JASA ARTICLE

Lateral vocalization in Brazilian Portuguese

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ABSTRACT:
Lateral vocalization is a cross-linguistically common phenomenon where a lateral is realized as a glide, such as [w, j], or a vowel [u, i]. In this paper, we focus on the articulatory triggers that could cause lateral vocalization. We examined Brazilian Portuguese, a language known for the process of lateral vocalization in coda position. We examined the lateral in onset and coda position in four vocalic environments and compared the dynamic tongue contours and contours at the point of maximum constriction in each environment. We also performed biomechanical simulations of lateral articulation and the vocalized lateral. The results indicate increased tongue body retraction in coda position, which is accompanied by tongue body raising. Simulations further revealed that vocalized laterals mainly recruit intrinsic lingual muscles along with the styloglossus. Taken together, the data suggest that vocalization is a result of positional phonetic effects including lenition and additional retraction in the coda position.
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I. INTRODUCTION

Lateral vocalization is a typologically common process where a lateral approximant (e.g., /l, lʲ ʎ/) is realized as a non-lateral approximant (e.g., [w, j]) or a vowel (e.g., [u, i]). However, it has been difficult to characterize the surface forms because of the cross-linguistic and contextual variation of the phonetic realization. For example, variations observed across languages include vocalization of a velarized lateral, /ɫ/, to a high-back vowel [u̯] in many dialects of Lower Sorbian (Schaarschmidt, 1998) and of an alveolar lateral, /l/, to a mid-back vowel [o] in some dialects of English (Sato, 2014). In Standard Polish, the velarized [ɫ] has changed into the glide [w], a diachronic process which has almost been fully accomplished (Kraska-Szlenk *et al.*, 2018).

The primary aim of this study is to provide an articulatory explanation for vocalization of laterals by examining lateral vocalization in Brazilian Portuguese (BP), i.e., the process in which the alveolar lateral, /l/, undergoes coda vocalization in the coda position (e.g., mal [mau̯] "bad") (Câmara, 1970; Callou and Leite, 1990). Our hypothesis is that laterals are composed of a tongue body and a tongue tip gesture (cf. Proctor, 2011) and that lenition of the tongue tip gesture results in lateral vocalization in the coda position. To investigate this phenomenon, we utilized a two-pronged approach: (1) an ultrasound analysis of tongue contours and the movement of the tongue tip/blade and tongue body over time, and (2) computational simulation of the underlying biomechanics informed by the ultrasound data. We are using these methods in conjunction to get a finer grained understanding of the articulatory nature of lateral vocalization in BP.

This article is organized as follows: In Sec. I A, we discuss previous studies on laterals and lateral vocalization. We then narrow the focus to lateral vocalization in BP. In Sec. II, we present the methodology for our experiments and in Sec. III, we present the results. Finally, Sec. IV provides a discussion of the results and interprets them using articulatory phonology (Browman and Goldstein, 1992, *et seq.*).

A. Previous studies

From an articulatory point of view, laterals are complex segments created with the coordination of tongue body and tongue tip gestures (Proctor, 2011). The lateral side-channel is also a crucial aspect of lateral articulation. Different combinations of muscle activity could theoretically generate the side-channel: unilateral activity of superior longitudinal, styloglossus, hyoglossus, and perhaps even palatoglossus muscles could help to produce a channel on the contralateral side; activity of the transverse lingual muscles could draw the sides of the tongue medially concomitantly with constriction-generating expansion in the midsagittal plane (Ying *et al.*, 2021). Gick *et al.* (2017) simulated the biomechanics of lateral bracing and demonstrated that a minimal-effort non–laterally braced posture that is consistent with an /l/ can be achieved by means of roughly equal parts mylohyoid, transverse, and superior longitudinal muscles. In short, laterals are complex segments that require the recruitment and coordination of multiple articulators to produce. Previous researchers have suggested that there is a complex

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coordination between tongue body and tongue tip gestures (Sproat and Fujimura, 1993; Proctor, 2011; Turton, 2017). The precise magnitude and target of the gestures vary by both language and lateral, but the generalized representation that links all laterals together is the coordination of tongue body and tongue tip gesture. With this approach, the difference between alveolar and velarized alveolar laterals then is the target for the tongue body gesture. This approach can also easily account for palatal laterals by changing the tongue body target from a velar/uvular place to a palatal place of articulation. Theoretically, this approach can also account for retroflex laterals by changing the tongue tip location from dental/alveolar to a more retracted position between the alveolar ridge and the hard palate; however, it is unclear how this approach would account for the velar lateral, which has been shown to be produced by the formation of the lateral channel near the velar occlusion (Yip, 2011). This is not like coronal laterals that use the tongue lamina/apex to form the lateral channels. But a generalized model of lateral vocalization that accounts for the variation in phonetic realizations is still missing.

Lateral vocalization has been accounted for using an articulatory phonology (Browman and Goldstein, 1992; *et seq*.) perspective. Proctor (2011) argues that the gestural settings of laterals accounts for the type of phonological behaviour observed in the world's languages. Proctor's (2011) gestural account of lateral vocalization is not dissimilar to the phonological feature-based approach: lateral vocalization occurs because of lenition, deletion, or masking of the tongue tip gesture. The result of the manipulation of the settings of the tongue tip gesture results in the tongue body gesture creating a vocalic or glide-like segment. The increased tendency for lateral vocalization is also accounted for readily under the articulatory approach due to conspiring articulatory–phonetic tendencies. Gick *et al*. (2006) examined the gestural timing of liquids in six languages and found that there were differences in the coordination of an anterior and posterior gesture depending on syllable position. In the onset position, languages with observable anterior and posterior gestures (three/six languages tested) had delay in the achievement of the posterior gesture following the anterior gesture reaching its target. However, in the coda position, all the languages tested showed an anterior and posterior tongue gesture and that there was a tendency (four/six languages tested) for the posterior gesture to be achieved prior to the anterior gesture. Thus, the data suggest that there is a phonetic tendency for retraction of the posterior tongue gesture in the coda position, which causes secondary-velarization in the coda compared to the unvelarized lateral in the onset. This combined with the phonetic tendency of gestural undershoot in the coda position (Kirchner, 1998; Blevins, 2004) readily accounts for the tendency for vocalization in the coda over any other position.

Smith and Lammert (2013) and Smith (2014) both propose articulatory accounts for vocalization that differ from previous analyses due to the lack of reference to tongue constriction locations and instead focus on tongue shape as a defining factor. Smith and Lammert (2013) performed a magnetic resonance imaging study of laterals in American English. They found complex tongue shaping involving two tongue gestures: an anterior and posterior constriction. However, they also found that the multiple tongue constrictions formed a complex tongue curling which results in a concave anterior tongue body coupled with a retracted posterior tongue body. There was also a delay in the simultaneous achievement of the tongue tip and tongue body constriction as observed in previous studies. However, they noted that if constriction formation was measured from the point of maximum tongue curling, there was minimal delay between the simultaneous achievement of these two articulatory events. As a result, the authors suggest that lateral articulation is better thought of as a tongue shape target rather than a complex composition of multiple constriction locations. Smith (2014) also notes that even for vocalized laterals, tongue curling takes place and suggest that this supports the notion of a target tongue shape rather than constriction locations. It is also claimed that vocalization in the coda position takes place because the additional retraction of the posterior tongue body makes it possible to achieve the target tongue shape without anterior tongue bracing with the tongue tip against the palate. It has also been noted that coda vocalization is more frequent after /a/ and less after /o/, and more frequently before apicals than labials, velars, or a pause. Recasens (1996) explains that if there were conflict between consonant 1 (C1) and consonant 2 (C2) in a cluster such as /lt/, then we would expect reinforced apical articulation. Instead, Recasens (1996) proposes an interaction between the articulatory timing of the multiple gestures involved in lateral articulation and their perceptual consequences. The quicker achievement of the dorsal gesture in the coda position results in greater and more salient second formant (F2) transitions. This is more likely to be interpreted as a /w/ segment by listeners that precedes the lateral. Thus, the process is due to an interpretation of a separate /wl/ sequence followed by a subsequent elision of the /l/ due to unstable articulatory and perceptual properties associated with /VwlC/ sequences. Recasens (1996) suggests that this articulatory–perceptual explanation is likely the same mechanism that has caused the loss of palatalized nasals in many romance languages (i.e., /Vɲ/ → /Vjn/). Final vocalization is also explained by this general mechanism: lengthened vowel F2 transitions accompanied by a weakened tongue tip gesture or temporal delay results in the perceptual loss of a lateral.

