ATR IN SCOTTISH GAELIC TENSE SONORANTS

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1. Introduction

In the modern Goidelic languages, there are two classes of sonorants, called "tense" and "lax" in a traditional segmental analysis. One way that the two classes are distinguished is by the quality of the preceding vowel: before the so-called "tense" sonorants, vowels are either lengthened or diphthongized, depending on the vowel and on the dialect. For example, the vowel [a] followed by the lax nasal in *fan* 'before the' [fan] contrasts with the tense sonorant and the diphthongized vowel in *fann* 'delicate' [fauN][1]. It is not always clear, however, that there is an articulatory difference to be found in the actual sonorants themselves.

In this study, we explore the tense/lax contrast in the Skye dialect of Scottish Gaelic from an articulatory perspective using ultrasound technology. Our data consist of audio, video, and ultrasound images of a set of minimal pairs. We test two specific hypotheses with regard to Scottish Gaelic, exploring whether the synchronic phonological patterns are motivated by an articulatory mechanism.

To explain the phenomenon of vowel diphthongization in certain dialects of Modern Irish, such as Conamara Irish, Carnie (2002) argues that the tense sonorants bear an advanced tongue root [+ATR] feature. The [+ATR] feature is a gesture that is articulatorily sympathetic to the tongue raising gesture, Archangeli & Pulleyblank (1994): When the root of the tongue moves forward, the body of the tongue is forced up simultaneously. Thus, the [+ATR] feature of the tense sonorants, which advances the root of the tongue, is conducive to concomitant raising of the tongue body, a tongue position that is similar to that of the second half of a falling diphthong. This explains why tenseness of the consonant gesture leads to diphthongization.

[1] As is the tradition in the traditional literature on these languages tense sonorants are transcribed with capitals [L, R, N].

The Irish results reported in Carnie (2002) lead to our first hypothesis, that the tense sonorants in Scottish Gaelic are also accompanied by tongue root advancement while lax sonorants have no such gesture.

Hypothesis 1: Scottish Gaelic tense sonorants have advanced tongue root while lax sonorants do not.

We propose to test this hypothesis by examining ultrasound images of Scottish Gaelic tense and lax sonorants. We expect to find a difference in tongue root position, with the tongue root of tense sonorants more advanced and that of lax sonorants less advanced (but not necessarily retracted).

Our second hypothesis is derived from the theory of articulatory phonology (Browman & Goldstein 1992), in particular the view that speech can be understood as gestural coupling structures. Segments (or words) are understood as multiple gestures that cohere during articulation. Such coherence among component gestures can be observed by their temporal distribution and coordination (Saltzman & Byrd 2000). For example, the nasals, glides and liquids are all suggested to be the coupling between a primary oral gesture and a secondary gesture. The primary gesture is where the most constriction in the oral cavity is during articulation, and is usually more towards the front of the mouth. The secondary gesture is the locus of a smaller constriction (the pharyngeal gesture for [r], dorsal for [l] and velum for nasals).

Several studies (see Krakow 1999 for a review) have shown an effect of syllable structure on the temporal coordination of the primary and secondary gestures. For example, in a recent study by Byrd et al. (2009), the timing difference between the component gestures for the coronal nasal [n] in English is observed in onset, coda and intervocalic positions. In onsets, the gestures are found to be synchronized. In codas, the gestures are found to be offset, with secondary gestures in the back of the mouth commencing before the primary gestures in the front of the mouth. In intervocalic positions, the timing pattern is similar to those in the coda position, but the offset among the gestures is smaller when intervocalic.

The tense and lax sonorants in Scottish Gaelic are all coronal. As such, each is expected to have a tongue tip gesture as the primary gesture. Furthermore, by hypothesis 1, tense sonorants involve a secondary tongue root gesture (along with the secondary manner gestures noted above). Tense sonorants occur in codas in Scottish Gaelic. Based on results in Byrd et al. (2009), we expect that the timing of the gestures in tense sonorants is offset, with the tongue root gesture preceding the tongue tip gesture. Excessive misalignment between the two gestures results in the tongue root advancement and concurrent tongue body raising being perceived on the preceding vowel, resulting in vowel diphthongization.[2]

> **Hypothesis 2:** The tongue root gesture precedes the tongue tip gesture in Scottish Gaelic coda tense sonorants.

We test this hypothesis by comparing the relative timing of the tongue tip and tongue root gestures in Scottish Gaelic tense sonorants with their timing in the corresponding lax sonorants, as revealed by midsagittal ultrasound images.

2. Methods

2.1 Audio and Ultrasound Imaging

Ultrasound imaging is ideal for viewing movements of the tongue body during speech. We use ultrasound because it offers advantages in cost, portability, time resolution, and ease of use over other vocal tract imaging techniques, such as electro-magnetic midsagittal articulography (EMMA), magnetic resonance imaging (MRI), and X-ray microbeam. It is also minimally invasive. Ultrasound functions by passing high frequency sound waves through the soft tissues in the vocal tract. When the sound waves encounter a change in density, such as the contrast between soft tissue and either bone or air, they are reflected back to the transducer; the distance is measured and converted into an image.

With proper placement of the transducer beneath the chin, ultrasound can produce a midsagittal view of the tongue surface between the mandible and hyoid bone. Palate images are also possible by holding water in the mouth to eliminate the density difference between the air above the tongue and the tissue of the tongue. Video of the subject's profile, enhanced with Palatron hardware (see Mielke et al. 2005), is used to adjust for head movement and to produce a composite image showing both tongue surface and palate.

Ultrasound images were obtained with a SonoSite TITAN portable ultrasound unit and a C-11/7-4 11-mm broadband curved array transducer. Video of the subject's profile was recorded with a Sony Mini-DV Digital Handycam. Audio recordings were obtained using a microphone mounted close the subject's mouth and passed through a preamplifier, using and

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[2] As noted, in onsets Byrd et al. (2009) found that the gestures are temporally coordinated; since we encountered only coda tense sonorants, this point is irrelevant to our study.

Audio-Technica PRO 49Q condenser microphone and a Symetrix 302 dual microphone preamplifier. The ultrasound, profile videos and the audio of the subject's voice were combined and converted to digital format using a Videonics MXProDV digital video mixer and then recorded to a Sony GV-1000 NTSC MiniDV Recorder.

Images were captured from the MiniDV Recorder, and relevant still frames were identified (more detail on frame identification below). For those frames, using Palatron hardware and software (Mielke et al. 2005), the palate image and tongue surface images are superimposed to produce a composite image of the shape of the vocal tract, with the alignment adjusted to correct for head and/or transducer movement. See Mielke et al. (to appear) for further discussion of the methodology used for collecting ultrasound data.

