coda:Coronal	-0.0049	0.0029	.09
/Cˠ/:Coda:Dorsal	-0.0041	0.0031	.18

Range of values: [-0.2870, 0.2858] (Δ = 0.573)

Mean = 0.0003, median = 0, sd = 0.0716

Reference levels: labial, /Cʲ/, onset, /iː/

While the results in Table 5 imply that gestural alignment may be influenced by a number of factors, the precise patterns of alignment indicated by these results are a bit difficult to interpret, given the various overlapping interactions and main effects. Still, certain patterns do seem apparent. For example, while velarized /Cˠ/ shows evidence of backing at C end, relative to C start (negative estimate for /Cˠ/), this tendency is much weaker in coda position (roughly comparable positive effect for Coda × /Cˠ/). This suggests that velarized consonants may tend toward release alignment in onsets, but not in codas (or at least, not as strongly in codas).

However, the significant effects of Dorsal × /Cˠ/, Coronal × /Cˠ/, and Coronal × Coda suggest that these tendencies may vary depending on place of articulation — in particular, labial /Pˠ/ may be driving most of the onset vs. coda asymmetries for velarized /Cˠ/, as implied by Fig. 4. At a minimum, it seems that consonant place, secondary articulation, and syllable position play *some* role in determining patterns of gestural alignment in our data.

To clarify the structure of our results, Fig. 6 plots the distributions of backness values, relative to C start, for all combinations of consonant place, secondary articulation, and syllable position in our data. (We abstract away from vowel context because it is not related to the specific hypotheses we focus on here.) For each cell, we assessed whether the distribution of dorsal backness at C end was significantly different from zero (i.e. different from C start, since C start was subtracted from all timepoints for each token). This was determined by *t*-tests with conservative Bonferroni-corrected significance values of $\alpha = .05/12 = .0041$. Distributions which are significantly different from zero in Fig. 6 indicate patterns of gestural timing in which dorsal backness for secondary articulations peaks at either C end or C start (note that we do not analyze midpoint values at all here).[13] We label such distributions with Rel for 'alignment with C release' (= C end), and VC for 'alignment with VC transition in coda position' (= C start in coda position). These are the only two patterns of alignment that our statistical analysis uncovered.

Fig. 6 shows that there are clear asymmetries across conditions with respect to the timing of dorsal gestures for /Cˠ Cʲ/. In onset position, the dorsal fronting gesture for /Cʲ/ peaks at C release; this is consistent across labial, coronal, and dorsal places of articulation (see Fig. 8 below for a visual illustration with onset /Pʲuː/). Additionally, velarized labial /Pˠ/ also shows release alignment in onset position. Velarized /Tˠ Kˠ/ show no particular pattern of alignment in onset position in this data.

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[13] The significant results labeled in Fig. 6 remain the same if significance is assessed using the bootstrap estimation method described in section 7 rather than *t*-tests.

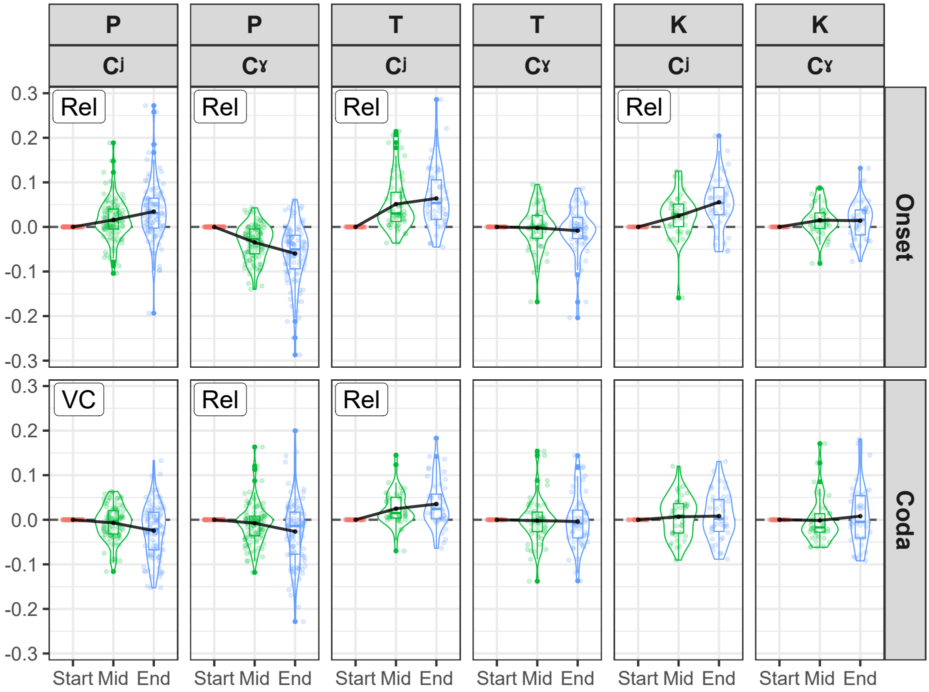

Figure 6: Values for backness of dorsal peak over C start, midpoint, end timepoints, relative to values at C start. Black lines connect mean values of distributions at each timepoint. Boxed text labels indicate statistically significant patterns of alignment in a given condition: 'Rel' indicates that alignment of the secondary articulation peaks at C release, and 'VC' indicates that alignment of the secondary articulation peaks at the VC transition in coda position.

In coda position, timing patterns are more varied. Coda /Pʲ/ shows VC alignment, while coda /Pˠ/ shows release alignment.[14] We illustrate this difference with a pair of examples from Ulster Speaker 1's data in Fig. 7.

Both /Pˠ/ and /Pʲ/ show backing over time in coda position after /ɔː/ in Fig. 7, indicating an *increase* in velarization over time, but a *decrease* in palatalization. This reflects different timing patterns for coda /Pˠ Pʲ/: release alignment for coda /Pˠ/, and VC alignment for coda /Pʲ/.

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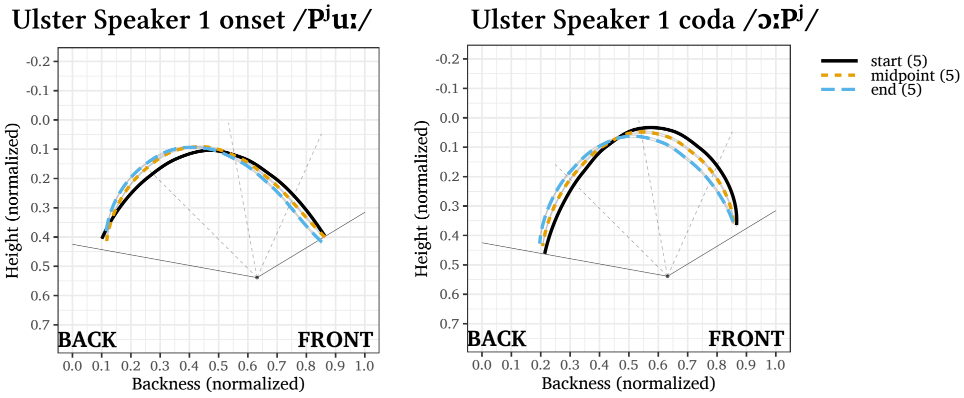
[14] It's important to remember that negative values at C end mean different things for /Cʲ/ vs. /Cˠ/. Negative values at C end indicate dorsal backing relative to C start: this implies stronger velarization over time, but *weaker* palatalization. So while the distributions of coda /Pʲ/ and /Pˠ/ are similar in Fig. 6, they reflect different alignment patterns: release alignment for /Pˠ/ (stronger backing over time), and VC alignment for /Pʲ/ (weaker fronting over time).


Ulster Speaker 1 onset /Pʲuː/

Ulster Speaker 1 coda /ɔːPʲ/

Figure 7: Loess curves for Ulster Speaker 1's coda /ɔːPˠ/ and /ɔːPʲ/ data showing change over time. The solid black line corresponds to C start, the short-dashed yellow line to C midpoint, and the long-dashed blue line to C end.

Coda /Tʲ/ also shows release alignment in Fig. 6, while the dorsal gesture for coda /Tˠ Kʲ Kˠ/ do not appear to show any particular alignment pattern at all.

Some of these results are also evident in the model output in Table 5. For example, the positive estimate for /Cˠ/ × Dorsal is consistent with the observation that coda labial /Pˠ/ (the reference level for C place) shows release alignment (negative values) across syllable positions, while dorsal /Kˠ/ shows values centered around zero for both onset and coda contexts.