Recasens and Espinosa (2010) build on the articulatory–perceptual explanation for lateral vocalization. Through a combination of EPG and perceptual studies, Recasens and Espinosa (2010) discovered that contextual cues affect the perception of the velarized lateral as /w/. They showed that low F2 is a necessary requirement for velarized laterals to be perceived as a /w/, suggesting a strong link between the acoustics, perception, and lateral vocalization. However, low F2 alone was not enough for higher numbers of /w/ identification of velarized laterals. Specifically, velarized laterals that had a lowered F2 and a lower degree of tongue palate contact in the anterior region of the mouth were identified more frequently as /w/ than velarized laterals that had only positional lowering of F2 and no reduced tongue palate contact. In short, the literature has proposed articulatory and acoustic–perceptual factors play a significant role in the process of lateral vocalization.

Lateral vocalization is a complex phenomenon and has been approached from articulatory, acoustic, and perceptual viewpoints. However, the vocalization process in BP is not well studied from an articulatory perspective and ultrasound analysis in conjunction with biomechanical simulations could reveal important information about the process.

B. Laterals in Brazilian Portuguese

The present paper specifically deals with the process of lateral vocalization which is currently observed in Brazilian Portuguese (BP). BP is described as having two laterals: an alveolar lateral, /l/, and a palatal lateral, /ʎ/ (Barbosa and Albano, 2004). However, Charles and Lulich (2018) postulated that the phonetic evidence from their three-dimensional ultrasound study is consistent with a 1, 2, or 3 lateral system containing an alveolar lateral, /l/, minimally, but maximally also including a palatalized lateral, /lʲ/, and a palatal lateral, /ʎ/. BP differs from European Portuguese (EP) in several ways, but the most relevant difference to our research is that the alveolar lateral, /l/, undergoes coda vocalization in BP (e.g., *mal* [maṷ] "bad"), while in EP, the alveolar lateral does not (e.g., *mal* [mal] "bad") (Cristófaro-Silva and Oliveira, 2001).

Lateral vocalization (along with other systematic sound changes in BP) are due to different innovations in Brazil and Portugal that initiated in the 1500s. Evidence of this change can be observed in dialects that do not have lateral vocalization in coda position. In these dialects, the coda lateral is realized as a velarized lateral, [ɫ]. However, these dialects are rare and are principally found in the South of Brazil. Additional coda variants are observed in the Rio Grande do Sul dialect. It has an alveolar lateral [l] as a coda variant of /l/ (Massini-Cagliari *et al.*, 2016).

In most dialects of BP, the coda lateral is realized as a back rounded glide (Camara, 1970; Callou and Leite, 1990) and can cause homophony (e.g., *mal* /mal/ > [maṷ] "bad"; *mau* /maw/ > [maw] "badly"). Affixation provides strong evidence supporting that vocalization that occurs in coda position (e.g., papel > pape[ṷ] "paper," but, papelada > pape[l]ada "a lot of paper"; Collischonn and Costa, 2003), while root internally there is no such evidence. Battisti and Moras (2016) note that in some dialects of BP, the lateral variably undergoes vocalization, such as in the rural towns in the southern states of Catarina and Rio Grande do Sul (Quednau, 1993; Tasca, 1999). Although this study represents speakers from more than a decade ago, at the time, vocalization was nearly categorical for younger speakers (20–30 year of age) of BP, while older speakers (60–75 years of age) commonly produced the velarized lateral (Collischonn and Costa, 2003).

However, there has been robust interpretation on the actual status of the alveolar lateral in BP. The variation in interpretations is centered strongly around the previously discussed positional alternations, specifically, whether /l/ is realized as [l], [ɫ], or [w] in the coda position. For example, Azevedo (2005) maintains that the alveolar lateral is never velarized, while Silva (1996) maintains that it is always velarized. A significant number of researchers have suggested that velarization only takes place in the coda position (Cagliari, 1981; Reis and Espresser, 2006), while others describe complete vocalization in the coda position (Charles and Lulich, 2018). Therefore, currently, there is no consensus on the status of the coda lateral in BP.

Furthermore, it is possible to analyze the alternation as two phonological entities, /l/ in the onset and /L/ in the coda. The coda /L/ can be treated as an "archiphoneme" (D'Angelis, 2002) and is undergoing a change to a labiovelar approximant throughout Brazil, while the onset /l/ is produced as an alveolar lateral. As such, we will examine the onset lateral and the coda /L/ and not necessarily the *de facto* vocalization of the lateral /l/. Our position is that BP undergoes lateral vocalization in coda position, which we investigate in detail in this paper. We examine the extent of the difference between the plain alveolar lateral and the vocalized lateral in the state São Paulo, Paulista, dialects of BP.

C. Hypotheses

For our study, we will be referring to the alveolar lateral, /l/, as the onset lateral, and the vocalized lateral as the coda lateral. We will use the IPA symbols, [l, ṷ], respectively. Previous research (e.g., Proctor, 2011) has hypothesized that laterals are composed of a tongue tip/blade and tongue body gesture and that lateral vocalization is a product of gestural lenition. We define gestural lenition as an automatic/mechanical process that is characterized by a weakening or loss of an articulatory gesture. We hypothesize that the onset lateral will be composed of a tongue tip/blade gesture accompanied with a tongue body gesture. The tongue body gesture will be observed to have relative invariance in target location despite potential anticipatory coarticulatory effects. We predict a pull back of the tongue tip/blade for the coda lateral and a raising and retraction of the tongue body. This prediction is expected under the hypothesis of gestural lenition. *Closure undershoot* (Lindblom, 1963), on the other hand, would predict the vocalized lateral will have less advancement of the tongue tip/blade relative to the onset lateral. To test our prediction, we collected and analyzed lingual ultrasound imaging and created biomechanical models informed by the ultrasound data. We predict differences in the tongue tip/blade location at the point of maximum constriction (i.e., the maximum displacement of the articulators): the onset lateral will have a higher and more forward tongue tip/blade indicative of tongue–palate contact, while the coda lateral will have a lower and more retracted tongue tip/blade, suggesting no tongue–palate contact. Additionally, we predict that the tongue body will be higher and more retracted for the coda lateral compared to the onset lateral.

With respect to the biomechanical simulation, our prior expectations were informed primarily by theoretical anatomical sources (e.g., Zemlin, 1998) and Gick *et al.* (2017), which presents simulations of lateral tongue–palate bracing. From these sources, we might expect lingual muscles, such as the posterior genioglossus and superior longitudinal, to be active for the onset lateral to help maintain alveolar closure by helping to advance and elevate the tongue tip, respectively. The transverse may also help in this role, by drawing the sides of the tongue toward the midline and driving expansion of the tongue in the midsagittal plane through its hydrostatic (volume preserving) property (see Smith and Kier, 1989). Reduction of the anterior gesture in a coda lateral may be produced through a reduction of activity of the aforementioned muscles, but activity might also be expected from muscles such as the styloglossus, which can cause retraction and elevation of the tongue body towards the soft palate, and inferior longitudinal, which shortens the tongue and pulls the tip away from the anterior palate region (Sanders and Mu, 2013). We should note that the model is driven purely by midsagittal ultrasound data. We do not have any information from our ultrasound data about the lateral channeling gesture, and we do not attempt to impute this action in the model. Thus, the results of the model need to be interpreted with this limitation in mind. First, we will present data from Experiment 1, the ultrasound data (Sec. II), then we present the data from Experiment 2, the biomechanical simulations (Sec. III).