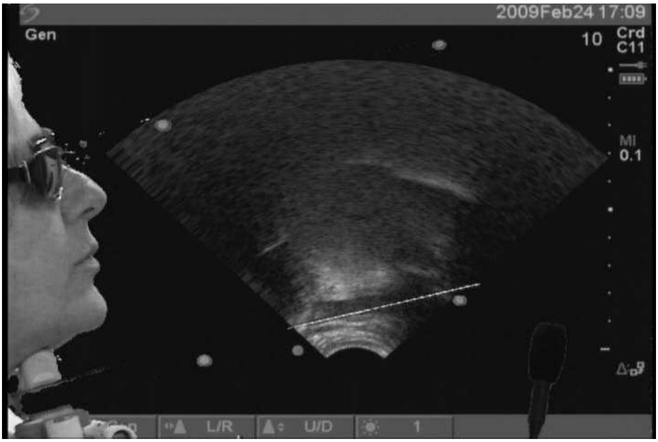

Figure 1: An ultrasound image of the tongue during the word *bann*. The dark portions on the left and right side of the image are shadows created by the hyoid and jawbone respectively. The tongue contour can be seen as the bright curve in the center of the image. Although the dorsum and tongue tip can be seen, the exact shape of the tongue root is lost in speckle noise.

2.2 Participant

One native speaker of the Skye dialect (Central Hebrides) of Scottish Gaelic volunteered to take part in this study.

2.3 Stimuli

Scottish Gaelic words containing either tense or lax sonorants were culled from Gaelic dictionaries, and reviewed by the subject. This was to ensure that the items used were actually part of the subject's language; not all relevant items in the dictionary were familiar.

Words selected as stimuli were minimal pairs or near-minimal pairs. With ultrasound studies, it is best to find items containing the target sound and only labial consonants or [h], since these consonants have minimal lingual co-articulation. Unfortunately, there were not many such Scottish Gaelic items available to us; our stimuli include several items with consonants that are known to cause co-articulation. The words were presented in traditional orthography. A list of our stimuli is found in table 1.

Lax sonorant	**Tense sonorant**
an 'the'	*ann* 'in it/there'
bàn 'white'	*bann* 'sash, belt'
bàr 'bar'	*bàrr* 'top'
càl 'cabbage'	*call* 'calamity'
cor 'case'	*còrr* 'balance/excess'
fan 'before them/before the'	*fann* 'delicate/decrepit'
fear 'man'	*fearr* 'better/prefer'
fon 'under the'	*fonn* 'sound'
gal 'wail'	*gall* 'foreigner'
geal 'white'	*geall* 'promise/bet/prize'
lon 'elk'	*lonn* 'anger'
màl 'rent'	*mall* 'slow'
meal 'enjoy'	*meall* 'beguile'
mol 'praise'	*moll* 'chaff/dust'
Pol 'Paul'	*poll* 'mud, bog'
tòn 'buttocks'	*tonn* 'ocean wave'
tor 'heavy shower'	*tòrr* 'mound/pointy hill'

Table 1: Stimuli

2.4 Data Collection

The subject was seated comfortably in an optometry chair; an arm of the optometry chair held the ultrasound transducer firmly in place under the subject's chin. The subject sat facing a computer screen where stimuli were presented; the subject pressed a button on a mouse to advance to the next stimuli, which enabled the subject to set the pace of the experiment. The subject was asked to read the prompts, which were randomized and presented one at a time using the E-Prime software package. Stimuli were presented in a frame sentence: *Thubhairt Calum . . .mu dheidhinn Morag*, which translates to “Calum says . . . about Morag”. The frame sentence was chosen because it both makes sense (although it is occasionally humorous!) and it has labial consonants flanking the stimulus. Labials are preferred because they do not have a contrastive tongue gesture and so minimize coarticulatory effects from the frame sentence words.

Four repetitions of each stimulus word were collected in randomized blocks. Some tokens were excluded from analysis due to poor imaging quality, resulting in at least three useable repetitions for each item. The audio, video, and ultrasound images were collected and digitized following the procedure outlined in section 3.1.

2.5 Data Extraction

For each token, frames corresponding to the stimulus were identified and extracted. Head/transducer movement was adjusted for using Palatoglossatron (Baker 2005). Tongue surfaces were hand-traced by trained graduate students. The “fan” of the ultrasound image is divided by radii; each trace then is represented by a series of points where the trace crosses each radius. These points constitute the “tongue surface tracings” used subsequently.

The adjusted tongue surface tracings were imported into Matlab to create a linguagram (see Figure 4); step-by-step details follow:

When the tongue surface tracings for an item are imported into Matlab, the frames are sequenced in the appropriate chronological order, as in Figure 2, which shows a sequence of 25 frames for the word *Pol* (a man’s name). Note that each “rib” represents one frame in the video, at 30 frames/second. The data points are not continuous, but occur only along those ribs.

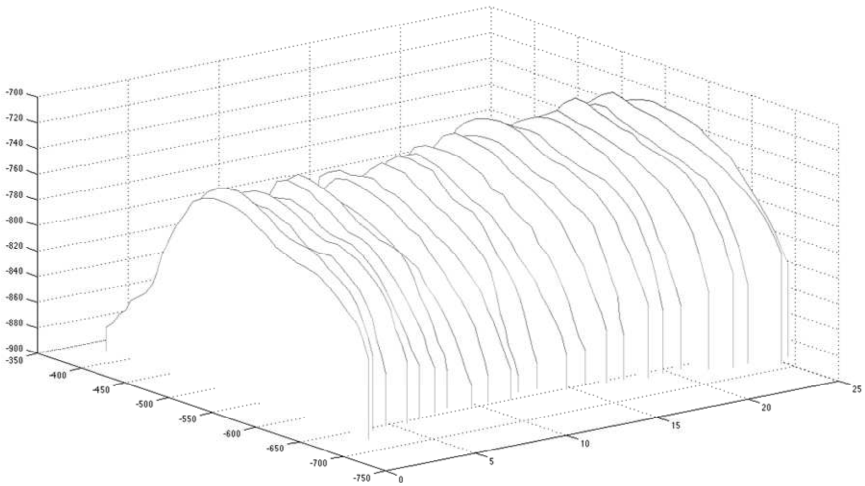

Figure 2: Frames chronologically ordered in Matlab.

The sequenced tongue contours are used to create a topographic surface, as in Figure 3 (again the name *Pol*). The topographic surface shows changes in the tongue contour over time. This is similar to the method developed by Parthasarathy et al. (2005), but without data smoothing or interpolation. Darkness at the periphery corresponds to lowness of the tongue while darkness in the center corresponds to highness. The tip is pointed down and right on the page while the back of the tongue is at the top and left. Time progresses from left to right.