The significant trends in Fig. 6 are readily apparent from visual inspection of our raw tracings and corresponding loess-smoothed curves like Fig. 7.[15] For example, Fig. 8 confirms that the tongue body in onset /Pʲuː/ tends to be raised and/or fronted at C release (C end) relative to C start for most speakers. The degree of fronting involved varies — it is clearest for Connacht Speaker 2, and the Ulster speakers — but the overall pattern appears to hold for 5/7 participants (Connacht Speakers 1 and 3 being apparent exceptions).

Fig. 9 provides a side-by-side comparison of raw tracings for Munster Speaker 1's onset /Pʲuː/ productions at C start and C release (C end). We note that (i) this speaker's productions are fairly consistent from token-to-token, and (ii) there is clear raising and fronting of the tongue body at C start relative to C end, despite the fact that the following vowel is back /uː/ (CV coarticulation for backness is limited in Irish; Ní Chasaide & Fealy 1991, Bennett et al. 2018, 2023).

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[15] The full set of raw tracings and loess curves discussed in this section is available at https://github.com/rbennett24/articles/tree/master/Irish_pal_timing_syll_FACL.

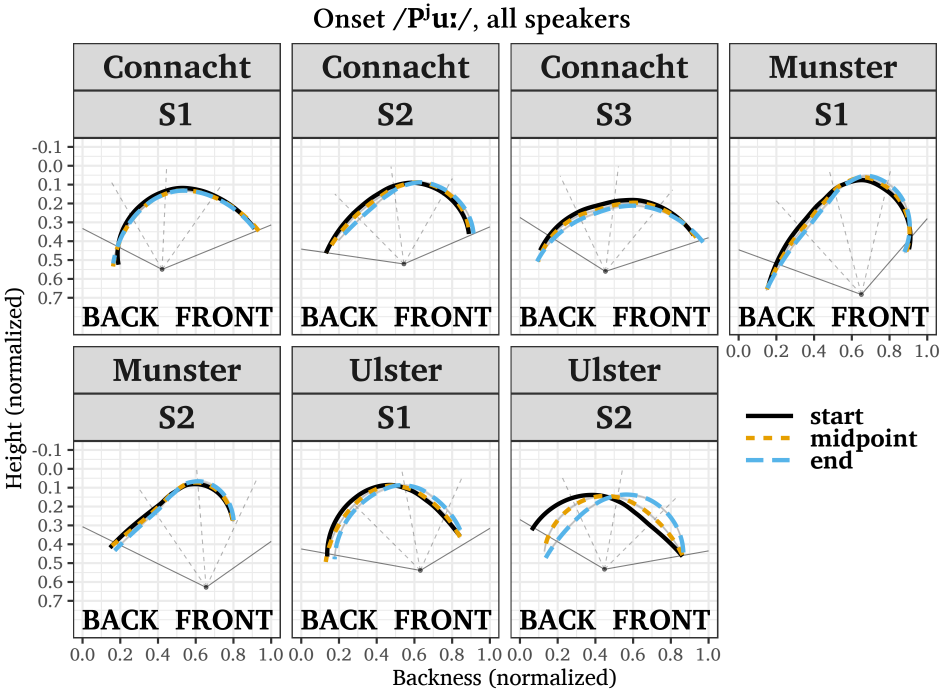

Figure 8: Loess-smoothed ultrasound tracings for every speaker's /Pʲuː/ tokens at C start, midpoint, and end.

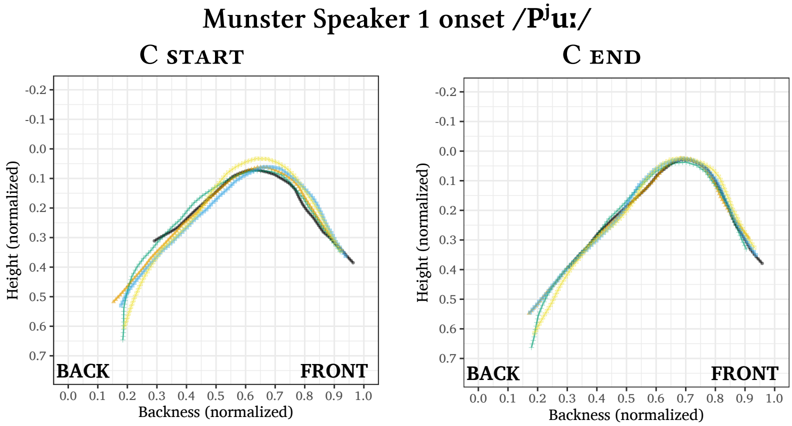

Figure 9: Raw ultrasound tracings for Munster Speaker 1's onset /Pʲuː/ tokens at C start (left) and end (right).

We conclude that the significant results in in Fig. 6 are reflected in qualitative patterns as well as quantitative ones.

The *non*-significant results in Fig. 6 must be interpreted with caution, for two reasons. First, in frequentist statistics it is not generally valid to draw conclusions from the *lack* of a statistically-significant effect (this is sometimes called 'accepting the null hypothesis'; Frick 1995 and many others).[16]

The second issue of interpretation surrounding Fig. 6 is that a non-significant effect could correspond to two different scenarios regarding articulatory timing. First, it could be that backness values at C start are comparable to those at C end because the secondary articulation reaches its peak at C start, and is then maintained more or less constant until C end. In this scenario, we expect a fairly tight cluster of points around zero at C end in Fig. 6, since the position of the tongue body should be more-or-less the same, consistently, at C start vs. C end.

Alternatively, it could be that articulatory timing is more noisy and variable: sometimes the secondary articulation peaks at C start, sometimes at C end, and sometimes in-between. In this scenario, we might expect a looser grouping of points around zero at C end. This is because differences in dorsal position at C end, relative to C start, would be less stable than in a scenario in which the secondary articulation peaks at C start and is held till C end.[17]

To try to disentangle these two interpretations, we can first consider some qualitative patterns in our data. Fig. 10 provides loess-smoothed ultrasound tracings for coda /Tˠ/ following /iː/ for one speaker (U2), at C start, midpoint, and end. We've chosen this context as an example because (i) coda /VTˠ/ is one of the non-significant conditions in Fig. 6, and (ii) some of our other work on Irish suggests that velarized /Cˠ/ is often significantly fronted after /iː/ in coda position

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[16] In principle, Bayesian modeling can be used to justify acceptance of a null hypothesis (e.g. Kruschke 2013). However, in the specific case at hand, nothing is gained on this front by using Bayesian rather than frequentist statistics. Bayesian t-tests, implemented using the ttestBF() function in the BayesFactor package and the describe_posterior() function in the bayestestR package in R (Morey & Rouder 2023, Makowski et al. 2019), suggest that there is indeed sufficient evidence to accept the significant effects labeled in Fig. 6. For the remaining conditions, the Bayesian t-tests suggest that the evidence is insufficient to either accept or reject the null hypothesis of no difference. When it comes to drawing inferences about the distributions in Fig. 6, Bayesian methods leave us in the same place as regular frequentist ones.

[17] A third scenario, which we reject, is that the peak of the secondary articulation varies categorically between C start and C end for those conditions which lack a significant skew away from zero. In this scenario we would expect to find a *bimodal* distribution of points on either side of zero, with one peak for tokens showing clear C start alignment, and another peak, on the opposite side of zero, for tokens showing clear C end alignment. However, the distributions in Fig. 6 appear to be consistently unimodal across conditions and timepoints, and so we reject this possibility. See also Padgett et al. (2023), who use Hartigan's dip test to argue that all of the distributions in Fig. 6 are unimodal.

(Bennett et al. 2023). Coda /iːTˠ/ is thus a condition in which we might expect to find greater backing at C end than C start, where influence from the vowel /iː/ could pull the consonant articulation for /Tˠ/ forward at the VC transition.

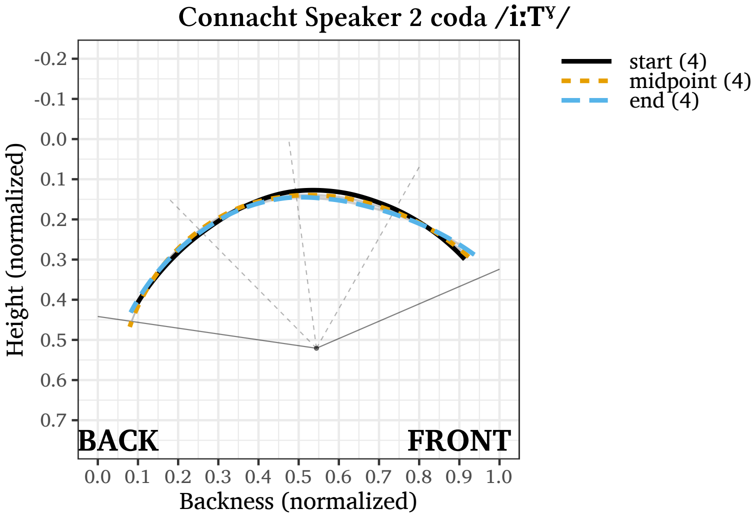

Connacht Speaker 2 coda /iːTˠ/

Figure 10: Loess-smoothed ultrasound tracings for Connacht Speaker 2’s /iːTˠ/ tokens at C start, midpoint, and end.