II. EXPERIMENT 1

The goal of the first experiment is to provide tongue contours and dynamic tongue movements for the onset lateral, [l] and the coda lateral, [u̯]. In Sec. II E 1, we present the results for the static tongue contours and in Sec. II E 2, we present the dynamic tongue movements.

A. Methods

Six native speakers of BP (four females, two males, all 20–25 years of age), born and raised in São Paulo, Brazil, participated in the study. All participants lived in the state of São Paulo, Brazil their whole lives and were visiting Toronto on a 2-month summer language exchange. Participant names were anonymized to maintain privacy. We denote each speaker as BP + a number (e.g., BP1). Participants had no self-reported history of speech or hearing disorders.

B. Instrumentation and procedure

Recordings were performed at the Phonetics Lab at the University of Toronto. Data were recorded with a Telemed EchoB ultrasound (60 fps) using the Articulate Assistant Advanced (AAA) recording and analysis software (Articulate Instruments Ltd., 2012). An ultrasound stabilization headset (Articulate Instruments Ltd., 2008) was also used to prevent movement of the ultrasound probe.

/l/ was produced in word-initial and word-final positions (taken to represent onset and coda position, respectively) in four different vocalic environments, /i, ɛ, a, and ɔ/. The lateral always occurred in the stressed syllable. The stimuli were presented to participants in a randomized order. Participants produced each of the stimuli in the carrier phrase *diga _____ para si mesmo* [ʤigɐ _____ parɐ si mɛzmʊ] "say _____ for yourself." This was done to facilitate more natural productions and to avoid declination effects. Each phrase was produced six times. Participants read each sentence three times before moving on to the next sentence and went through the list twice in the same randomized order. Participants produced 288 tokens (6 speakers $\times$ 6 repetitions $\times$ 2 word positions $\times$ 4 vocalic contexts = 288). Table I presents the list of stimuli. Transcription is based on Barbosa and Albano's (2004) illustration of BP.

C. Segmentation

Tongue contours were extracted using the AAA program (Articulate Instruments Ltd., 2012). We first annotated the lateral in both word-initial and word-final position using acoustic cues. Lowering of F2 in the vowel preceding the onset and coda laterals was taken to indicate the transitional tongue movements towards the articulation of the target segment and as such, was marked as the left edge of the annotation. We set the right edge of the annotation after the presence of lowered formant energy for the lateral in the onset position to capture the dynamic tongue motion away from the maximum constriction. Thus, we marked the right edge at the end of the F2 transition following the onset lateral. In the coda position, the right edge was set as the end of the stop closure for [p] after the articulation of the coda lateral. Thus, the point of maximum constriction (i.e., the mid-point for segmentation purposes) for the coda lateral was typically the last ultrasound frame with a corresponding acoustic output associated with it. Figure 1 presents example spectrograms with annotation in the AAA software suite (Articulate Instruments Ltd., 2012). The onset initial lateral is on the left and the coda lateral is on the right marked by a red line.

The automatic tongue tracing function in AAA (Articulate Instruments Ltd., 2012) was used to fit the spline to the surface of the tongue for all annotated time intervals. However, each interval was then manually examined by P. J. H. to ensure that the tongue surface and only the tongue surface was present in the fit spline. We extracted tongue

TABLE I. Stimuli set used for data elicitation. Phonetic transcriptions are in square brackets.

Context		*l*			*u̯*	
i	*lista*	[lʲistɐ]	list	*mil*	[miu̯]	thousand
ɛ	*leste*	[lɛstḛ]	east	*mel*	[mɛu̯]	honey
a	*lasca*	[laskɐ]	chip (of wood)	*mal*	[mau̯]	bad
ɔ	*losna*	[lɔsnɐ]	plant; absinthe	*sol*	[sɔu̯]	sun

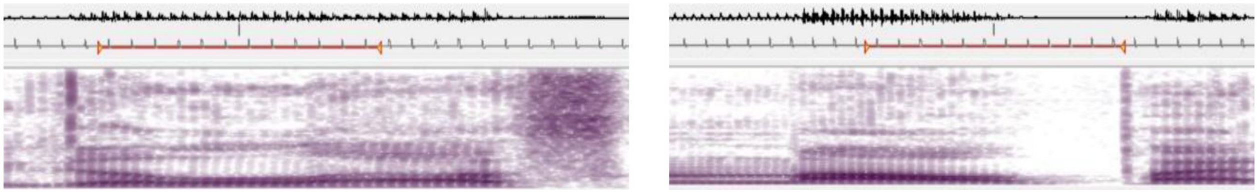

FIG. 1. (Color online) Spectrogram and wave form for the annotation of [l] from lesta (left) and [u̯] from mel (right). The annotation is the thin red line above the spectrogram, the black image above that is the waveform, and the purple image is the spectrogram.

contours for two analyses. The first analysis was for the point of maximum constriction (i.e., the maximum displacement of the tongue tip/body during articulation). Tongue contours extracted at this time point were used for static comparisons and were identified by visual inspection. We determined the point of maximum constriction for the onset and coda laterals based on two criteria: (1) maximum displacement of the tongue blade/tip, and (2) maximum retraction/advancement of the tongue body. The second analysis was 11 intervals throughout articulation to plot temporal dynamics. Intervals were adjacent frames (spaced approximately 16.33 ms apart). The sixth interval was the same interval that was used for the point of maximum constriction.

D. Statistics

Static analysis was done using Generalized Additive Mixed models (GAMMs) of the tongue contours (Crawley, 2012; Wood, 2017) using polar coordinates (Heyne and Derrick, 2015). We generated tongue contours with the extracted coordinates from the AAA suite (Articulate Instruments Ltd., 2012).

As the onset lateral, [l], and coda lateral, [u̯], are in complementary distribution (Cristófaro-Silva and Oliveira, 2001), it was impossible to directly compare them in the same syllabic position; therefore, in this study, we directly compare onset and coda lateral tongue shapes in the same tautosyllabic vowel contexts /i, ɛ, a, and ɔ/ (e.g., *leste* "east" vs *mel* "honey"). In addition, all the onset laterals were compared against each other to determine the effect of different vocalic environments, as were the coda laterals (six models: onset lateral [l], coda lateral [u̯], and the comparison of onset lateral, [l], and coda lateral, [u̯], in each of the four vocalic contexts, /i, ɛ, a, and ɔ/).