Viewing the image in Figure 3 “from above” gives an image similar to a spectrogram or a contour map, the upper and lower images in Figure 4 respectively. The upper image is the linguagram. The dimensions are arbitrary but consistent across linguagrams. Here and in other linguagrams, the tongue tip is at the bottom of the image. Darkness in the center corresponds to areas where the tongue is high in the mouth (called “tongue height” here). Darkness on the periphery corresponds to areas where the tongue is low in the mouth (“tongue lowness”). Each vertical line corresponds to a frame from the ultrasound video, approximately 30 frames/second. These are numbered; we refer to frame number in subsequent discussions. The linguagrams are a visual representation of the data to be analyzed.

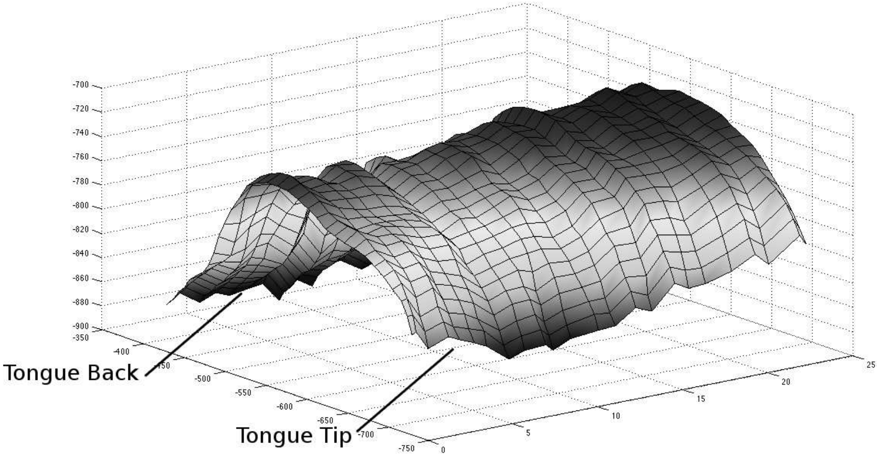

Figure 3: Example Linguagram from an angle.

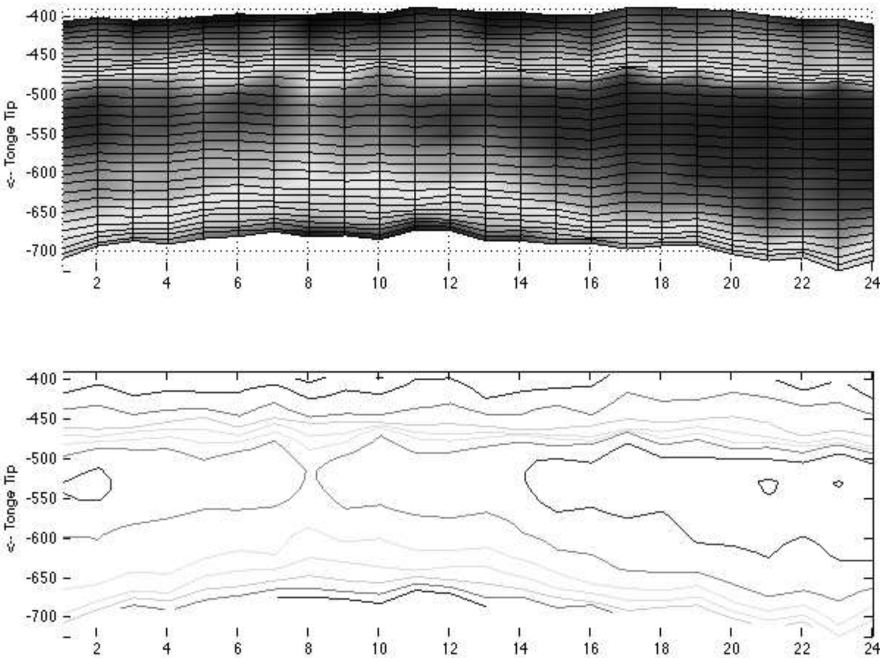

Figure 4: Example Linguagram.

The lower panel in Figure 4 shows a “relief map” of the tongue’s movements over time, with each line corresponding to a different altitude, or distance from the transducer. This figure is included in case it helps make the upper panel clearer; the upper panel shows the same tongue height differences, but uses gradiently changing color rather than marking individual contours.

2.4 Data Analysis

Because we are interested in the role of tongue root advancement and retraction in this study, we are most interested in the very back of the tongue. A second issue is the relative timing of the coronal gesture at the tip of the tongue *vis à vis* the tongue root gesture. These two areas of interest are darker in Figure 5. In Figure 5, the horizontal lines correspond to equidistant points in the individual tongue traces, with time again progressing left to right and tongue tip at the bottom of the image. The lower dark band measures tongue tip position. The upper dark band measures tongue body position, which we used as an indirect measure of tongue root position.

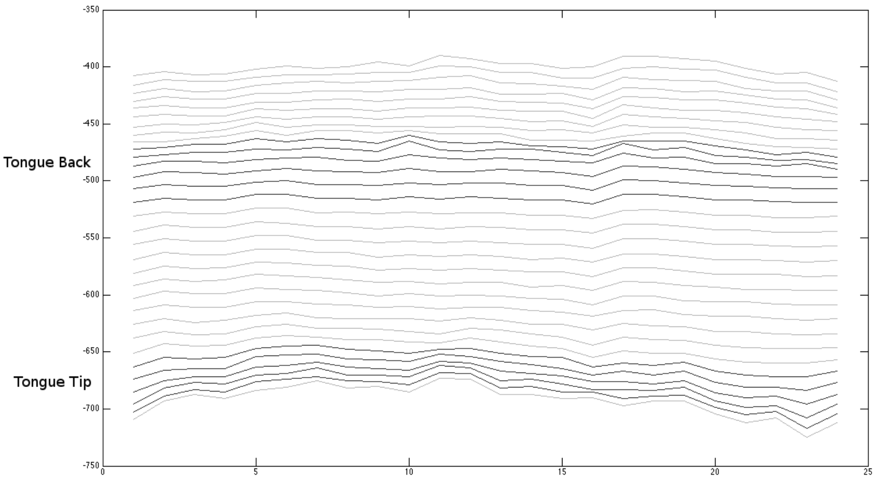

Figure 5: Tongue regions of interest. The upper dark band indicates the position of the tongue body. The lower band indicates the tongue tip.

When identifying tongue root position, a preferred measure would have been that of Gick et al. (2006), which identifies tongue root advancement by the position of the tongue root at the left edge of the ultrasound image. However, we had access to only one subject and the imaging quality was particularly poor at the tongue root (see Figure 1); this problem also explains why the upper and lower edges of the linguagrams are ragged – we did not interpolate points at the edge of the tongue, so where the image does not include a data point, the linguagram also does not have a data point. Thus, we were not able to use the Gick et al. system. We use the tongue body position as an indirect indicator, due to the correlation between tongue root advancement and tongue body raising (see Archangeli & Pulleyblank 1994).

