CONTRAST ENHANCEMENT AND CUE TRADING IN IRISH SECONDARY CONSONANT ARTICULATIONS

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ABSTRACT

Lip rounding and dorsum backing both lower F2, and tend to co-occur in speech sounds (e.g. back vowels). This likely reflects contrast enhancement: the co-occurrence of rounding and backing exaggerates F2 differences associated with phonemic contrasts. We investigate this correlation with an articulatory study of Irish, a language with contrastively palatalized and velarized consonants. We confirm that velarized consonants are realized with additional lip rounding. However, we find no token-wise correlation between the *amount* of rounding and dorsum backing. This suggests that rounding is primarily associated with dorsum backing at an abstract phonemic level, not surface phonetics.

Coronals show weaker velarization in Irish, and likely recruit cues beyond F2 (e.g. spectral COG) to signal /Cʲ Cˠ/ contrasts. Speakers in our study show no correlation between the degree of velarization on coronal /Cˠ/ and COG separation for coronal /Cʲ Cˠ/, suggesting that speakers may not compensate for weak velarization with other phonetic cues.

Keywords: Irish, palatalization, contrast enhancement, ultrasound, cue trading

1. BACKGROUND ON IRISH

Irish (or 'Gaelic') is spoken daily by ∼74,000 people in Ireland. These speakers are heavily concentrated in Irish-speaking communities on the western coast, though significant speaker populations are present in Dublin and other urban areas as well. A much larger proportion of the Irish population (∼1.75 million) reports at least some ability in the language. While Irish enjoys a certain amount of state support in the Republic of Ireland, the language is at risk of marginalization even in traditional Irish-speaking communities, thanks to the centuries-long hegemony of English [16]. We focus here on the variety spoken in the central-western region of Connemara.

All phonemic consonants in Connemara Irish are contrastively velarized or palatalized [12], as in (1). Though a central part of the phonology of Irish, some secondary /Cʲ Cˠ/ contrasts are undergoing attrition for younger speakers, even in Irish-speaking communities [19].

(1) a. *tuí* [tˠiː] 'straw'
    b. *tí* [tʲiː] 'house (GENITIVE)'
    c. *tús* [tˠuːsˠ] 'beginning'
    d. *tiús* [tʲuːsˠ] 'thickness'

1.1. The articulation of /Cʲ Cˠ/ contrasts in Irish

Bennett et al. [1], on which the present work builds, is an ultrasound study of the lingual articulation of the voiceless obstruents /pʲ pˠ tʲ tˠ kʲ kˠ fʲ fˠ sʲ sˠ xʲ xˠ/ in Irish. These consonants were elicited in word-initial position preceding the long high vowels /iː uː/, as in (1) above. (/bˠ bʲ/ were used in place of /pˠ pʲ/ for some items to fill lexical gaps.)

Five native speakers of Connemara Irish (three male; ages 35-60) participated, and repeated each of the 24 experimental items 6-8 times each in a frame sentence. Midsagittal images of the tongue body were obtained using a portable Terason T3000 ultrasound system with a model 8MC3 probe (58-60fps, or 1 frame every ∼17ms). The probe was held in place with an Articulate Instruments ultrasound stabilization headset [25]. Using a time-synchronized audio recording, the consonant offset in the [#CV] transition was located for each token, and the ultrasound frame corresponding to that timepoint was extracted. (Palatalization gestures typically peak at C offset in [CV] contexts, [8, 9].) These ultrasound images were then traced using EdgeTrak [10].

[1] found that tongue body backness systematically distinguished /Cʲ/ vs. /Cˠ/ for all consonants matching in place and manner, in both vowel contexts (1). This is illustrated in Figs. 1-2, which use a Smoothing Spline ANOVA [4] to summarize the raw tracings of tongue surfaces for /bˠ pʲ tˠ tʲ/ at C offset before [iː] for one speaker.

[1] analyzed tongue body position at C offset using principal component analysis (PCA) [5]. PCA inspects data sets for patterns of covariation between data points (in this case, the position of points on a traced tongue surface) and re-expresses those pat-

Figure 1: Tongue body position for /bˠiː pʲiː/ at C offset for one speaker (lips to right, /pʲ/ dashed).