We used the mgcv package (Wood, 2017) to construct six GAMMs. We constructed two models to examine the contextual effects on the lateral and vocalized lateral (one for onset lateral and one for coda lateral). Context in our models refers to each of the possible vowel contexts (four levels: /i, ɛ, a, and ɔ/). Because we used polar coordinates for all of our models instead of Cartesian coordinates, we used the measures Theta (the angle from the origin) and r (the distance from the origin). For both the onset lateral and the coda lateral models, we used the following parameters:

$$
\begin{aligned}
r \sim\ & Context + s(Theta,\ bs = "cr",\ k = 35) \\
& + s(Theta,\ by = Context,\ bs = "cr",\ k = 35) \\
& + s(Theta,\ bs = "fs",\ k = 35,\ m = 1, \\
& by = Context\ :\ Participant). \qquad (1)
\end{aligned}
$$

We further constructed four models for each of the comparisons of the lateral and vocalized lateral. We divided the data by Context into four groups (four levels: /i, ɛ, a, and ɔ/) and compared each segment. Segment in these models refers to either the lateral or the vocalized lateral (two levels: [l, u̯]). We used the following parameters for each of the four models:

$$
\begin{aligned}
r \sim\ & Segment + s(Theta,\ bs = "cr",\ k = 35) \\
& + s(Theta,\ by = Segment,\ bs = "cr",\ k = 35) \\
& + s(Theta,\ bs = "fs",\ k = 35,\ m = 1, \\
& by = Segment\ :\ Participant). \qquad (2)
\end{aligned}
$$

In each of the formulas, r is the distance of the fitted contour point from the virtual origin (i.e., the radius), Theta is the angle in relation to the virtual origins, the smooth for each Participant is a random effect, and m is the penalty assigned to the random smooth. We used cubic regression spline basis (cr) in each of the models. We also coded a factor smooth (fs) that allowed for a random smooth of the interaction between Segment or Context and each of the participants (Sóskuthy, 2017; Wieling, 2018). We first generated the smoothing contours and confidence intervals using the package itsadug (van Rij *et al.*, 2020) and then plotted all the contours together using the plotly package (Sievert, 2020). This process was done with a custom script developed and used in Heyne *et al.* (2019). We also performed individual analyses for each speaker in the onset and coda contexts to determine that the observed effects were not the result of just one or two speakers. We used the following parameters for each of the 12 models:

$$
\begin{aligned}
r \sim\ & Context + s(Theta,\ bs = "cr",\ k = 35) \\
& + s(Theta,\ by = Segment,\ bs = "cr",\ k = 35). \qquad (3)
\end{aligned}
$$

GAMM plots and statistics are shown in Figs. 10 and 21 and Tables V–XVI (see the supplementary material for GAMM plots and statistics).[1]

We also performed a dynamic analysis of the tongue tip/blade and tongue body using GAMMs. First, we extracted coordinates from the three frontmost coordinates of the tongue contour. We also extracted the three most posterior tongue coordinates for the tongue body. The three most posterior coordinates on the tongue body curvature were extracted for this analysis (see Fig. 2 below for an example). Coordinates were extracted for each token at the point of maximum constriction and 5 intervals before and 5 intervals after it, for a total of 11 time intervals that were used in the GAMM analysis. Each frame represents approximately 16.33 ms. For this analysis, Cartesian coordinates were used because single x- or *y* axis values are directly transferable to relative height or frontness of the measured articulator. Figure 2 presents an example of where the three tongue points were extracted from the tongue tip/blade (in blue) and body (in red). We plotted the data using the ggplot2 (Wickham, 2016) in R (R Core Team, 2021). The tongue tip is on the right side of the figure.

X- and Y-coordinates were then compared individually using GAMMs to see how the tongue tip/blade and tongue body advanced or retracted and raised or lowered over time. We performed a total of four different GAMMs: TT *x* axis, TT *y* axis, TB *x* axis, and TB *y* axis. We then compared by Segment (2 levels: [l, u̯]). Each model had the following formula:

$$(1): X\, or\, Y \sim Segment + s(Interval, bs = "cr") + s(Interval, by = Segment, bs = "cr") + s(Interval, bs = "fs", m = 1, by = Segment : Participant).$$

The static tongue contour and dynamic articulator analysis both used the "fREML" method and we also had discrete set to True in order to discretize covariates for efficiency.

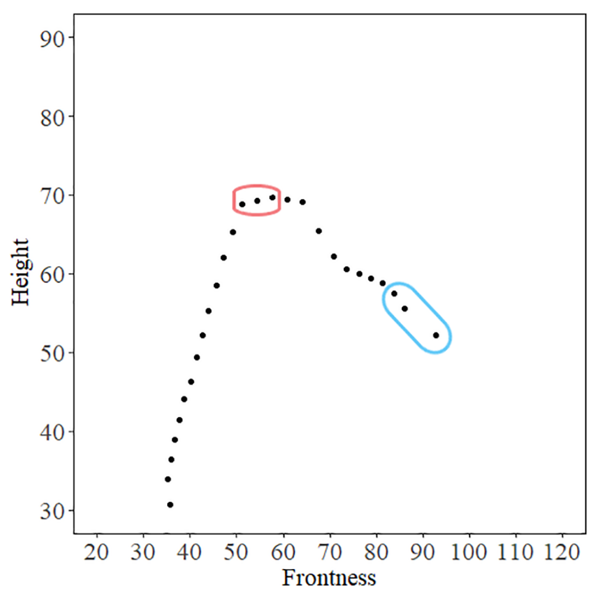

FIG. 2. (Color online) Scatter plot showing a single contour for BP1's articulation of "mal" at the point of maximum constriction. The coordinates used for the tongue blade analysis are circled in blue and the coordinates used for the tongue body analysis are circled in red.

E. Results

First, we present a comparison of the phonetic environments. We provide the results of the onset lateral and coda lateral individually across environments and then compare the contour of the onset lateral and coda lateral in each environment. Second, we present the results of the dynamics of analysis of the tongue tip/blade and tongue body.

1. Phonetic environment comparisons

Figure 3 presents the GAMM comparison of the onset lateral across all the phonetic environments. The tongue tip is on the right side of the image. Table II summarizes the GAMM smoothing term statistics.

The model R^2 was 0.971. The plot of the GAMM smooths indicated that [#li] had a more advanced tongue root and raised tongue body compared to the other tongue contours. The tongue contours for [#lɛ, #la, #lɔ] were not significantly different from each other, although the best fit lines indicate that the tongue dorsum was slightly more retracted for [#la] than for [#lɛ, #lɔ]. It should also be noted that across speakers, an effect of vowel height was observed for some speakers such that the lateral was lower for the /a/ condition and raised in the /i/ condition (see the supplementary material for individual plots for each speaker).[1]

Figure 4 presents the GAMM plot for the coda laterals across all the phonetic environments. The tongue tip is on the right side of the image. Table III summarizes the GAMM smoothing terms statistics.

The model R^2 was 0.740. The plot of the GAMM smooths revealed that the anterior tongue body for [iu̯#] was slightly more advanced when compared to the other vocalic environments. [ɛu̯#, au̯#, ɔu̯#] showed no significant difference from each other, although the best-fit contour line indicated a lower tongue body for [a] and a higher tongue body for [ɛ, i] contexts. This can be observed through the small magnitude differences in the best-fit lines for the anterior tongue body and tongue blade.

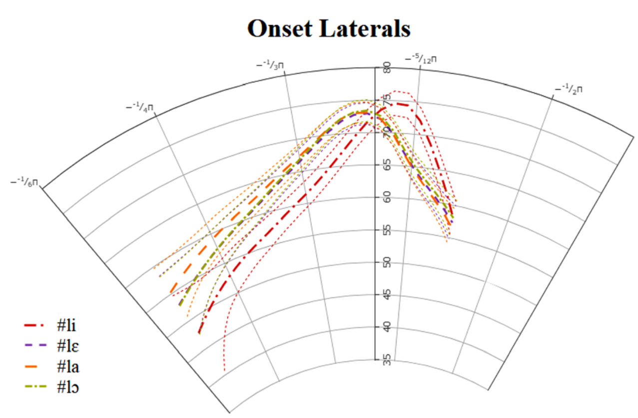

FIG. 3. (Color online) Results of the GAMM comparison of each of the laterals in onset position: /i/ (long dash dot), /ɛ/ (dash), /a/ (long dash), and /ɔ/ (dash dot). Thin dotted lines indicate the 95% confidence intervals. Tongue tip on the right.