This study is designed first to test whether lax and tense sonorants differ in tongue root position, with a secondary question of whether the tense sonorants show tongue root advancement. In advanced sounds (by hypothesis, the tense sonorants), we expect that the backmost raised region of the tongue will be further forward in the mouth than it is in non-advanced sounds (by hypothesis, the lax sonorants). Because the advanced sounds have less space for tongue body raising to occur in, a secondary prediction is that the backmost raised portion of the tongue will be higher in advanced sounds than in other sounds.

In order to determine whether there is a tongue root distinction between lax and tense sonorants, we examine the backmost highest part of the tongue to compare (i) its position in the mouth (along a front-back dimension, the horizontal lines in the linguagrams) and (ii) its height. Figure 6 shows the linguagrams of *fann* [fauN] (tense) vs. *fan* [fan] (lax). In *fann* (the left-hand linguagram), the frames identified in the text below correspond to [N] while in *fan* (the right-hand linguagram), the identified frames correspond to [n]. Tongue root advancement together with tongue back raising can be seen in frames 12-22 in *fann*, with raising indicated by the increasing darkness in the region centered on row -500, and the more forward tongue root indicated by the close contour lines from -500 approaching -400. In contrast, the *fan* token shows no root advancement or tongue back raising during the [n] (frames 13-18). In the same region centered around -500, *fan* shows a pale band and spread out contour lines between -500 and -400, using the full space to -400. We expect tense and lax sonorants to show similar differences in the height of the tongue back region of interest.

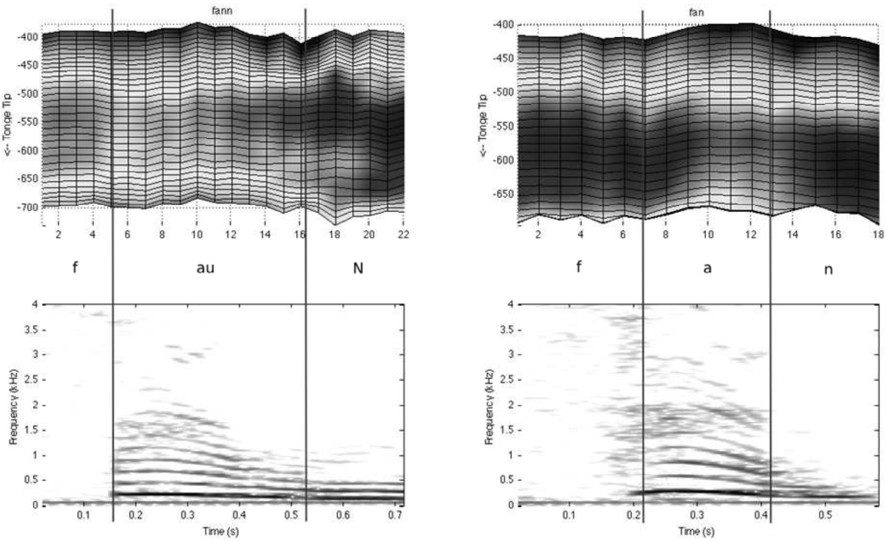

Figure 6: Linguagrams and traces suggesting advancement vs. retraction.

Our second question concerns the temporal coordination of tongue body and tongue tip gestures in tense sonorants. In order to determine the relative timing of the tongue tip and tongue body gestures, we create simple contours of each for the duration of each word by taking the average height across each region of interest. A high tongue tip corresponds to the coronal gesture while a high tongue back contour corresponds indirectly to tongue root advancement. To measure this, we took the average of six data points from each tongue tracing for the tongue back gesture. The data points selected are shown in the dark bands in Figure 5 above; these were identified by visually inspecting the linguagrams as corresponding to the highest part of the tongue in the back of the mouth. The same strategy was used to identify five data points to average for the tip gesture, corresponding to the five dark lines in the lower stripe in Figure 5. Based on the gesture height contour, the corresponding derivatives (rate of change) are also derived for each stimulus token. An example is given in Figure 7. The linguagram is at the top, followed by the contour and derivative of the tongue body and the tongue tip. Waveform and spectrogram complete the data display.

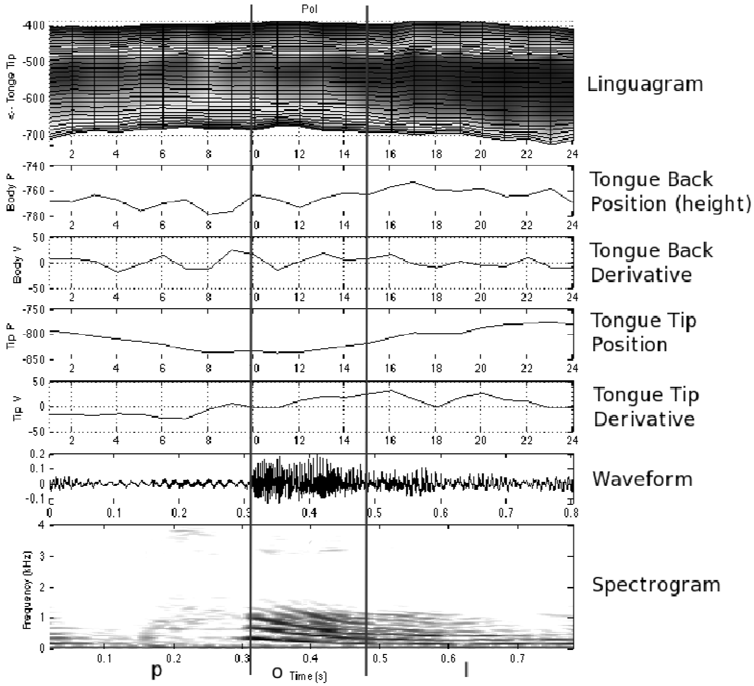

Figure 7: Example showing the temporal alignment of different aspects of the tongue surface. The vertical dark lines indicate the boundaries of the vowel *o*, with *p* to the left and *l* to the right.

We measured three dependent variables for each token to test our two hypotheses. The dependent variables RANGE and BPERCENT are measured to test Hypothesis 1; the dependent variable LAG is measured to test Hypothesis 2. These variables are defined below.

RANGE is defined as the difference between the highest point and the lowest point for the tongue back gesture during the articulation of the token. The RANGE of the tongue root gesture for the word *fon* ([fɔn], lax [n]) is illustrated in the 'Body P' graph in Figure 8 by the little bar labeled RANGE. Due to the [+ATR] feature, we expect greater movement of the tongue back for tense sonorants, and therefore greater RANGE for tense sonorants than lax sonorants.