As is evident from Fig. 10, tongue body position and posture are very similar across timepoints. There is perhaps a slight lowering of the tongue body at C end and midpoint relative to C start, but otherwise, very few differences when comparing these three landmarks. This implies that the constriction for /Tˠ/ is already achieved by the beginning of the consonant in /iːTˠ/ for this speaker.

Loess-smoothed curves are a kind of average, which could potentially hide some informative variability across tokens. However, we can also see from Fig. 11 that there is little variability in tongue body position across tokens at either C start or C end. This too is consistent with the claim that the constriction for /Tˠ/ is achieved at the VC transition (C start) and maintained basically constant until C release (C end).

Visual inspection of raw tracings and loess curves suggests that, generally speaking, the non-significant conditions in Fig. 6 resemble Figures 10 and 11: tongue body position is more or less the same at C start as at C end.

There are two interesting exceptions to this generalization. First, coda /Cˠ/ is sometimes realized with a fronter (less velarized) dorsal constriction at C start than at C end when following /iː/ (Fig. 12). This reflects coarticulation for backness between /iː/ and a following /Cˠ/.

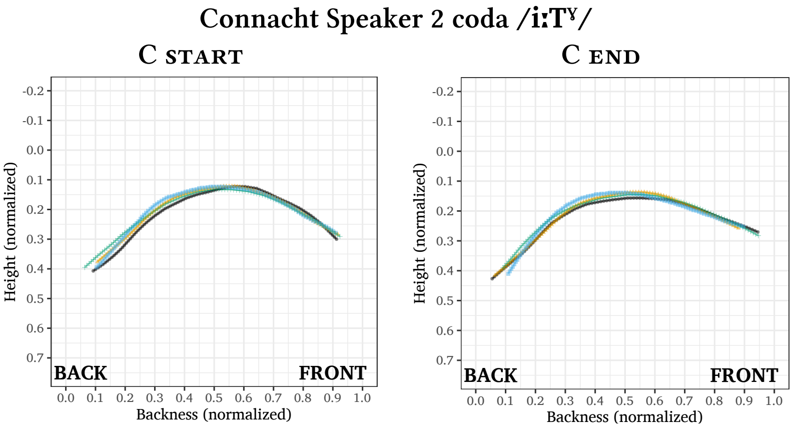


Figure 11: Raw ultrasound tracings for Connacht Speaker 2's coda /iːTˠ/ tokens at C start (left) and end (right).

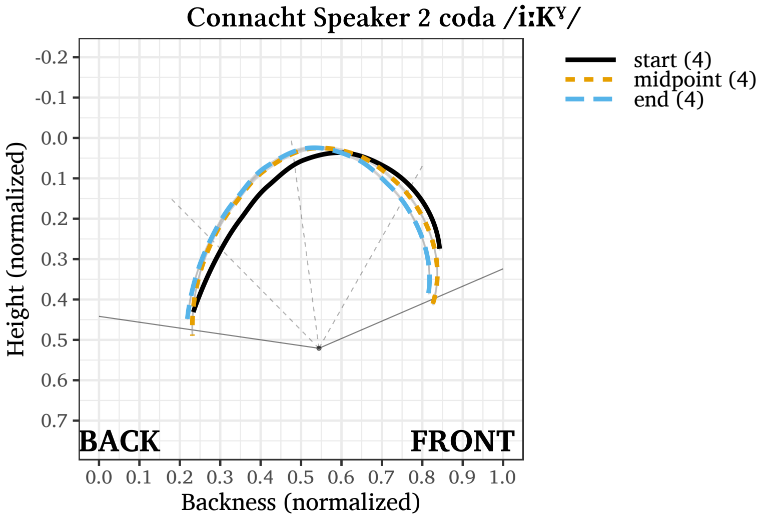
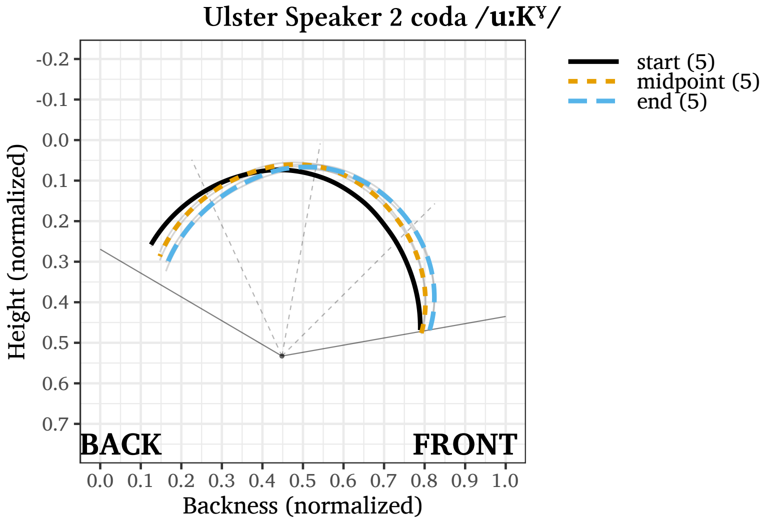


Figure 12: Loess-smoothed ultrasound tracings for Connacht Speaker 2's /iːKˠ/ tokens at C start, midpoint, and end.

At the VC transition, /Cˠ/ is fronter than at /Cˠ/ release, where the influence of the /iː/ is more removed. This is consistent with Bennett et al.'s (2023) finding that /iːCˠ/ is the context in which consonant backness is most affected by coarticulation with a neighboring vowel in this dataset:

Second, in some conditions, some speakers appear to transition towards a more neutral tongue body position at the end of coda C. For example, Fig. 13

shows that Ulster Speaker 2 has a fronter tongue body at C end than at C start in coda /uːKˠ/. Both the vowel and consonant are back in this context, so fronting is not motivated by the segments themselves.



Ulster Speaker 2 coda /uːKˠ/

Figure 13: Loess-smoothed ultrasound tracings for Ulster Speaker 2's /uːKˠ/ tokens at C start, midpoint, and end.

Our target words were produced in a frame sentence (section 4.3), which means that each target word was followed by the word [əˈnˠʊrˠə] 'last year'. The fronting observed in 13 could reflect anticipatory coarticulation with the upcoming [ə] in [əˈnˠʊrˠə]. Alternatively, it could correspond to a phrase-final tongue posture of some kind, since our target words were generally produced with focus prosody, and so may have been prosodically phrase-final. (See e.g. Gick et al. 2004, Katsika 2016 for related discussion.)

Taking these observations together, our overall conclusion is that the non-significant conditions in Fig. 6 generally represent a production pattern in which the secondary articulation is achieved at the VC transition (C start) and held more or less consonant through C release (C end). That said, we recognize that other factors (e.g. coarticulation) may play a role as well.

Further support for this interpretation comes from a more quantitative interpretation of the patterns in Fig. 6. Our statistical question concerns the spread of the distributions in Fig. 6: in cases where backness values at C end overlap with those at C start, are the distributions at C end tightly clustered (≈ alignment at C start, continued to C end) or more widely spread out (≈ variable alignment)?

To answer this question, we can compare the variability in our non-significant conditions to the variability in conditions where we believe there *is* a specific, consistent pattern of gestural alignment. Table 6 reports summary statistics, including standard deviations and inter-quartile ranges, at C endpoint for each of the 12 conditions shown in Fig. 6.

Table 6: Summary statistics for distributions shown at C endpoint in Fig. 6. Starred rows indicate conditions with statistically significant differences from zero in Fig. 6. sd = standard deviation, IQ range = inter-quartile range, Δ(X) = size of range for X.