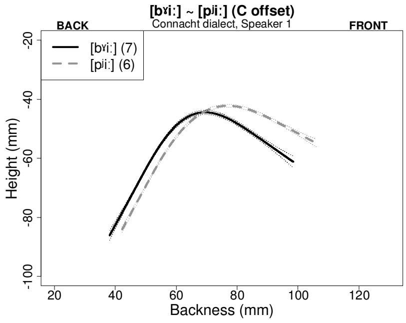
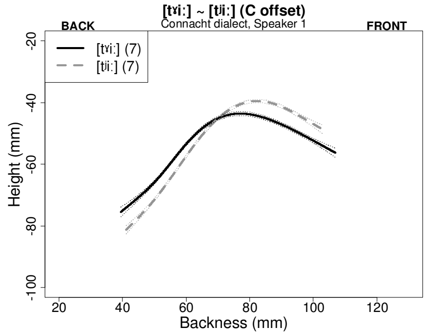


Figure 2: Tongue body position for /tˠiː tʲiː/ at C offset for one speaker (lips to right, /tʲ/ dashed).



terns of covariation as a new dimension known as a principal component. The first principal component (PC1) in this study (Fig. 3) corresponds approximately to overall tongue body backness, and explains 40.4% of the variance in the data. [1] take PC1 values to be a good proxy for overall tongue body backness for individual tokens in this data.

Figure 3: PC1 in [1] (lips to right)

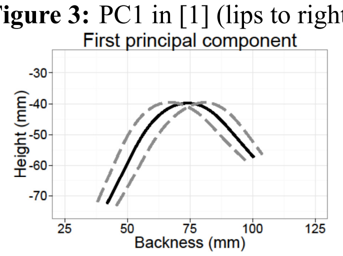
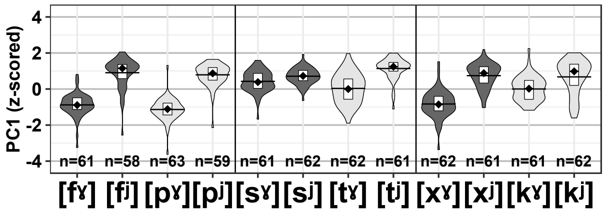


Fig. 4 shows that PC1 systematically distinguishes secondary /Cʲ Cˠ/ articulations for each combination of manner and place (PC1 values were *z*-score normalized for each speaker, and pooled across vowel contexts for plotting). This is clearest for the labials and velars; coronals, particularly /sʲ sˠ/, show less separation in their PC1 values. This is consistent with past descriptions of Irish reporting weaker velarization for coronal consonants [11] (Fig. 2). These interpretations of Fig. 4 are supported with a linear mixed effects analysis in [1].

Lastly, [1] found little evidence of [CV] coartic-

Figure 4: Distributions of PC1 (dorsal backness) values for place x manner combinations at C offset. Overlaid box plots show 25%–75% range, black diamonds = medians, black lines = means.



ulation for backness in their study, presumably because dorsal backness is contrastive for consonants in the language [17].

1.2. Acoustics of /Cʲ Cˠ/ contrasts

A major acoustic correlate of the /Cʲ Cˠ/ contrast in Irish is F2 at [CV] and [VC] transitions, which is raised for /Cʲ/ relative to /Cˠ/ [13]. Additionally, the release phase for palatalized stops is longer, more intense, and has higher spectral center of gravity (COG) than the release phase for velarized stops. These differences in release noise are largest for coronal stops, which tend to be affricated when palatalized. These acoustic properties closely resemble what has been reported for other languages with palatalization contrasts, such as Russian [7–9].

2. CONTRAST ENHANCEMENT IN IRISH

2.1. Lip rounding

Impressionistic descriptions of Irish report a correlation between secondary lingual articulations and lip rounding: /Cˠ/ is produced with lip rounding, while /Cʲ/ is produced with less rounding, or even active spreading of the lips [2, 12, 15, 20]. The existence of such a correlation would be unsurprising, as both lip rounding and dorsum backing lead to lowered F2 at [CV]/[VC] transitions [23]. Lip rounding may thus be an *enhancement gesture* for /Cˠ Cʲ/ contrasts in Irish, exaggerating F2 differences associated with the phonological /Cˠ Cʲ/ contrast [6, 9, 22, 24].

Enhancement of /Cˠ Cʲ/ contrasts with lip rounding could be implemented in at least two ways. First, the magnitude of lip rounding could co-vary with the magnitude of dorsal backing on a *token-by-token basis*. For example, rounding might be stronger whenever backing is weaker, so as to consistently achieve a particular acoustic target for F2 in [CV] transitions. We call this the PHONETIC ENHANCEMENT hypothesis, because it presumes that enhancement gestures like lip rounding are recruited to produce specific physical values of some phonetic parameter (e.g. F2) on actual instances of speaking [14, 18].