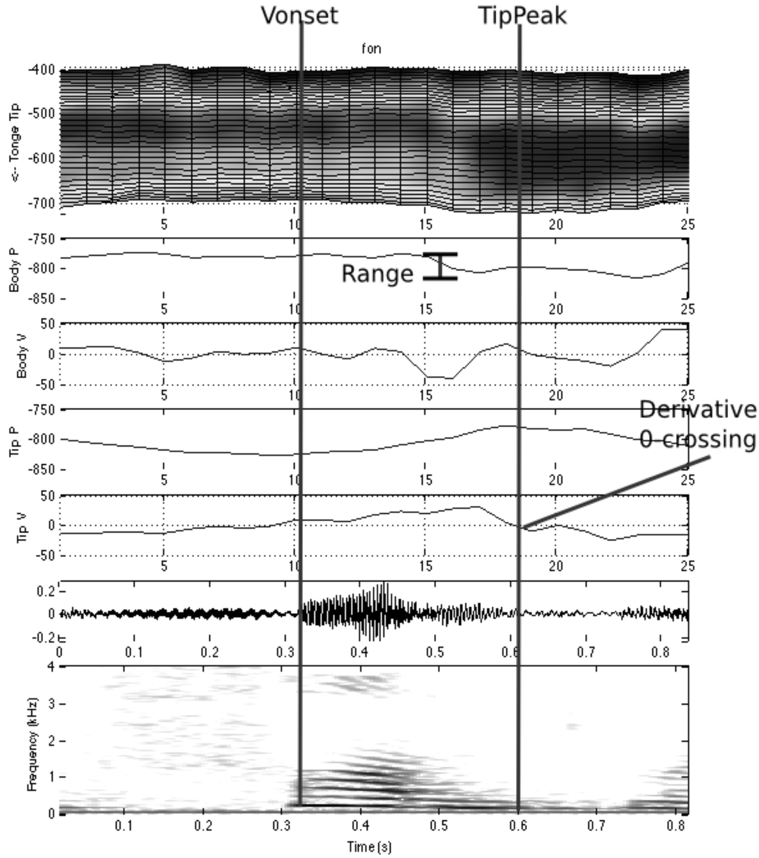

Figure 8: [fɔn]: RANGE of movement of tongue tip and tongue back.

BPERCENT is defined as the point in time at which the peak of the tongue back occurred, measured as a percentage of "word length". "Word length" is defined as the time from the onset of voicing in the vowel to the peak of the tongue tip in the coda.[3] Peaks are identified by locating zero-crossings of the corresponding derivative graph; the tip peak is labeled 'Derivative 0 Crossing' in the Tip V graph in Figure 8. Following Byrd et al. (2009), we expect that in codas the primary tongue tip gesture will occur later than the

[3] The measurement "word length" instead of "vowel length" is adopted because the acoustic/articulatory boundary between the vowel and its following sonorant is not clear, and the duration of the vowel is therefore hard to identify.

non-primary tongue back gesture, so the percentage is expected to always be less than 100%.

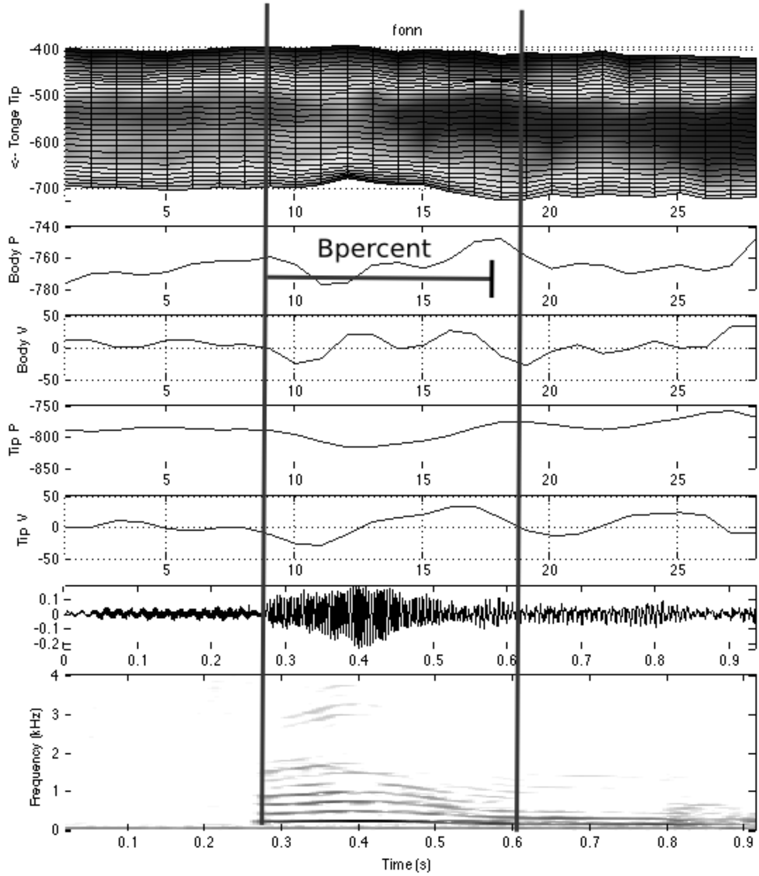

Figure 9: [fauN]: BPERCENT.

A large BPERCENT indicates that the back raising (which we assume results from tongue root advancement) is closer to the late tongue tip gesture with the relative timing reference to "word length". This suggests that the back raising gesture adheres to the coda consonant. Since tense sonorants are hypothesized to have [+ATR], we expect words with tense sonorants exhibit a larger BPERCENT, i.e. the back raising peak will be late in the word, relatively near the tongue tip peak. Sonorants lacking [+ATR] are expected to have no back peak relatively near the tongue tip peak because there is no tongue root advancement. In these words, the back-raising gesture is limited to the vowel gesture earlier in the word. Figure 8 is an example of a (lax) sonorant coda lacking [+ATR], where the back peak occurs roughly midway through the vowel onset and tip peak marks, near frame 15 (four frames from the end of the word), suggesting that the tongue body raising is not connected to the coda consonant. In contrast, Figure 9 illustrates a large BPERCENT for the word *fonn* [fauN], a word with a final tense sonorant, where the back peak occurs much closer to the tongue tip peak – only one frame away.

LAG is defined as the time between the onset of the last gesture in the tongue back and the onset of last gesture in the tongue tip. We expect multiple peaks in each token because we are looking at peaks in "word length": It is necessary to consider the vowel as well as the coda consonant because we are interested in the coda's effect on the length/quality of the vowel. We identify the onset (and offset) of each peak as 20 percent of a local maximum, illustrated by Figure 10.