	Mean	Range	Δ(Range)	sd	IQ range	Δ(IQ range)
*Onset Pʲ	0.017	[-0.194,0.272]	0.466	0.049	[0,0.036]	0.036
***Onset Pˠ**	**-0.031**	**[-0.287,0.061]**	**0.348**	**0.050**	**[-0.056,0]**	**0.056**
***Onset Tʲ**	**0.038**	**[-0.045,0.286]**	**0.331**	**0.058**	**[0,0.062]**	**0.062**
Onset Tˠ	-0.004	[-0.204,0.095]	0.299	0.041	[-0.011,0.004]	0.015
***Onset Kʲ**	**0.027**	**[-0.159,0.204]**	**0.364**	**0.049**	**[0,0.052]**	**0.052**
Onset Kˠ	0.010	[-0.082,0.132]	0.214	0.032	[0,0.024]	0.024
*Coda Pʲ	-0.011	[-0.153,0.133]	0.286	0.042	[-0.027,0.004]	0.031
*Coda Pˠ	-0.011	[-0.228,0.2]	0.428	0.051	[-0.027,0]	0.027
*Coda Tʲ	0.019	[-0.07,0.183]	0.253	0.040	[0,0.033]	0.033
Coda Tˠ	-0.002	[-0.138,0.154]	0.292	0.044	[-0.016,0.003]	0.019
Coda Kʲ	0.005	[-0.09,0.131]	0.221	0.040	[-0.012,0.026]	0.038
Coda Kˠ	0.002	[-0.092,0.181]	0.273	0.048	[-0.021,0.002]	0.022

As benchmarks, we can consider the three conditions with the largest deviations from zero, as determined by the absolute value of the mean. These are boxed and in bold in Table 6: they are onset /Pˠ Tʲ Kʲ/. These three conditions are the clearest examples of consistent articulatory alignment in our dataset, with secondary articulations seeming to peak at C end (= release) for all three conditions.

If we compare the measures of variance for the *non*-significant conditions in Fig. 6 and Table 6, we see that those measures are similar in size to the measures of variance in our three significant benchmark conditions. For example, the mean of onset /Tˠ/ (-0.004) is not significantly different from zero. The measures of dispersion for this condition — sd = 0.041, ΔRange = 0.299, and ΔIQ Range = 0.015 — are in fact *smaller* than the same measures for all three of our benchmark significant conditions (onset /Pˠ Tʲ Kʲ/). This suggests that the values for onset /Tˠ/ are at least as tightly clustered as the values for our significant benchmarks. The same general point can be made for *all* the non-significant conditions in Fig.

6 and Table 6: the dispersion around the mean appears to be basically the same, and sometimes smaller, than found for the significant conditions demonstrating specific patterns of articulatory alignment. This is also consistent with simple visual inspection of the distributions in Fig. 6.[18]

We conclude that the distributions for the non-significant conditions in Fig. 6 and Table 6 are not particularly loose or spread-out around zero. Instead, they appear to be about as tightly clustered as the distributions in our significant conditions. This is consistent with the claim that the secondary articulations in our non-significant conditions typically reach a peak at C start, and are then maintained more-or-less unchanged until C end. In the discussion below, we sometimes use the term 'held alignment' to refer to this scenario, in which there is no significant change in dorsal backness from C start to C end.

6 Interim discussion

Recall our hypotheses from section 3.4:

1. *The relative timing of primary and secondary articulations should be more variable in the coda than in the onset, by (and possibly within) speaker and consonant type.* Our measures of dispersion in Table 6 do not support this prediction. (Nor do they support an analogous hypothesis concerning labials compared to other places of articulation.) This hypothesis would lead us to expect more spread-out distributions for codas, relative to onsets, at C end in Fig. 6. This is not the case, either visually or numerically (Table 6).

However, we find some *tentative* support for this hypothesis below when we examine the results by individual participant.

2. *In onset stops, both palatalization and velarization gestures should be aligned roughly with the release of the consonant closure.* As expected based on previous findings, for palatalization this prediction holds across all three places of articulation (Figs. 4, 6): values at C end for onset /Pʲ Tʲ Kʲ/ skew positive, and are significantly different from zero, indicating greater fronting at C end relative to C start.

As we noted earlier, previous work has not found such a clear pattern for onset velarization, and we do not find compelling evidence *overall* for release

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[18] Padgett et al. (2023) report that the distribution for non-significant onset /Tˠ/ is more spread out than expected for a normal distribution according to a Shapiro-Wilks test with Bonferroni-corrected $\alpha = .015/12 = .0042$. However, this is also true of significant onset /Pʲ Pˠ Tʲ/ and coda /Tʲ/, and so this measure of dispersion also fails to distinguish our significant and non-significant conditions in Fig. 6.

alignment of velarization (= significant negative skew at C end) in this study either (but see the discussion below).

3. *In coda stops, both palatalization and velarization gestures should be roughly simultaneous with the primary articulation, achieved around the beginning of the consonant and maintained through to the release.* Here we must be more cautious, given limitations of our analysis discussed in the previous section. Still, our results support such an interpretation for /Tˠ Kʲ Kˠ/ (Figs. 4, 6, discussion around Table 6): values at C end seem to be centered around zero for coda /Tˠ Kʲ Kˠ/.

Also in a more speculative vein, we hypothesized that secondary articulations in the coda might be more aligned with the *beginning* of labial closures but with the *end* of coronal closures. This is based on the relative strength of formant cues for labial stops vs. release cues for coronal stops, and it has been observed for limited Russian data. (Section 3.3). Our findings depart from predictions 1 and 2 above in ways that are suggestive in this regard.

First, though in our data neither secondary articulations in the coda, nor velarization anywhere, generally favors alignment to a particular landmark — C beginning or release — /P/ contradicts these trends in having alignment with a landmark in all four conditions (syllable position x secondary articulation). In three out of these four conditions alignment favors vowel formant transitions (release alignment for onsets, beginning or VC alignment in codas). The exception is coda /Pˠ/, which favors release alignment. Second, coda /Tʲ/ also contradicts the above trends, in favoring release alignment. All of these facts except for that of coda /Pˠ/ are consistent with the hypothesis that alignment of secondary articulations is fine-tuned not just to the location but to the relative *importance* of cues in labials vs. coronals. Assuming there is validity to these considerations, it's not clear why /Pˠ/ does not follow the expectation.

There is a separate, articulatory, consideration relevant to the facts about labials. In the case of /Tʲ Tˠ/ or /Kʲ Kˠ/, there is tongue coupling, and possibly direct articulatory competition, between the primary articulator and a secondary dorsal one, while this is not true of /Pʲ Pˠ/. Perhaps this allows other factors — such as constraints on perceptibility like those discussed here — to more freely determine timing in the latter case. However, we *do* find alignment with C release in onset /Tʲ Kʲ/ and coda /Tʲ/, casting some doubt on the importance of such an articulatory effect. (See Bennett et al. 2018 for related discussion.)

7 Inter-speaker variation

In this section we provide a preliminary investigation of inter-speaker variation in timing patterns in our data. The goal is to see how well the generalizations above hold up by speaker. In addition, previous research has reported inter-speaker variation in the production of /Cˠ Cʲ/ contrasts in Scottish Gaelic (Sung et al. 2018) and in Russian (Kochetov 2002, 2009). As for Irish, drawing on the same dataset analyzed here, Bennett et al. (2023) find that speakers differ in how robustly /Cˠ Cʲ/ contrasts are distinguished by dorsal position across contexts. For example, some speakers seem to completely merge coda labi/Pˠ Pʲ/ following /iː/, at least in terms of dorsal shape and position, while other speakers maintain distinct dorsal postures for these consonants in this context.[19] This pattern of inter-speaker variation, along with others observed by Bennett et al. (2023), raises the question of whether speakers might differ with respect to the patterns of gestural timing reported in aggregate in section 5.

Fig. 14 shows loess-smoothed regressions for the trajectories of dorsal backness values across consonant start, midpoint, and end, for all combinations of syllable position, consonant place, and secondary articulation. This is akin to Fig. 4, but here separate regressions are provided for each speaker. For the sake of readability, we omit lines corresponding to the trajectories of specific tokens, as well as confidence intervals around the loess-smoothed estimates.

In general, the gestural timing patterns we observed in section 5 are broadly reflected in the patterns of timing observed for each individual's data. For example, the secondary articulation for onset /Kʲ/ seems to peak at C release for all three speakers whose data is included in this condition. Similarly, for both onset and coda /Tʲ/, speakers mostly show a consistent pattern of aligning peak dorsal fronting with C release. However, still focusing on /Tʲ/, speakers also seem to differ in how distinct dorsal position is at C end vs. C start for this sound, and two speakers seem to show no significant fronting over time for onset /Tʲ.

To quantify these patterns, we computed confidence intervals around the mean of each speaker's dorsal backness values at consonant end, relative to consonant start, using a non-parametric bootstrapping resampling method, implemented using the smean.cl.boot function in the Hmisc package in R (Harrell Jr. 2023, R Development Core Team 2020). If the confidence interval around each speaker's mean at C end is significantly different from zero, this would indicate that the dorsal position of the secondary articulation peaks at release, assuming that the mean values are fronter for /Cʲ/ and backer for /Cˠ/. If instead the mean values are *backer* for /Cʲ/ and *fronter* for /Cˠ/, this would indicate that secondary articulations peak at C start.

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[19] Bennett et al. (2023) report measures taken at C release for onset consonants, and at C start in the VC transition for coda consonants; they do not investigate possible changes in articulatory posture across timepoints within a given consonant, as we do here.