Alternatively, it could be that the *presence or absence* of a supplementary rounding gesture is specified for a given segment in Irish, but the *strength* of that gesture is left unspecified. On this view gestural reinforcement is more abstract, being specified at the level of the phoneme (a consonant *type*) rather than the individual production (a consonant *token*) [6]. We call this the PHONOLOGICAL ENHANCEMENT hypothesis, as it involves a categorical relationship between lip rounding and dorsal backing; it is consistent with the absence of any token-by-token correlation between the magnitude of those gestures.

2.2. Coronals: cue trading between noise and F2?

Secondary velarization is relatively weak for coronal /C^{ɣ}/ in Irish [1]. At the same time, coronal /C^{ɣ} C^{j}/ contrasts are supported by robust acoustic cues during constriction noise (fricative closure and stop release) [13]. These cues include spectral shape differences (e.g. center of gravity), duration, and intensity. The physical articulations producing these noise-related cues are at least partially independent from the dorsal articulations (and F2 differences in adjacent vowels) associated with velarization and palatalization. For example, spectral COG during fricatives and release depends primarily on the configuration of the front cavity, and is thus mostly affected by the position of the tongue tip/blade for coronal consonants, not the dorsum [23].

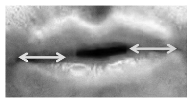
We speculate that individual speakers may show an inverse relationship between the strength of velarization on coronal /C^{ɣ}/—that is, how widely separated /C^{ɣ}/ and /C^{j}/ are with respect to F2—and the extent to which coronal /C^{ɣ} C^{j}/ contrasts are distinguished by the duration and spectral COG of their noise portions. The hypothesis is that speakers will compensate for weaker velarization on coronal consonants by enhancing the distinctiveness of coronal /C^{ɣ} C^{j}/ contrasts along other dimensions. If correct, there should be a *negative* correlation between the average degree of velarization for /s^{ɣ} t^{ɣ}/ for each speaker, and the degree to which that speaker separates /s^{ɣ} t^{ɣ}/ from /s^{j} t^{j}/ using noise cues.

This hypothesis could be assessed by comparing F2 values and noise parameters directly. However, the audio recordings collected by [1] are somewhat noisy, making it hard to accurately calculate F2 values. Instead, we assess this hypothesis by asking whether the strength of *articulatory* velarization is correlated with the *acoustic separation* of coronal /C^{ɣ} C^{j}/ contrasts along the dimensions of noise duration and noise COG.

3. ANALYSIS OF LIP ROUNDING

Camcorder video of the lips was collected along with ultrasound and audio recording [1] using a Casio EXILIM-Pro EX-F1 (30fps, 640x480 pixels). Our measure of lip rounding in this study was side contact, the extent to which the upper and lower lips touch during consonant production (Fig. 5). Side contact is a reliable measure of lip rounding/protrusion for vowels [3], and we believe it is a plausible measure of secondary labialization on consonants as well. Side contact was measured in pixels using ImageJ [21], for lip images corresponding to the offset of the target consonant in the [#CV] transition for each token, the same timepoint used for ultrasound analysis. (As with palatalization, the magnitude of secondary lip rounding gestures tends to peak at [CV] transitions crosslinguistically [9].)

Figure 5: Measurement of side contact



Side contact values for all target consonants in the study, pooled across vowel context, are shown in Fig. 6 (values were *z*-score normalized for each speaker before being pooled for plotting and analysis). The labial stops are excluded from analysis because side contact is at ceiling for all bilabial stops at C offset. Other measures of lip rounding, or measures of side contact taken during the initial portion of the following vowel, might reveal differences in lip rounding between /p^{j} b^{j}/ and /p^{ɣ} b^{ɣ}/.

Figure 6: Side contact values at C offset

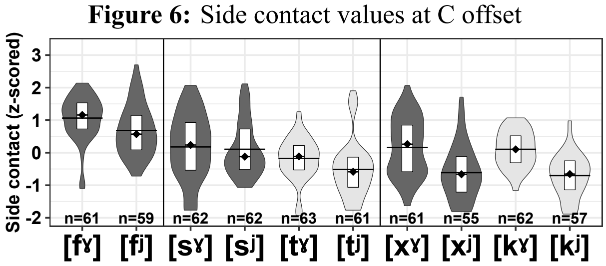


Fig. 6 confirms that velarized consonants are realized with higher values of side contact than their palatalized counterparts. This result seems clearest for labial /f^{j} f^{ɣ}/ and velar /k^{j} k^{ɣ} x^{j} x^{ɣ}/; coronals, particularly /s^{j} s^{ɣ}/, show weaker lip rounding distinctions for secondary articulations than consonants at other places of articulation.