LAG is shown in Figure 11 for the word *fonn*, measuring the time between the onset of the rightmost back peak and the onset of the tip peak identified in Figure 10. The leftmost of the two shorter lines indicates the onset of the back gesture and the right-hand shorter line shows the tip gesture onset.

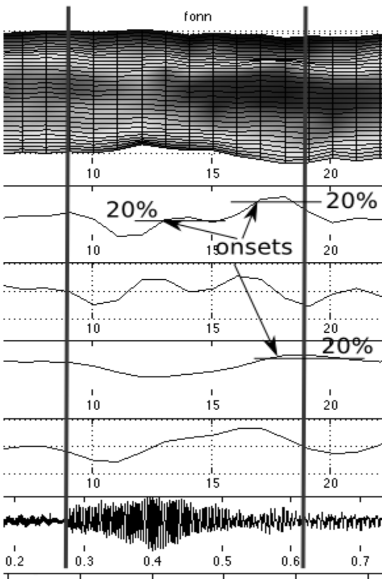

Figure 10: Locating Peak Onsets.

The purpose of LAG is to measure the degree of offset between the tongue tip gesture and tongue back gesture for the coda sonorants. Since the tongue back gesture precedes the tongue tip gesture in all consonants, we expect the lag to be negative. However, we expect tense sonorants to show less LAG (i.e. be closer to 0) than is found in corresponding lax sonorants, indicating that the back and tip gestures occur closer together in time as a coupled unit for tense sonorants. In tense sonorants, the back and tip gestures are hypothesized to both be consonantal gestures and so are likely to occur close together. Lax sonorants are hypothesized to have no back/ATR gesture, so any such gesture belongs to the preceding vowel, not to the sonorant coda. This predicts a greater LAG in lax sonorants.

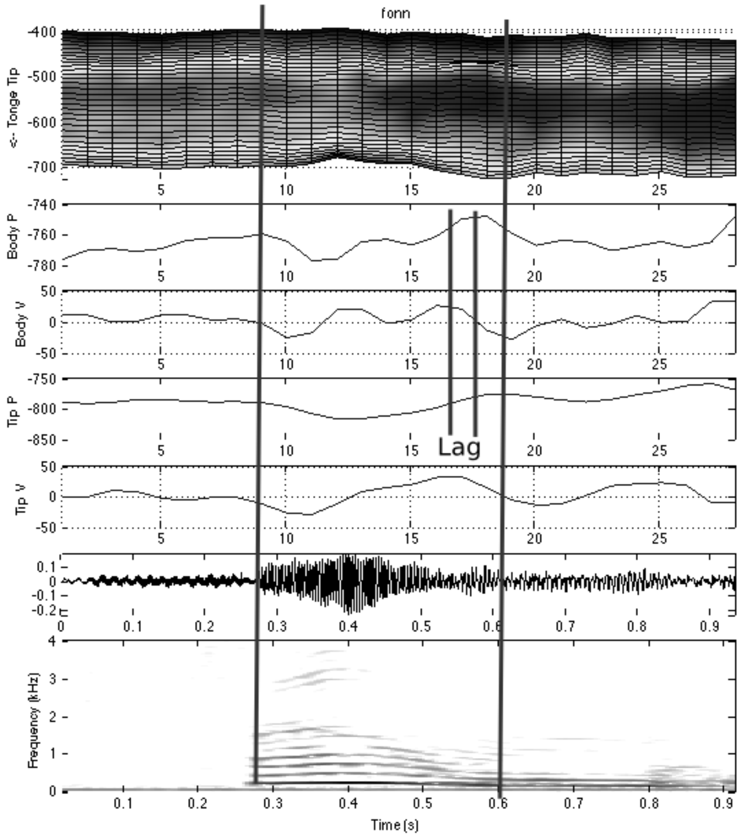

Figure 11: LAG. The left line is the onset of the back gesture and the right line is the onset for the tip gesture.

3. Results

A repeated measures analysis of variance (ANOVA), with factors Degree of Tenseness (Tense, Lax), Consonant Type (*n, l, r*), and Vowel (*a, ea, o*) was conducted on each of the three dependent variables. The means for each condition of each dependent variable are provided in Figures 12, 13, and 14.

RANGE

We predicted that tense sonorants would show a greater RANGE of movement in the back region of interest. This prediction was supported by the mean measurements of RANGE as shown in Figure 12. However, in the repeated measurements of ANOVA on RANGE, there was no significant effect of tense vs. lax sonorants [F(1; 18) = 3:65; p = 0:072]. There was a significant effect of Consonant Type [F(2; 18) = 4:21; p < 0:032], and for Vowel [F(2; 18) = 7:76; p < 0:004]. There were no significant interactions.

BPERCENT

The means of BPERCENT are shown in Figure 13. These results confirm our prediction that tense sonorants have greater BPERCENT than lax sonorants. In the repeated measures ANOVA of BPERCENT, there was a significant effect of tense vs. lax [F(1; 18) = 8.56; p < 0.009]. There were no effects of Consonant Type [F(2; 18) = 1.41; p = 0.27], or Vowel [F(2; 18) = 0:51; p = 0.61], and no interactions.

Hypothesis 1 states that tense sonorants have advanced tongue root, as shown by the rise in the back region of interest corresponding to the tongue tip raising. The results of BPERCENT provide evidence for hypothesis 1. The mean differences in both RANGE and BPERCENT from Figures 12 and 13 support hypothesis 1 as well.