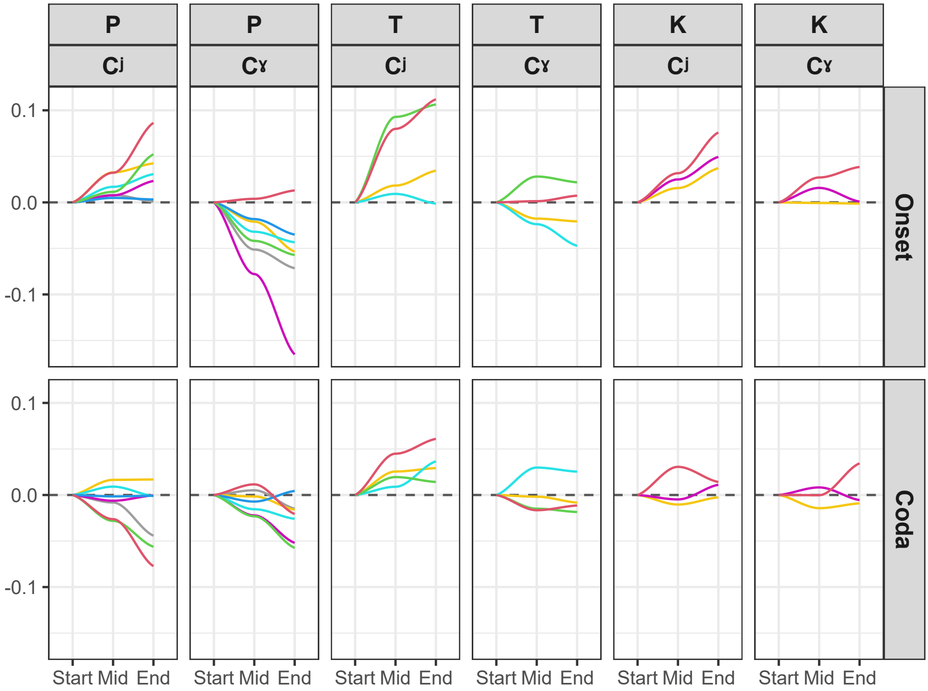

Figure 14: By-speaker trajectories for backness of dorsal peak over C start, midpoint, end timepoints, relative to values at C start. Colored lines represent loess-smoothed regressions over each speaker's values at each timepoint.

In order to reduce the number of statistical comparisons involved, we limited this analysis to backness values at C end. We chose non-parametric bootstrapping to estimate the means and confidence intervals, rather than a parametric method like a *t*-test, because (i) bootstrapping methods do not assume that the underlying data is normally distributed, and (ii) bootstrapping is more robust for smaller sample sizes. Sample size is a potential concern here, since splitting our data up by speaker substantially reduces the number of observations per comparison: for most combinations of speaker and condition, we have just 10-15 observations at C end (minimum = 8; 58/60 comparisons have at least 10 observations). In applying non-parametric boostrapping to this data we sampled with replacement 10,000 times for each combination of speaker and condition. This resulted in 60 total bootstrapped estimates (Fig. 14).

We reiterate that caution must be taken in interpreting these results, given the small sample sizes involved (see e.g. Chernick 2011: Ch.9 with respect to bootstrap methods, specifically). We nonetheless think it is useful to consider, in a broad and exploratory sense, the extent to which individual speakers might differ in their patterns of gestural timing for secondary articulations across contexts. Table 7 reports the significant results produced by this method, with a significance threshold of $\alpha = .05$.[20]

Table 7: Significant differences between distributions of backness values, relative to C start, at C end, by condition. Counts refer to number of speakers showing each pattern.

	P^{j}	T^{j}	K^{j}
Onset	Release: 5/7	Release: 3/5	Release: 3/3
Coda	VC: 3/7	Release: 3/5	0/3 significant

	P$^{\text{ɣ}}$	T$^{\text{ɣ}}$	K$^{\text{ɣ}}$
Onset	Release: 6/7	Release: 2/5, C start: 1/5	C start: 1/3
Coda	Release: 3/7	Release: 1/5, VC: 1/5	VC: 1/3

Again, the results in Table 7 broadly reflect the findings of section 5. First, palatalized /C^{j}/ consistently shows release alignment in onset position. For each place of articulation, the majority of speakers represented in that condition show release alignment, though it is not everyone. Two speakers do not align the peak of onset palatalization with the release of /P^{j}/, and likewise for /T^{j}/. In most other conditions few or no speakers show alignment with either consonant landmark. The exceptions are familiar from the discussion in section 6: several/most speakers *do* align secondary articulations for labials and for /T^{j}/.

Fig. 15 plots the same data as in Fig. 14, but pooled across places of articulation, so that each estimated trajectory is based on a larger number of observations. One can see in this figure our overall findings that onset palatalization aligns with C release while coda secondary articulations remain relatively unchanging throughout. We see release alignment for onset velarization as well, but this is mostly attributable to onset /P$^{\text{ɣ}}$/ as we have seen.

On the whole, we can draw two tentative conclusions from the above. First, alignment patterns for individual speakers more or less replicate the overall population trends reported in section 5. Second, however, there are signs of the variability predicted by our first hypothesis in section 6. Though we did not find

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[20] Given the fact that Table 7 reports multiple comparisons, we should arguably use a Bonferroni-corrected significance threshold of $\alpha = .05/60 \approx .0008$. Since this is an extremely conservative threshold for significance, and since our aims here are mostly exploratory, we opted for the standard $\alpha = .05$ instead. Using the conservative threshold of $\alpha = .0008$ shrinks the number of significant results in Table 7 from 33 to 21, but does not affect the broad qualitative conclusions we would draw from this data.

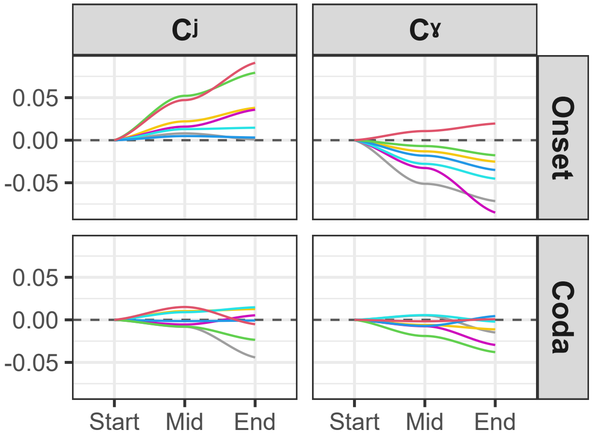

Figure 15: By-speaker trajectories for backness of dorsal peak over C start, midpoint, end timepoints, relative to values at C start. Colored lines represent loess-smoothed regressions over each speaker's values at each timepoint, collapsing across place of articulation.

greater variability for codas (or for labials) in our pooled data, here we see that more *patterns* of alignment occur in codas than in onsets. Specifically, while *release* alignment and *held* alignment are the only patterns found for onset consonants (except for one speaker who aligned with C start for /T^j/), we find release, VC transition, and held alignment in the case of codas.[21] There is likewise some suggestive evidence here that speakers may differ, to some extent, in their preferred timing patterns across different contexts.

To be sure, more work needs to be done to verify that these patterns of variability reflect bonafide inter-speaker differences, rather than accidental facts about our particular sample of speakers and recordings. Confirming these patterns of variability in a larger dataset, and exploring potential underlying causes (e.g. dialect variation), is a clear topic for future research.

8 Against anti-phase timing as the source of onset-coda asymmetries in palatalization

Our discussion has assumed that secondary dorsal articulations in Irish are coordinated with consonantal landmarks, as defined by the production of the conso-

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[21] When alignment is not aligned uniquely with the beginning or end of the consonant (= 'held alignment'), this might be understood as alignment with both, i.e. simultaneous production, as discussed earlier.

nant's primary articulation. This strikes us as a reasonable assumption: after all, palatalization and velarization are properties of consonants, at least phonologically.

Beyond alignment with consonant landmarks, we have suggested (section 3.3) that timing of secondary articulations might be constrained in perceptually adaptive ways. For example, in coda position, speakers must 'choose' whether to align the peak of a secondary articulation near the V-C boundary, where formant transition cues reside, at C release, where there are cues from burst quality, or with both landmarks. Both of these landmarks are important, perceptually speaking, for expressing secondary articulation contrasts. In coda position, unlike in onset position, these landmarks do not coincide, and so speakers can align peak /Cʲ Cˠ/ gestures at the V-C transition, or at the C release; or they can try to maintain the peak /Cʲ Cˠ/ gesture throughout the entire consonant, so that the gesture occurs at *both* the V-C transition and C release. Evidently, speakers adopt different timing strategies in coda position depending on the place and secondary articulation of the consonant, in ways that seem largely consistent with the hypothesis of perceptual optimization (section 5).