For our statistical analysis of lip rounding, we fit a linear-mixed effects model over *z*-score normalized side contact values (Fig. 6). We first averaged side contact and PC1 over each unique combination of {place, manner, secondary articulation, vowel context, speaker} to reduce noise from measurement error. This left 120 data points for analysis, from an initial 603 tokens. (Our results are qualitatively the same when we analyze individual tokens directly.) The fixed effects included three controls: C PLACE, C MANNER, and V CONTEXT. We also included a categorical fixed effect of SECONDARY ARTICULATION, and a continuous fixed effect of TOKEN BACKNESS, the average PC1 value associated with that particular combination of C place, C manner, and V context. If contrast enhancement occurs on a token-by-token basis, as under the phonetic enhancement hypothesis, TOKEN BACKNESS should be a better predictor of lip rounding than SECONDARY ARTICULATION. We also included all two-way interactions between these fixed effects in the model (apart from C MANNER X C PLACE, since labial stops were not analyzed). The random effects included an intercept for SPEAKER and by-speaker intercepts and slopes for TOKEN BACKNESS and SECONDARY ARTICULATION. All categorical predictors were sum-coded. The fixed effects were simplified through a step-down criticism procedure using the log-likelihood test with $\alpha = 0.10$ as the criteron for inclusion in the model. Interactions were considered for removal before simple effects, and all simple effects were kept in the model if they were also part of an interaction.

The resulting model is shown in Table 1. The significant effect of SECONDARY ARTICULATION, and its interaction with C PLACE, confirm that velarized consonants show greater lip rounding than palatalized consonants, especially for dorsals. While the categorical predictor SECONDARY ARTICULATION remained in the final model, the continuous predictor TOKEN BACKNESS did not reach significance and was dropped during model selection. This suggests that there is no token-level, gradient correlation between the magnitude of lingual articulations and the amount of lip rounding in our data. We interpret this result as being most consistent with phonological enhancement at the level of the abstract phoneme type, rather than phonetic enhancement at the level of individual segment tokens. (We also fit two full models differing only in whether C backness is encoded as SECONDARY ARTICULATION or TOKEN BACKNESS; the SECONDARY ARTICULATION model has a modest advantage in model fit, AIC = 182.5 vs. 186.5.)

[18] suggest that enhancement gestures like lip rounding may be more robust for productions which would otherwise result in acoustically ambiguous segments. Our data fails to support this idea: tokens with less extreme dorsal positions ($|z(\text{PC1})|<0.75$) are *less* correlated with side contact than the data as a whole (r=-0.18, n=274 vs. overall r=-0.27, n=609).

Table 1: Final lip rounding model (insignificant predictors omitted). Negative $\beta \Leftrightarrow$ less rounding.

Predictor	β	p-value
SEC. ARTIC. (/Cʲ/)	-0.26	.001*
C PLACE (Coronal)	-0.19	.01*
C PLACE (Dorsal)	-0.46	.001*
MANNER (Fricative)	0.12	.05*
V CONTEXT (/#Ciː/)	-0.34	.001*
CORONAL : /Cʲ/	0.15	.05*
DORSAL : /Cʲ/	-0.21	.005*
DORSAL : /#Ciː/	-0.21	.005*
FRICATIVE : /#Ciː/	-0.19	.001*

4. CORONAL VELARIZATION

Our acoustic data confirms that /sˠ sʲ/ have widely separated spectral centers of gravity (4640 vs. 3400Hz, p<.001), as do /tˠ tʲ/ (3320 vs. 4200Hz, p<.001; measured over 10ms following release). Additionally, /tʲ/ tends toward longer releases than /tˠ/ (97 vs. 81ms, p<.001). Durational differences between /sˠ sʲ/ did not reach signficance via *t*-test (218 vs. 200ms, p<.10). This confirms that coronal /Cʲ Cˠ/ contrasts are cued by noise properties which are acoustically and articulatorily separable from velarization and its effect on F2 in following vowels.

However, we find no speaker-level correlation between the average degree of velarization (PC1) for /sˠ tˠ/, and the difference in average COG between /sˠ sʲ/ and /tˠ tʲ/ (r=0.11, *n.s.*; n=5). This could indicate that there is no systematic trading relation between these articulatory-acoustic parameters. Alternatively, this null result may reflect our small sample size (5 speakers = 5 data points for correlation).

5. DISCUSSION

We find quantitative support for claims that velarized consonants are realized with additional lip rounding, thus enhancing the /Cʲ Cˠ/ contrast. We find no support for a token-by-token correlation between rounding and backing, suggesting a more abstract, phonological enhancement process. Coronals, which exhibit reduced velarization and lip rounding, are more clearly differentiated by other cues (e.g. COG) which do not seem to interact directly with dorsum backing.

6. ACKNOWLEDGMENTS

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