JASA
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TABLE II. Approximate significance of smooth terms.

	edf	Ref. df	F	p-value
s(Theta)	15.080	17.090	71.803	< 0.001
s(Theta): i	13.780	15.580	18.230	< 0.001
s(Theta): ɛ	0.000	0.000	0.006	1.000
s(Theta): a	1.000	1.000	0.876	0.349
s(Theta): ɔ	1.000	1.000	0.063	0.802

TABLE III. Approximate significance of smooth terms.

	edf	Ref. df	F	p-value
s(Theta)	11.911	14.041	27.575	< 0.001
s(Theta): i	6.993	8.278	4.267	< 0.001
s(Theta): ɛ	3.854	4.479	1.145	0.300
s(Theta): a	2.871	3.522	1.185	0.208
s(Theta): ɔ	1.000	1.000	0.154	0.695

Figure 5 presents the GAMM plot for the onset and coda lateral across all the phonetic environments. The tongue tip is on the right side of the images. Table IV summarizes the GAMM smoothing terms statistics and R^2 for each model.

The GAMM plots revealed that the tongue blade for [u̯] was lower when compared to [l] in each of the contexts. The analysis further revealed that the tongue body was lowered and retracted for [u̯] in the /i/ context, when compared against [l]. However, we did not observe any significant difference in tongue body or root between [l, u̯] for vocalic contexts [ɛ, a, ɔ], although the smooth always had a best-fit line that was higher for [u̯] compared to [l].

Individual comparisons confirmed that the general results we presented above captured the articulation of the majority of speakers. However, we did observe that for the onset lateral, BP1 showed variation in tongue height congruent with the following vowel, while BP2 showed a partial difference ([#la] was lower than [#lɛ, #lɔ], while [#li] was higher than [#lɛ, #lɔ]). As for the coda lateral, only BP2 showed differences based on vocalic environment: [iu̯#] was higher and more advanced than other contours, [ɛu̯#] was as advanced as [iu̯#] but not as high, [au̯#] was lower than other contours, and [ɔu̯#] was the most retracted. We also observed that for most speakers, there was more variance for the coda lateral as noted by larger confidence intervals. Figures 10 and 21 in the supplementary materials present individual comparisons. (See the supplementary material for individual comparisons in Figs. 10 and 21.)[1]

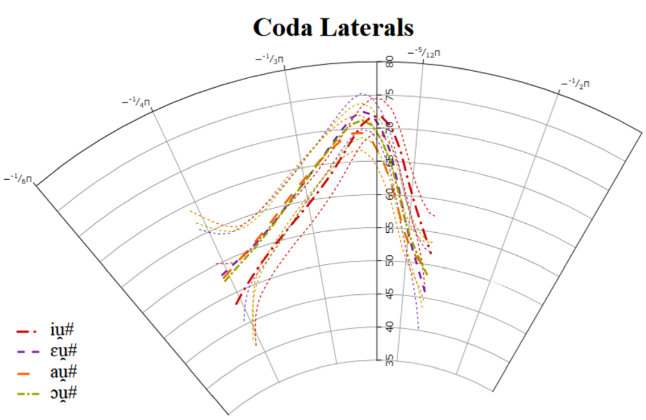

FIG. 4. (Color online) Results of the GAMM comparison of each of the laterals in coda position: /i/ (long dash dot), /ɛ/ (dash), /a/ (long dash), and /ɔ/ (dash dot). Thin dotted lines indicate the 95% confidence intervals. Tongue tip on the right.

In general, we found that speakers had slightly more retraction and raising of the tongue body in the case of the coda lateral, although this effect was not always significant. We also observed a lowered and retracted tongue tip in the case of the coda lateral when compared against the onset lateral. We also observed data that suggests the onset lateral does not undergo strong anticipatory coarticulation effects for most speakers. The exception to this is the palatalization effects on the lateral that the [i] environment had. This was observed by the non-significant smoothing terms for all the vocalic environments, except when the onset lateral was followed by [i]. More variation on tongue shapes were observed in the coda lateral, although we only found a significant effect when the coda lateral was preceded by [i], suggesting that constriction location and the posterior tongue has a relatively stable target.

2. Dynamic results

Figure 6 presents the GAMM results for each of the four models *x*- and *y* axis of the tongue tip/blade and the tongue body.

The model of the tongue body frontness revealed a significant effect for the smoothing condition of the coda lateral [$F(4.31, 5.24) = 12.14$, $p < 0.001$], but not the onset lateral ($p = 0.759$). The model R^2 was 0.612. The GAMM plot showed that the significant effect for the coda lateral, [u̯], was due to continual retraction of the tongue body. The tongue body movement for the onset lateral, [l], did not achieve significance because its position on the *x* axis remained relatively stable.

The model of the tongue tip/blade frontness showed a significant effect for the smoothing condition of the coda lateral [$F(5.67, 6.76) = 30.27$, $p < 0.001$] and the onset lateral [$F(3.59, 4.43) = 19.38$, $p < 0.001$]. The model R^2 was 0.635. The GAMM plot again revealed that the significant effect for the tongue tip of coda lateral, [u̯], was due to an initial retraction, followed by a fluctuation in *x* axis position. However, despite the fluctuation in position after the initial retraction, the *x* axis position remained more retracted for the coda lateral than the onset lateral. Again, there was no significant retraction for the onset lateral, [l], resulting in no significant effect.

The model of the tongue body height showed a significant effect for the smoothing condition of the coda lateral [$F(4.15, 50.8) = 20.97$, $p < 0.001$] and the onset lateral [$F(4.59, 5.59) = 21.90$, $p < 0.001$]. The model R^2 was 0.650. The GAMM plot revealed that the significant effect for the

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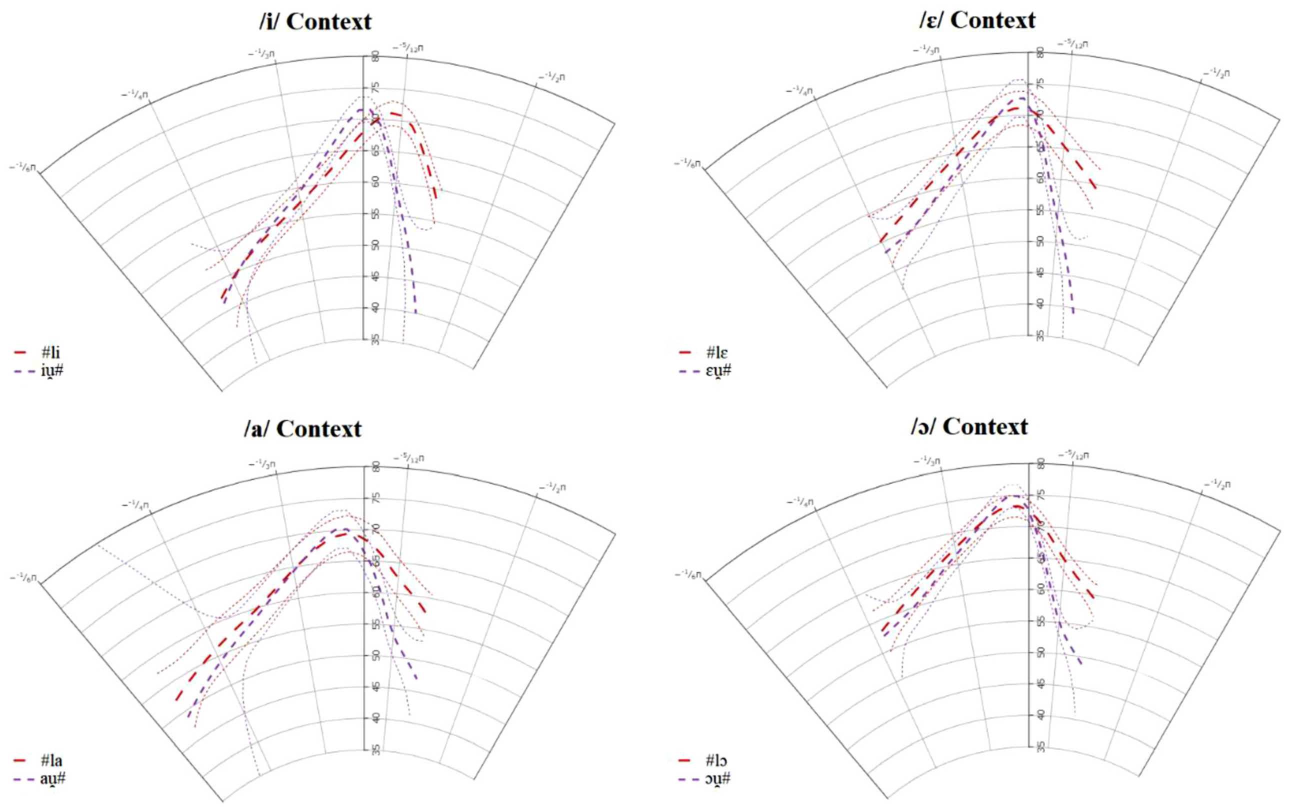