However, given the broad asymmetry we find between patterns of gestural alignment in the onset vs. coda for palatalization, we might look elsewhere for an understanding of what is happening. Studies of articulatory coordination have reported asymmetries in how segment-internal gestures are timed in onset vs. coda position. To illustrate, consider the American English lateral /l/, which has both a primary tongue tip constriction, and a secondary, vowel-like dorsal constriction (e.g. Krakow 1999, Sproat & Fujimura 1993, Proctor 2009, Lee-Kim et al. 2013, Turton 2017). In onset position (e.g. *lab*), the coronal and dorsal gestures for /l/ are largely synchronous. However, in coda position (e.g. *ball*), they appear to be produced sequentially, with the dorsal constriction preceding the coronal constriction in time. In codas, the overlap of the dorsal constriction for /l/ with the preceding vowel leads to a distinct and highly audible coloration of the vowel itself.

Similar observations have been made for the relative timing of oral closure and velum lowering in the American English nasals /m n/ (Krakow 1999, Byrd et al. 2009). In this case, velar lowering is largely synchronous with oral closure formation in onsets, but precedes closure formation in codas, producing extensive coarticulatory nasalization on the preceding vowel. Generalizing over these results, we can perhaps say that more open constrictions tend to precede more narrow constrictions for articulatorily complex consonants in coda position, at least in American English (Krakow 1999, Sproat & Fujimura 1993, Iskarous & Kavitskaya 2010).

These asymmetries in articulatory timing have been interpreted as a reflection of different underlying patterns of gestural coordination in onsets vs. codas. In onsets, gestures tend to be coordinated *in-phase*, or synchronously. In codas, gestures tend to be coordinated *anti-phase*, or sequentially. It has been argued that in-phase coordination is inherently more stable than anti-phase coordination, not just in speech but in motor planning and execution more generally (e.g. Goldstein et al. 2006, Nam et al. 2009, Parrell 2012 and references there). We might thus expect gestural alignment between primary and secondary constrictions to be more variable in codas for /Cʲ Cˠ/, exactly as we find (at least for palatalization), if those constrictions are timed in an anti-phase relationship.

There are at least two reasons to doubt this alternative analysis. First, Irish palatalization timing is more variable in the coda only in the sense of allowing more *patterns* of alignment depending on place of articulation (and to some extent speaker), as just discussed: alignment tends toward C start for /Pʲ/, C release for /Tʲ/, and neither for /Kʲ/. In other words, as shown in Figure 6 and Table 6, differences between onset and coda position in our study mostly boil down to which landmark the secondary articulation is coordinated with. Measures of variance for the timing of primary and secondary articulations actually imply similar variance in onset vs. coda position, *not* increased variance in codas.

Second, palatalization is *not* simultaneous with the primary constriction in onset position; rather, this study and previous ones have found a very consistent lag in the palatalization gesture, in both Irish and Russian, such that the peak occurs around the release of the primary constriction (see also Shaw et al. 2021). As for coda position, though secondary articulations in our data peak around the onset of the primary constriction in the case of /Pʲ/, this is not true at all for other conditions. Furthermore, as we saw in section 3.3, for Russian consonants other than stops, the facts suggest secondary articulations that are co-extensive with the primary ones, as we have found for some conditions here.

In the current study, we can investigate this question empirically, building on the discussion of Russian in Iskarous & Kavitskaya (2010). If secondary /Cʲ Cˠ/ are timed anti-phase (sequentially), then the gestural peak for /Cʲ Cˠ/ should occur during the vowel, well prior to the achievement of the primary constriction. This would mirror findings for American English /l/ and nasals in coda position, in which the dorsal constriction for /l/, and the velar lowering for /m n/, are timed to reach a peak during the vowel itself.

A major acoustic correlate for the /Cʲ Cˠ/ contrast in Irish (and other languages) is the F2 transition on neighboring vowels. F2 largely reflects dorsal backness in this context; it is also affected by lip rounding (e.g. Bennett et al. 2019). If /Cʲ Cˠ/ gestures peak during the vowel in VC# coda sequences, as predicted by anti-phase alignment, F2 values should show evidence of peaking during the vowel as well.

To assess this prediction, we measured F2 during the vowel in /VC#/ sequences, where our target consonant was a word-final coda consonant. The vowel was segmented from the preceding consonant at the beginning of voicing: since our focus is on VC transitions, not CV transitions, the criterion used to identify the beginning of the vowel is not especially important. The vowel was segmented from the following target stop consonant at the point where spectral energy in the vowel abruptly dropped off, particularly in the region of F2 (see e.g. Turk et al. 2006). Any preaspiration on the following final consonant was segmented as part of the vowel itself, since significant formant transitions may occur during periods of aspiration (e.g. Stevens & Klatt 1974; see also Clayton 2010). Formant tracking may be less accurate during preaspiration than during vowels, given the presence of aperiodic noise, and the relative weakness of higher formants during aspiration. That said, visual inspection of a number of preaspirated tokens suggests that F2 was still tracked fairly well during preaspirated transitions. 630 vowels were segmented in this analysis.[22]

F1, F2, and F3 were extracted from each vowel using the Fast Track Praat plugin (Boersma & Weenink 2020, Barreda 2021; https://github.com/santiagobarreda/FastTrack). The first three formants were measured every 2ms during the vowel, and the resulting formant trajectories were then time-normalized before plotting (Fig. 16). Formants were extracted using the default settings of the Fast Track plugin, except that the number of analysis steps was set to 24.

In order to pool F2 measurements across speakers, each speaker's formant values were normalized using Barreda-Neary log-additive regression normalization (Barreda & Nearey 2018). These normalized values were highly correlated ($r = 0.96$) with normalized values produced by a different method, namely dividing F1 and F2 by F3 at the same measurement point (e.g. Monahan & Idsardi 2010). Outliers were excluded from analysis by removing values for F2 which were greater than 2 standard deviations away from the mean for each formant. This resulted in the elimination of 460 F2 measurements, about 0.7% of the original F2 data. This left 66,677 F2 measurements for analysis (630 vowels, with a mean of 106 F2 measurements per vowel).

Figure 16 provides loess-smoothed F2 trajectories during the vowel in /VC#/ sequences, comparing coda /Cˠ Cʲ/ at each place of articulation, in combination with the vowels /iː ɔː uː/.

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[22] F1 tracking was noisy, particularly for our Ulster speakers. We assume this is due to preaspiration, which appears to have less of an effect on F2 tracking, the formant we're mostly interested in here.

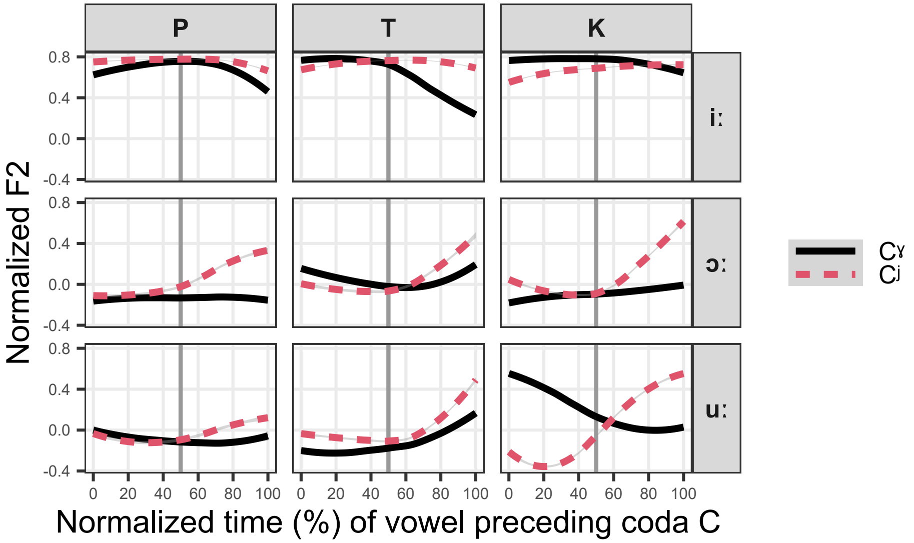

Figure 16: Pooled, speaker-normalized F2 trajectories across time-normalized steps, grouped by primary place of articulation and vowel context, for coda /VC#/. Lines represent loess-smoothed regressions over F2 values preceding /Cˠ Cʲ/ in each condition: solid black line for /Cˠ/, dashed red line for /Cʲ/. Gray vertical line marks 50% point of the vowel.

Our empirical question is when F2 peaks for /Cʲ/, or reaches a minimum for /Cˠ/, in /VC#/ sequences. Since F2 is our acoustic surrogate for dorsal fronting and backing, extreme values for F2 should correspond to the timepoints at which the tongue body is furthest front for /Cʲ/, or back for /Cˠ/.