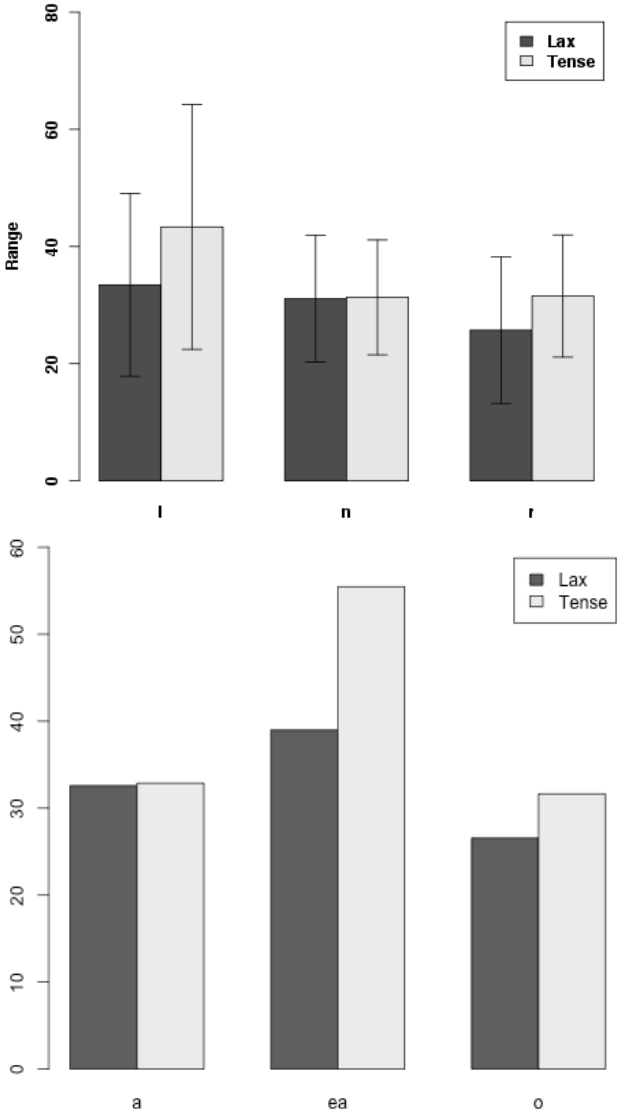

Figure 12: Means of RANGE for Consonant Type (left), and Vowel (right). Although the averages are in the predicted directions, the difference between tense and lax was not significant. The differences in Consonant Type and Vowel are significant.

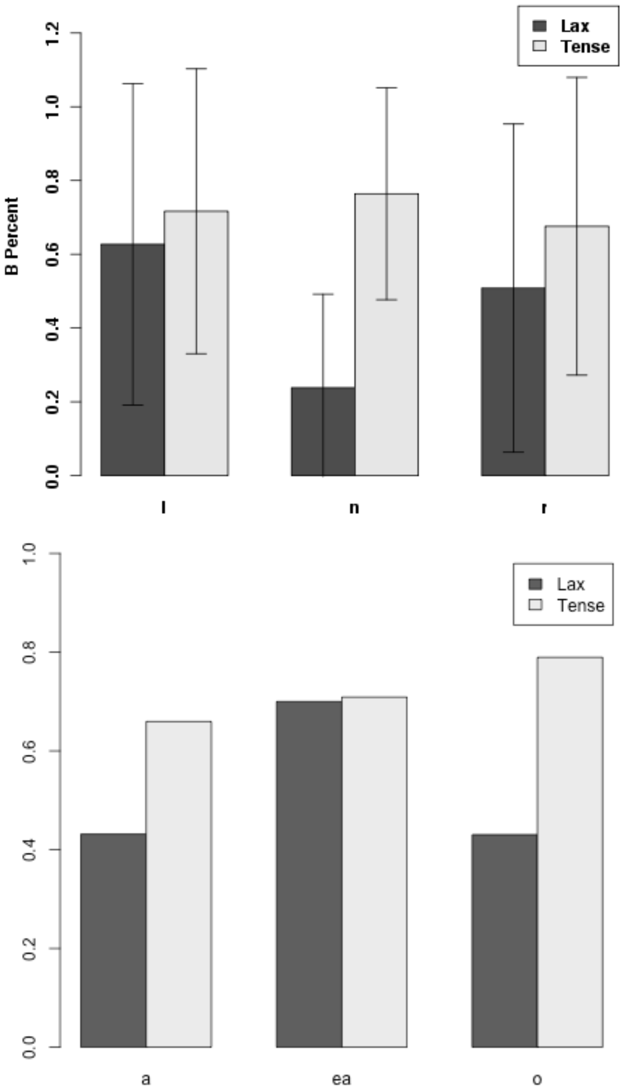

Figure 13: Mean of BPERCENT for Consonant Type (left), and Vowel (right). The difference between tense and lax sonorants is statistically significant, but the differences between Consonant Type and Vowel are not.

LAG.

We predicted that tense sonorants have less LAG than lax sonorants. Figure 14 shows that this prediction is supported for [n] vs. [N] but not the others. Furthermore, the differences for LAG in [n] vs. [N] is more prominent than those for [l] vs. [L] and [r] vs. [R]. The LAG for *ea* turned out to be positive, likely due to the tongue tip remaining relatively high throughout the vowel.[4]

The repeated measures of ANOVA in LAG showed significant differences for tense vs. lax [F(1; 18) = 6.85; p < 0.018], as well as for Consonant Type [F(2; 18) = 9.78; p < 0.001], and Vowel [F(2; 18) = 7.27; p < 0.005]. There was also a significant interaction between Tenseness and Consonant Type [F(2; 18) = 4.29; p < 0.03]. Tests for simple effects showed that the difference between tense vs. lax was significant for [n] vs. [N] [F(1; 10) = 23.99; p < 0.001], but not for [l] vs. [L] [F(1; 12) < 1], or [r] vs. [R] [F(1; 6) < 1]. No other interactions were significant.

In general, the results for LAG are in the direction of support for hypothesis 2, namely that the tongue back gesture precedes the tongue tip gesture in time for the tense sonorants. As liquids have a secondary backing gesture, it is not necessarily surprising that the LAG effect reaches significance only with the nasals.

[4] The orthographic *ea* only follows palatalized consonants, and corresponds to both [a] and [ɛ]. In our data, we discovered one item with the [ɛ] vowel, *fear*. We eliminated both *fear* and its counterpart *fearr* (with [a]) from our calculations to minimize the confounds brought in by the different vowel quality.

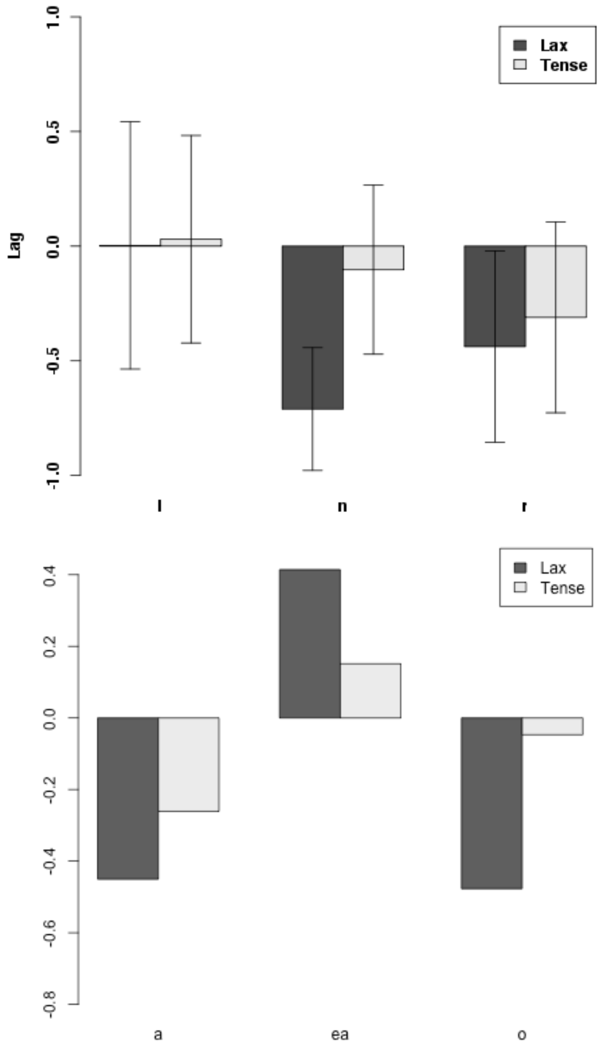

Figure 14: Mean of LAG for tense vs. lax sonorants by Consonant Type (left), and Vowel (right). The differences between tense vs. lax is significant, as are the differences between Consonant Type and Vowel, and the interaction between Tenseness and Consonant Type (left).