FIG. 5. (Color online) Comparison of the prevocalic (long dash) and postvocalic (dash) lateral in the contexts /i/ (top-left), /ɛ/ (top-right), /a/ (bottom-left), and /ɔ/ (bottom-right). Thin dotted lines indicate the 95% confidence intervals. Tongue tip on the right.

coda lateral was due to tongue body elevation, while the significant effect for the onset lateral was due to tongue body depression.

The model of the tongue tip/blade height showed a significant effect for the smoothing condition of the coda lateral [$F(5.26, 6.33) = 57.24$, $p < 0.001$], and the onset lateral [$F(4.92, 5.96) = 51.04$, $p < 0.001$]. The model R^2 was 0.718. Finally, the GAMM plot revealed that the significant effect for the coda lateral was due to lowering that leveled out at interval 7. The significant effect for the onset lateral was due to an increase in tongue tip height that occurred during intervals 6 and 7.

We observed that the onset lateral had slightly earlier maximum constriction achievement for the tongue body (interval 5) compared to the tongue tip (interval 6). For the onset lateral, there was a significant difference in tongue tip/blade lowering and retraction on the one hand and tongue body raising and retraction on the other hand. There is often a lag in achievement of the tongue body and tongue tip/blade constrictions for laterals (Gick *et al.*, 2006), and BP appears to have a slight difference between the two gestures. Gick *et al.* (2006) observed for several languages that, in the coda position, the tongue body retracts and achieves its target before the tongue tip. Our study shows a tongue body retraction and raising in the coda position, accompanied with loss of a tongue tip constriction for the coda lateral. This implies that positional effects may work in concert to trigger lateral vocalization by increasing dorsal retraction and weakening the tongue tip/blade gesture.

TABLE IV. Approximate significance of smooth terms and R^2 for each of the four models for /i, ɛ, a, and ɔ/ contexts.

		edf	Ref. df	F	p-value	R^2
	s(Theta)	2.85	3.229	0.289	0.603	
i	s(Theta): l	6.521	7.820	3.462	0.001	
	s(Theta): u̯	9.787	11.689	9.531	< 0.001	0.818
	s(Theta)	8.038	9.236	14.667	< 0.001	
ɛ	s(Theta): l	0.000	0.000	0.085	0.998	
	s(Theta): u̯	10.600	12.270	9.596	< 0.001	0.860
	s(Theta)	9.154	10.820	31.850	< 0.001	
a	s(Theta): l	0.000	0.000	0.163	0.998	
	s(Theta): u̯	9.673	11.520	13.282	< 0.001	0.870
	s(Theta)	8.284	9.524	14.402	< 0.001	
ɔ	s(Theta): l	0.000	0.000	0.121	0.999	
	s(Theta): u̯	7.708	9.074	5.772	< 0.001	0.816

III. BIOMECHANICAL SIMULATIONS

A. Methods

Our objective in constructing biomechanical–articulatory simulations of the BP laterals was to determine how onset and coda laterals differ in their lingual muscle activations. We used the ArtiSynth simulation framework (see Lloyd *et al.*, 2012) to conduct these simulations. The

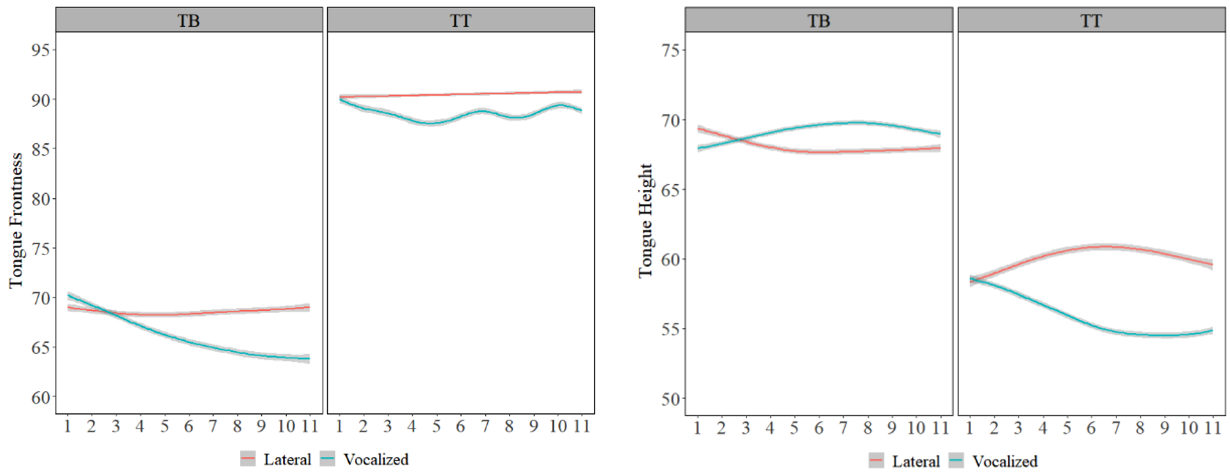

FIG. 6. (Color online) GAMM plots for the models of the tongue body (TB) and tongue tip/blade (TT) for tongue frontness (left) and tongue height (right). The x axis shows time intervals (each interval is 16.33 ms), with interval 6 indicating the point of maximum constriction. The y-axis shows r (the distance from the origin). The red line is the lateral and the blue line is the vocalized lateral. The gray ribbon represents the 95% confidence intervals.

different articulatory structures of the vocal tract are well represented in ArtiSynth (see Anderson *et al.*, 2017), and these have been used in numerous prior studies to examine speech articulatory biomechanics (e.g., Stavness *et al.*, 2012; Stavness *et al.*, 2013; Moisik and Gick, 2017; Gick *et al.*, 2017). For our purposes, we employ mainly the rigid skeletal framework of the vocal tract (specifically the maxillary complex, mandible, and hyoid bone) and the deformable, finite element model (FEM) of the tongue (modified as described in Dediu *et al.*, 2021).