Answering this question is easiest for /VC#/ sequences in which the vowel and following consonant have different backness specifications. This is because we expect to find very salient F2 movements in cases of mismatched vowel and consonant backness (Bennett et al. 2018), which should make it easy to see where F2 trajectories reach their most extreme values. In our data, this corresponds to /iːCˠ/ sequences for velarized coda consonants, and /uːCʲ/ and /ɔːCʲ/ sequences for palatalized coda consonants.[23]

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[23] It should be acknowledged that our use of the symbols /iː uː ɔː/ to describe vowel quality obscures some variation in the quality of these vowels between speakers. Most notably, our Ulster speakers tend to front /uː ɔː/, often producing them as something like [ʌː ɛː]. Note, though, that the fronting of /uː ɔː/ should actually make palatalized /Cʲ/ seem *less* front, by comparison, in this context. Despite that fact, we still see clear fronting at C start relative to the preceding vowel for /Cʲ/ after /uː ɔː/ in Fig. 16.

We begin with /uːCʲ/, corresponding to dashed red lines in the bottom row of Fig. 16. Here, it is clear that F2 begins to rise around V midpoint, or even earlier, and does not reach its peak until the beginning of the following consonant. The same pattern holds, perhaps even more clearly, for /Cʲ/ after /ɔː/ (dashed red line, middle row).

For /iːCˠ/ sequences (solid black line, top row) it is again clear that F2 reaches an extreme value at C start, rather than any earlier timepoint. A potential exception is /iːkˠ/, which shows a relatively flat F2 trajectory throughout the vowel; but even here we can see a slight lowering of F2 at the VC transition, into the beginning of the consonant.

The same patterns are visible if we plot F2 trajectories in physical rather than normalized time. Fig. 17 shows vowel F2 for up to 200ms preceding the following coda consonant. Vertical arrows mark when F2 reaches its expected extreme value in each loess curve for /iːCˠ uːCʲ ɔːCʲ/, the contexts in which there is a mismatch in backness between the vowel and following coda consonant.

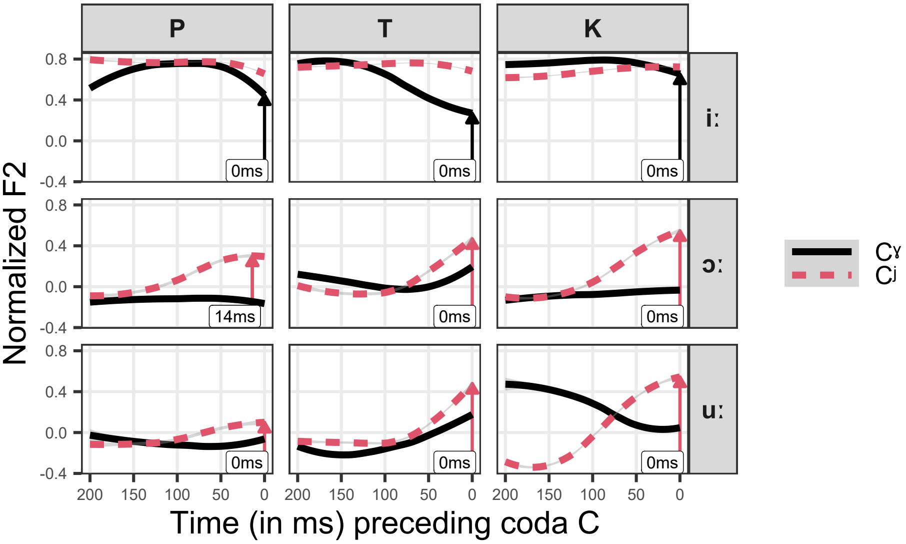

Figure 17: Pooled, speaker-normalized F2 trajectories across time, grouped by primary place of articulation and vowel context, for coda /VC#/. X-axis shows ms preceding closure of following coda consonant (up to 200ms). Arrows mark F2 extrema of loess curves for /iːCˠ uːCʲ ɔːCʲ/ (peak for /Cʲ/, trough for /Cˠ/).

We can compare the timecourse of F2 movement in Fig. 17 to the timing lags for the tongue tip and body gestures of non-contrastive dark [ɫ] reported by e.g. Sproat & Fujimura (1993) and Gick et al. (2006). Sproat & Fujimura (1993: 299,303) report lags of 30-110ms between an earlier dorsal constriction and a later tongue tip constriction for coda [ɫ] in American English. Gick et al. (2006: Tab. 2) report smaller lags (≈ 20-25ms) for Western Canadian English, Quebec French, and Squamish Salish.[24] Browman & Goldstein (1995) present 4 X-ray microbeam tokens of 'peel' [pʰiɫ] from 1 speaker, and find that tongue body retraction for [ɫ] peaks approximately 20-50ms before tongue tip closure for [ɫ] is completed, i.e. during the preceding vowel.

In contrast, Fig. 17 shows that F2 extrema for these loess curves generally occur at the beginning of closure for the coda consonant, at least in those conditions where F2 transitions are most visible and interpretable due to a mismatch in backness between the vowel and following coda consonant. The only exception is /ɔːPʲ/, which has just a 14ms lag between the F2 peak during the vowel and the following coda /Pʲ/ in our data. There is clearly a contrast between these timing patterns, which imply (near) simultaneity between primary and secondary articulations in /VC/, and the more sequential timing reported for non-contrastive dark [ɫ] in Sproat & Fujimura (1993), and Gick et al. (2006) (see also Browman & Goldstein 1995, Krakow 1999).[25]

These patterns are incompatible with the claim that dorsal gestures for secondary /Cˠ Cʲ/ articulations in coda position peak during the preceding vowel. Consequently, they are also incompatible with the claim that secondary /Cˠ Cʲ/ articulations are timed to precede primary articulations in coda position. That is, the available evidence argues *against* the hypothesis that primary and secondary articulations are timed in a sequential, anti-phase relation in coda position.

The alternative hypothesis, which we adopt, is that secondary /Cˠ Cʲ/ articulations are timed *in*-phase with either C start or C release, or with both, in coda position. (See also Shaw et al. 2021 on the timing of palatalization gestures with primary articulations in onset position.) We propose that this variability in timing reflects the fact that there is no single perceptually-optimal timing pattern in coda position, unlike onset position. In the absence of a unique, optimal timing

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[24] The difference in lag magnitudes reported by Sproat & Fujimura (1993) vs. Gick et al. (2006) likely reflects the fact that Sproat & Fujimura investigated /l/ darkening across a wider range of contexts, leading to greater variability in segment duration. Inter-speaker variation may also play a role, as Gick et al. (2006: 65) note. Gick et al. (2006) is also an ultrasound study with a relatively low framerate (30 fps ≈ 1 frame every 33ms), so their reported lag values are not particularly precise.

[25] Gick et al. (2006) similarly find simultaneous alignment of primary and secondary articulation in Serbo-Croatian /lˠ/, rather than anti-phase alignment as in English, and relate this finding to the fact of a palatalization contrast for laterals in the language (/lˠ/ vs. /lʲ/).

pattern, speakers may be expected to show variation between different alternatives, giving rise to the gestural timing patterns we report here.

9 Discussion and conclusion

We began with the observation that secondary /C$^{(ɣ)}$ C^{j}/ contrasts are often eliminated in coda position and among labial consonants. This typological fact likely has a phonetic source in the relative difficulty of perceiving /C$^{(ɣ)}$ C^{j}/ contrasts in these contexts (e.g. Kochetov 2002, 2004, Ní Chiosáin & Padgett 2012, Padgett & Ní Chiosáin 2018), and the tendency to reduce articulatory gestures, including palatalization gestures, in codas (e.g. Kochetov 2002, 2006, 2009, Bennett et al. 2023).

Our results may extend this broad line of reasoning, to the extent that they suggest greater variability in timing strategies in coda position compared to onset position. Timing patterns which are more variable across contexts (such as place and syllable position) might be harder for listeners to attend to. If timing patterns also differ by speaker, this would be even more clearly true, since listeners cannot know ahead of time when the peak dorsal gestures for /C$^{(ɣ)}$ C^{j}/ contrasts will occur.

However, we have also argued that productions may be organized in ways that make life easier for listeners (whether this is intentional or not, see discussion in section 3.1). In our data, secondary articulations in onset position are either timed to peak at C release, or appear to be held constant from C beginning to C release. In either case, gestural timing makes key acoustic information about /C$^{(ɣ)}$ C^{j}/ contrasts available at crucial perceptual landmarks, namely C release itself, and the following CV transition for onsets.