4. Discussion

We have investigated the phenomenon of tenseness in sonorants in Scottish Gaelic from an articulatory perspective. We collected data of tongue movement during speech using the ultrasound imaging technique. We then traced tongue surfaces and plotted linguagrams. We tested two hypotheses, namely, tense sonorants in Scottish Gaelic have the [+ATR] feature, and the offset between the tip gesture and the back gesture in tense sonorants is smaller than that in lax sonorants. We designed three dependent variables to test the two hypotheses. All the mean measurements of each dependent variable conform to our original predictions. The repeated measures ANOVA tests show that the former (Hypothesis 1) is supported by the BPERCENT measurements, and the latter (Hypothesis 2) by the LAG measurements.

Our data also suggest that RANGE is more sensitive to the preceding vowel type (*a, ea*, or *o*) and the manner of the coda consonant ([l/L], [n/N] or [r/R]) rather than to whether the coda is tense or lax. This could be due to the important role of the tongue body position in distinguishing one vowel from another and in distinguishing the manner of the different consonants –the range of movement in the tongue body for gross segment type distinctions may subsume the range for the details of tense/lax distinctions in consonants.

With respect to the manner of consonants, RANGE is biggest for [l/L], followed by [n/N] and then [r/R]. This shows that the back region of the tongue has the greatest movement during articulation of [l], which may have a secondary tongue backing gesture. The tongue back moves least during articulation of [r], which may have a secondary pharyngeal constriction gesture, a gesture that is antagonistic to raising the tongue. It is intermediate for nasals, which involve the velum as its secondary gesture, not the tongue: the secondary articulation for nasals neither augments the tongue body gesture (in contrast to laterals) nor suppresses it (in contrast to rhotics).

Our results also show that RANGE is much greater for the vowel ea than it is for *a* and *o*. (See footnote 4 on the pronunciation of *ea* in our data.) This result is also expected, due to the fact that palatalized consonants require that the tongue launch from a resting position to a fairly high position, thereby producing a large movement of the tongue body.

With regard to LAG, our results show that degree of tenseness, consonant type and vowel are all significant predictors. Specifically, we found not only that tense sonorants have significantly less LAG than lax sonorants, but also that the difference with LAG is largest for [n/N], medium for [r/R], and virtually non-existent for [l/L]. Although the tip and tongue body gestures for all three sonorant classes are less offset for the tense ones compared to the lax ones, the consonants still reveal individuality in the timing pattern between the two gestures. We suspect this is a consequence of the secondary articulations of the three manners of consonant. With [n/N], the secondary articulation is movement of the velum; this has little effect on the position of the tongue body (though see Baker et al. 2008 for discussion of tongue position in English nasal consonants), and LAG is greatest. This contrasts sharply with laterals, where the small LAG of [l] shows that tongue tip and tongue body gestures are synchronized. Laterals typically have a tongue body backing gesture coupled with the tongue tip gesture; in Scottish Gaelic, there may be such a backing gesture that is independent of yet overlaps with the tense/lax gesture. If so, the distinction might be lost in our measurements because we are measuring tongue root position indirectly through the tongue body position (due to the poor image quality at the tongue root). The behavior of [r/R] is in-between; its secondary articulation is typically pharyngeal constriction that might also affect the timing of the tongue body raising.

For the effect of vowels on LAG, we found that the orthographic vowel *ea* has positive LAG whereas the other vowels have negative LAG. This means that for tokens that contain the *ea* vowel, the tongue tip gesture actually precedes the tongue back gesture, contrary to what we predicted. This suggests that the vowel type can significantly affect the timing pattern of gestures.

As shown above, the predictions from our original hypotheses are supported in some cases by our measures; in other cases, the trend is in the right direction, but results did not attain significance. There are a variety of possible explanations. First, the sample includes a very small number of items, and generally only three repetitions of each item were of adequate quality for analysis. A greater number of items and/or of repetitions might produce significance. Second, the small number of items (due to limiting the stimuli to minimal pairs familiar to the participant) includes words with initial velars (four items) and coronals (two items); these consonants might induce coarticulation effects on the vowels that confound the impact of the coda consonants. The stimuli also include a small number of items with palatalized initial consonants, another possible source of confounds as noted above in the discussion of vowel quality. To address these issues, we hope to repeat the study using only vowel-initial and labial-initial words with a higher number of repetitions of each, a more limited set of vowels, and, ideally, more subjects.

There does remain one puzzling aspect of Scottish Gaelic sonorant codas: "tense consonants" are not perceived as different from "lax consonants." Rather, what is perceived is a diphthong before [N], [L], and vowel length before [R]. Why should this be the case? Suppose that Carnie (2002) is correct, and advanced tongue root is – or historically was – the correct representation for consonantal tenseness. In codas, the tongue root gesture precedes that of the tongue tip. As this distance increases, measured here both by LAG and by BPERCENT, the more possible it is for the first gesture to be perceived as part of the vowel, not as part of the consonant. And where the tongue root advancement is accompanied by tongue body raising, the sequence can be perceived as a glide-like element between vowel and consonant, a sound that can be interpreted as the second half of a falling diphthong. Where speakers make this interpretation, the erstwhile tense consonant feature [ATR] is now reanalyzed as a diphthong in the preceding vowel[5] (see Blevins 2004 on this type of misinterpretation resulting in language change).

[5] This explains how diphthongization results from an [ATR] (tense) coda consonant; what is not explained is why [N] and [L] produce diphthongization but [R] produces length in the preceding vowel. We suggest this is a result of the nature of the secondary articulations of the three consonants. With [N], the secondary articulation is velum raising, while with [L] it is raising and backing of the tongue body. With [R], by contrast, the secondary articulation is a pharyngeal narrowing---the very antithesis of tongue root advancement, which widens rather than narrows the pharyngeal cavity. In this case, the pharyngeal component of the [R] is also antagonistic to tongue body raising, preventing the appearance of diphthongization. In order to indicate the contrast between the two types of codas, an alternative is used; in this case, it is vowel length.