To empirically inform the simulations, we used the ultrasound tongue contour data gathered in experiment 1 of the study. These data contain productions from six participants, each of whom produced six repetitions of two types of lateral (onset and coda) contextualized in words representing four different vowel contexts ([i, ɛ, a, ɔ]). After visual inspection, four samples were excluded because of failure of the tongue tracing algorithm to produce a sensible trace of the tongue contour. Altogether we used 284 ultrasound tongue contours as target data in the biomechanical simulations. Using MATLAB R2020b (The Mathworks Inc., 2020), we performed Procrustes superimposition registration on the ultrasound tongue contours to remove scale, rotation, and translation variation from the samples and to bring them into the ArtiSynth world space [see the supplementary material for the methods outlined in Dediu *et al.* (2021)].[1] In short, first we computed the participant-wise mean on just the tokens representing the [i] and [a] vowel contexts (we restricted the process in this way because initial experiments using all vowels to generate these mean contours resulted in too great a bias towards a low and back tongue posture because of the unbalanced set of vowel contexts comprising the data, with [ɛ, a, ɔ] contexts being relatively more open and back than the [i] context). We then registered these participant means to the ArtiSynth tongue contour, sampled roughly from the tongue tip to just above the tongue root (around where the foramen cecum would be located). Following mean registration, we then applied the resulting per-participant transformations to each participant's set of respective tongue contour tokens. We then imported these data into ArtiSynth.

In the ArtiSynth environment, we used an inverse tracking-controller (Stavness *et al.*, 2012) to estimate lingual muscle activation for each of the ultrasound tongue contour tokens in the dataset. Briefly, biomechanics and multi-body systems in general (Otten, 2003) can be studied from two perspectives: forward and inverse dynamics. In forward dynamics, one starts with (usually) known forces acting on a system and solves for kinematic properties (such as position or velocity) resulting from these forces. In inverse dynamics, one starts with known kinematics and estimates the forces required to produce this motion. In our case, we started with the known static posture of the tongue given by the ultrasound data (the known "motion") and used the inverse tracking-controller to solve the inverse dynamics problem. This allowed us to estimate muscle forces needed to attain the target posture from a given neutral starting point after an arbitrary amount of time. Each such simulation was set to be 0.3 s (roughly on the order of timing used in very slow speech) in duration and employed full backward Euler integration with an adaptive time step. We used seven tracking points, linking motion source points (i.e., fixed points on the nodes of the ArtiSynth tongue) to motion target points (i.e., sample points on the ultrasound tongue contours), which represented a good compromise between accuracy and computation time. Each inverse simulation simply used linear interpolation to move the target points from the original source point locations at 0.0 s (representing the neutral, resting position of the tongue) to their final ultrasound contour locations by the end of the simulation at 0.3 s (representing the lateral/vocalized-lateral target). In all cases, the weight of the l^2-norm regularization term in the inverse solver was set to be 1.0 to help resolve muscle redundancy.

Because the mechanical system is stiff and the tongue contour shapes in the ultrasound data often represent large and complex deformations, there was a considerable risk of simulation failure due to numerical instability arising (primarily) from element inversion. Given the narrow focus of our simulations on tongue shape and the limitation of our data to the midsagittal tongue contour, we decided to make several simplifications to the simulation objectives so as to better improve the simulation yield in the face of these challenging conditions. In particular, we decided to fix both the mandible and hyoid bone and avoided simulating collision between any of the bodies involved. Furthermore, we were not very aggressive with the parameterization of the target weighting of the inverse simulation, opting for a conservative strategy. In particular, we performed three batteries of simulations, varying w_{ttw}, the tongue target weight (TTW), with $w_{ttw} \in \{0.9, 1.0, 1.1\}$. The TTW parameter controls how much the inverse model will attempt to minimize the velocity tracking error of the motion targets, and we expected that the higher the weight, the more accurately the simulated tongue contour would approximate the original ultrasound tongue contour shape, but also the higher the risk of simulation failure. Altogether, 900 simulations (300 in each TTW category) were conducted, and, despite the widely varying ultrasound tongue contour shapes, no failed simulations occurred (see the supplementary material for illustrative videos of the tongue simulations).[1]

B. Results

We first consider the accuracy of the simulations by examining how close the ArtiSynth tongue contour gets to the registered contours of the ultrasound data using the root mean square error (RMSE) of the Euclidean distances between the source points (ArtiSynth tongue model nodes) and the target points (sample points on the ultrasound contours). Figure 7 shows the results grouped by lateral type across tongue target weights and vowels. The standard error is slightly larger in coda lateral cases than lateral ones. From these data, we estimated that the RMSE decreases at a rate of approximately -0.06 mm per unit increase in TTW. The vowel contexts for which the model performed the most poorly differ by lateral type category: in the "onset lateral" case, the [i] context presents the greatest difficulty; in the "coda lateral" case, it is the [a] context. Within a given combination of vowel context, TTW, and lateral type category, we find that the error is very consistent among tokens (representing different participants and their repetitions), with a token-wise mean standard error of 1.1×10^{-4} mm. The muscle activation estimates produced at each level of TTW are also highly intercorrelated (when performing pairwise correlations of the different TTW levels, we found mean $\rho = 0.99$, s.d. $\rho = 0.0097$).

Because of the findings that TTW only has a small influence on simulation accuracy and that the muscle activations are strongly correlated between TTW levels, we conducted our analysis of muscle activation by pooling these three simulation sets together (thus, all subsequent analysis is on all 900 simulations pooled together except where indicated). Lingual muscle activity—gauged by the maximum muscle fiber bundle activation level for each muscle—is displayed in Fig. 8. Part (A) of this figure shows maximum muscle activation by vowel and by lateral type [LAT = onset (lateral) context; VOC = coda (vocalized) context]. Part (B) shows a summary of the difference between mean maximum activation levels (across vowel qualities) of the two lateral types: a negative difference (blue bars) means that activation is higher in the onset (lateral) context; a positive difference (red bars) means that activation is higher in the coda (vocalized) context. With reference to Fig. 8(A), we see that muscle activations differ by vowel context (as would be expected), but these differences are fairly consistent across the lateral types. Most notable is that the [i] context places large demands on the medial/oblique (GGM) and posterior (GGP) fibers of the

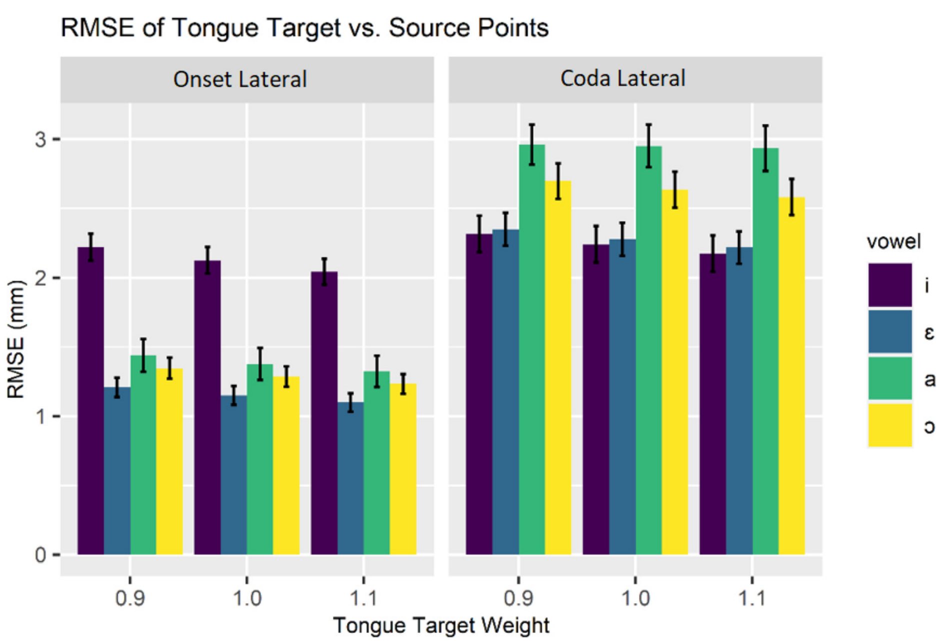

FIG. 7. (Color online) Error between simulation source points (ArtiSynth tongue model nodes) and target points (samples points on the ultrasound contours).