In coda position, consonants at different places of articulation show different timing patterns. The palatalization gesture for coda labial /P^{j}/ peaks at the VC transition. We have suggested that this reflects the perceptual importance of formant transitions for signaling /C$^{(ɣ)}$ C^{j}/ contrasts in labials, given the weak and relatively uninformative release bursts of labial stops. For coda coronal /T^{j}/, we instead find alignment of secondary articulations to C release; we have suggested that this reflects the acoustic and perceptual salience of coronal stop releases, which are very informative as to /C$^{(ɣ)}$ C^{j}/ contrast in Irish (e.g. Ní Chiosáin & Padgett 2012). If the secondary articulations for coda /T^{ɣ} K^{j} K^{ɣ}/ are held roughly constant until C release, as we've argued, that too may reflect the perceptual importance of release cues for coronal and dorsal stops.

We have seen that timing patterns for velarized /C^{ɣ}/ seem to be more ambiguous, or perhaps more varied, than the timing patterns found for palatalized

/Cʲ/, particularly in onset position (as also found by Bennett et al. 2018). Why should this be? One idea pursued in Bennett et al. (2023) connects this finding to an independently known fact about palatal constrictions: they are more resistant to coarticulation (and more likely to induce coarticulation in other sounds) than many other kinds of sounds. Put differently, palatal constrictions exhibit a high degree of articulatory constraint (Recasens et al. 1997, Recasens 1999, Recasens & Espinosa 2009, Farnetani & Recasens 2010, Recasens & Rodríguez 2016). A reviewer suggests a second (possibly related) idea: that tongue body fronting may involve less complex muscle engagement than tongue body raising and backing (see e.g. Gick et al. 2012: 152-8). Finally, we know that lip rounding plays a role in enhancing velarization in Irish (Bennett et al. 2019). A fuller understanding of gestural timing in /Cˠ Cʲ/ contrasts may therefore require attention to the movement of the lips, as well as the tongue. We leave all of these ideas for further research.

It should be borne in mind that our results here pertain only to stop consonants. As discussed in section 3.3, previous findings on Russian suggest that timing facts may depend on a consonant's manner of articulation.[26] Unlike stops, other consonants such as fricatives, nasals and liquids do not have release bursts, and they may carry internal cues to the palatalization contrast. Whether a lateral is palatalized or velarized, for example, is easily audible during closure. Hence we do not readily expect our findings to extend to other manners of articulation, and further reasearch on this topic is called for.

Our characterization of the issues has been oversimplified in an important way: we have discussed cues to palatalization without considering the larger phonetic context in which a word occurs. If a word like *píob* /pʲiːbˠ/ occurs in isolation, then indeed the cues to palatalization of the initial consonant lie only at the consonant's release, and those of the final consonant lie at both the VC transition and the consonant's release (assuming the consonant is released, as it generally would be in Irish). However our target words were in a different context, since we used the carrier sentence [ˈdˠuːrʲtʲ ˈiːfˠə __ əˈnˠʊrˠə] 'Aoife said ___ last year'. They were preceded by a vowel-final word and followed by a vowel-initial one. In such a context a listener could in principle have access to VC formant transitions, a burst and CV formant transitions for *both* initial and final consonants. Why, then, did we not find identical patterns of timing for initial and final consonants?

Had we manipulated the phrasal context, independently varying the immediate segmental context of initial versus final consonants, and had this had effects

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[26] Bennett et al. (2018) do not find a difference in timing between Irish stops and fricatives, but they only examine consonants in word-/syllable-initial position.

on timing, we might have concluded that speakers can adjust the relative timing of primary and secondary articulations 'online', that is, in a way that adapts to phrasal context. We did not manipulate phrasal context. However, since we in fact found *different* patterns of timing for initial and final consonants, even though the segmental context was the same (V_V), our conclusion might rather be that speakers *cannot* adjust the relative timing of articulations in this way. Though somewhat speculative, this conclusion seems well in line with the hypothesis that word-internal gestural timing is lexically-specified, and so less variable than the relative timing of gestures across a word boundary (Browman & Goldstein 1988, Byrd 1996, Browman & Goldstein 2000), an idea supported by the results of Cho (2001) (see Strycharczuk 2019, Mousikou et al. 2021 and references therein for further evidence and discussion). The question then becomes, what patterns of timing, fixed in the lexicon, would be most perceptually adaptive? Such patterns of timing would have to facilitate the perception of cues to palatalization not only in the most accommodating of environments (such as that of our carrier sentence); they would have to succeed in *all* environments, including ones where a consonant is preceded or followed by silence or a consonant (see Flemming 2001: 30-1 for a similar point). It is possible that lexically-specified gestural timing 'gravitates' to settings that work best for listeners across all environments.

Overall, our data suggests that relatively low-level timing patterns in the production of the Irish may be structured in such a way as to maximize the perceptual salience and recoverability of cues to $/\mathrm{C}^{(\text{ɣ})}\ \mathrm{C}^{\mathrm{j}}/$ contrasts.

Abbreviations

SG.	singular	P	labial stop
PL.	plural	T	coronal stop
GEN.	genitive	K	dorsal stop
fps	frames per second		

Contributions

Ryan Bennett and Jaye Padgett contributed to conceptualization of the project, design of the methodology and items, data collection, data analysis, and writing. Grant McGuire and Máire Ní Chiosáin contributed to conceptualization of the project, design of the methodology and items, data collection, reviewing of the manuscript, and editing. Jennifer Bellik contributed to data analysis.

Appendix

Table 8: Words used in the study: onset/word-initial position

	p/b	**t/d**	**k**
iː	bˠiː ‘yellow’	tˠiː ‘straw’	kˠiː ‘way’
	pʲiːsˠə ‘piece’	dʲiːnˠ ‘roof’	kʲiːrˠ ‘a comb’
uː	pˠuːkˠə ‘ghost’	tˠuːsˠ ‘a start’	kˠuː ‘a hound’
	bʲuː ‘would be worth’	tʲuːsˠ ‘thickness’	kʲuːnˠəsˠ ‘quiet (noun)’
ɔː	pˠɔː ‘pay, wages’	tˠɔː ‘is (be)’	kˠɔːrˠ ‘car’
	pʲɔːnˠ ‘pen’	tʲɔːnˠ ‘tight’	kʲɔːnˠ ‘one/head’

Table 9: Words used in the study: coda/word-final position

	p/b	**t/d**	**k/g**
iː	pʲiːbˠ ‘pipes (GEN.PL)’	iːədˠ ‘them’	iːəkˠ ‘pay’
	pʲiːbʲ ‘pipes’	trʲiːdʲ ‘through’	bʲeːkʲ ‘shout’
uː	lˠuːbˠ ‘stitch’	uːdˠ ‘that’	glʲuːkˠ ‘peep’
	lˠuːbʲ ‘stitch (DAT.SG./variant)’	klˠuːdʲ ‘covering’	bˠuːkʲ ‘pinnacle’
ɔː	lˠɔːbˠ ‘mud (variant)’	stˠɔːtˠ ‘state’	fˠɔːgˠ ‘leave’
	lˠɔːbʲ ‘mud’	ɔːtʲ ‘place’	rˠɔːgʲ ‘sudden rush’

Table 10: Token counts by speaker, place, and secondary articulation

Dialect	Speaker	C place	$/\mathrm{C}^{\gamma}\ \mathrm{C}^{j}/$	n
Connacht	1	Labial	C^{γ}	89
Connacht	1	Labial	C^{j}	90
Connacht	2	Labial	C^{γ}	72
Connacht	2	Labial	C^{j}	72
Connacht	2	Coronal	C^{γ}	71
Connacht	2	Coronal	C^{j}	66
Connacht	2	Dorsal	C^{γ}	72
Connacht	2	Dorsal	C^{j}	71
Connacht	3	Labial	C^{γ}	90
Connacht	3	Labial	C^{j}	89
Connacht	3	Dorsal	C^{γ}	84
Connacht	3	Dorsal	C^{j}	87
Munster	1	Labial	C^{γ}	90
Munster	1	Labial	C^{j}	90
Munster	1	Coronal	C^{γ}	85
Munster	1	Coronal	C^{j}	83
Munster	2	Labial	C^{γ}	86
Munster	2	Labial	C^{j}	88
Munster	2	Coronal	C^{γ}	79
Munster	2	Coronal	C^{j}	85
Ulster	1	Labial	C^{γ}	90
Ulster	1	Labial	C^{j}	90
Ulster	1	Coronal	C^{γ}	90
Ulster	1	Coronal	C^{j}	86
Ulster	2	Labial	C^{γ}	90
Ulster	2	Labial	C^{j}	90
Ulster	2	Coronal	C^{γ}	90
Ulster	2	Coronal	C^{j}	84
Ulster	2	Dorsal	C^{γ}	90
Ulster	2	Dorsal	C^{j}	90

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