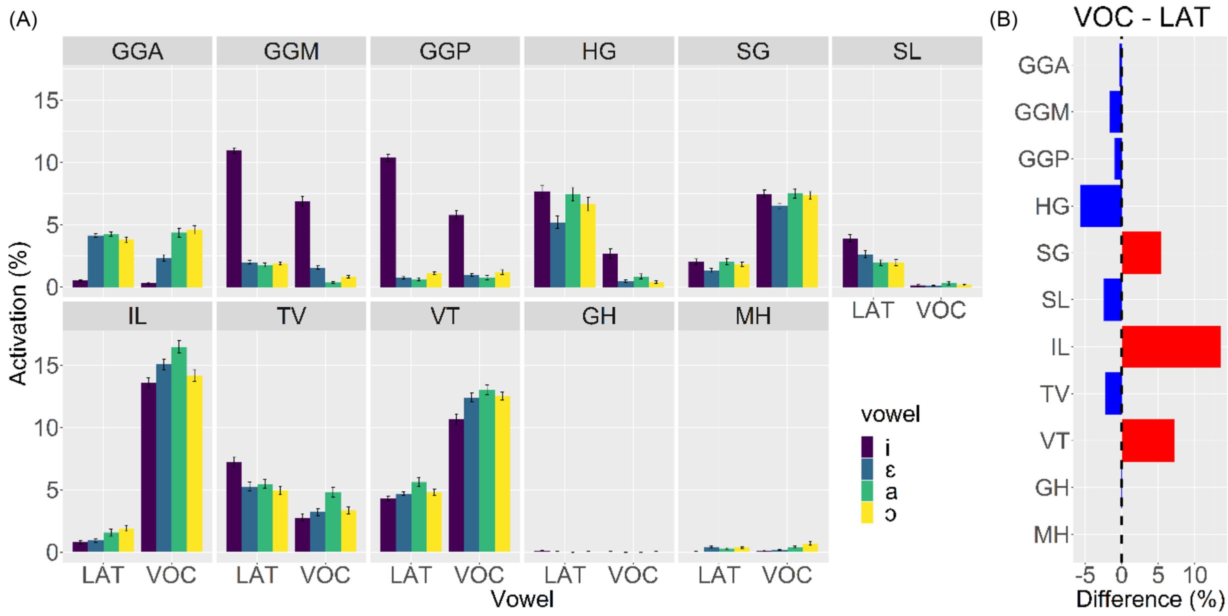

FIG. 8. (Color online) Maximum muscle activation (A) by lateral type [LAT = onset (lateral) context; VOC = coda (vocalized) context] and (B) across-vowel mean maximum muscle activation difference between types [coda (vocalized) activation minus onset (lateral) activation]. N.B.: Data are pooled by tongue target weight. GGA, genioglossus anterior; GGM, genioglossus medial; GGP, genioglossus posterior; HG, hyoglossus; SG, styloglossus; SL, superior longitudinal; IL, inferior longitudinal; TV, transverse; VT, vertical; GH, geniohyoid; MH, mylohyoid.

genioglossus, presumably for fronting of the posterior bulk of the tongue towards the palate in order to produce the stricture needed for the [i] vowel (see, e.g., Honda, 1996; Lulich and Cavar, 2019) as a coarticulatory effect on the laterals in this vowel context. With reference to Fig. 8(B), we see several differences across the intrinsic muscles. Most notable of which is the increased activity of the inferior longitudinal (IL) and vertical (VT) muscles in the coda (vocalized) context (positive difference/red bars). In this context, we also see a small decrease (negative difference/blue bars) in the case of the transverse (TV) and superior longitudinal (SL) muscles. Differences are also observed for the extrinsic muscles, especially styloglossus (SG), which is higher in the coda context (positive difference/red bar). The divisions of the genioglossus muscle (GGA, GGM, and GGP) and especially the hyoglossus (HG) are lower in the coda (vocalized) context (negative difference/blue bars).

Mm. 1. Biomechanical simulation of the onset lateral. This is a file of type "mp4" (193 KB).

Mm. 2. Biomechanical simulation of the onset lateral before /i/. This is a file of type "mp4" (189 KB).

Mm. 3. Biomechanical simulation of the coda lateral. This is a file of type "mp4" (187 KB).

Figure 9 shows GAMM-based smooths of the x ("frontness") and y ("height") coordinates of the midsagittal ArtiSynth tongue contours obtained for $w_{ttw} = 1.0$. (Some details of the GAMM specification are given in the caption of Fig. 9, but the purpose of this illustration is to help visualize the results of the biomechanical simulation, so we do not present all details of the GAMM specification and results here.) For the difference between lateral types (with a solid line indicating the onset/lateral context and a dashed line indicating the coda/vocalized context), we can consider the sizeable difference in IL activation to be associated with shortening the tongue longitudinally and withdrawing the anterior portion of the tongue (where the tip and blade are located) away from the alveolar ridge region as part of a ventroflexion motion (see Sanders and Mu, 2013), reflective of the vocalized nature of these productions. Also,

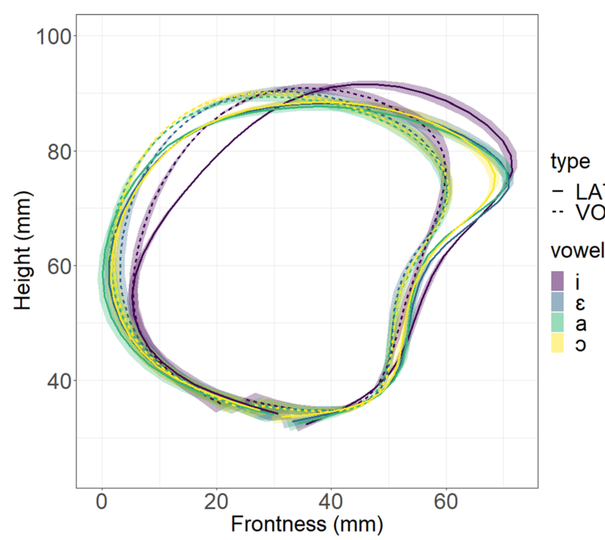

FIG. 9. (Color online) GAMM-smooth–derived shape of the ArtiSynth tongue contour of the two lateral types [LAT = onset (lateral) context; VOC = coda (vocalized) context] for $w_{ttw} = 1.0$. Tongue tip is on the right. N.B.: The confidence intervals here are based on a GAMM constructed with fixed effect smooths (and associated parametric terms) for vowel quality and lateral type and with random smooths for speaker and repetition.

consistent with this is the increased use of the VT muscles, which broadly act to flatten the tongue, and the reduction of SL, which will also reduce the elevation of the front of the tongue (particularly the tip). There is a preference for intrinsic vs extrinsic activation in the coda context, which may reflect the constraining influence of vowel context to maintain relative positioning of the lingual posture, with some remaining freedom for the tongue to alter its shape via the intrinsic muscles. The extrinsic muscles still vary by lateral type, with a tendency for the tongue to presumably be more elevated and retracted toward the velum in the coda context. This is indicated by the increase in SG, which can act to raise the body toward the uvula, and concomitant decrease in all the genioglossus bundles (GGA, GGM, and GGP), which act to increase the distance between the tongue and the soft palate, and a decrease in HG, which could excessively lower and retract the tongue into the hypopharyngeal region (Honda, 1996).

IV. DISCUSSION AND CONCLUSION

The ultrasound results revealed that in BP, the onset lateral uses the tongue tip to form a constriction in the alveolar region, while the posterior tongue body forms a coordinated second constriction in the uvular–pharyngeal or velar area. The biomechanical simulations indicate manipulation of the tongue tip in the vocalization process relies most heavily on retracting the tip, which is most directly a consequence of increased inferior longitudinal activation with support from styloglossus and reduction of superior longitudinal and genioglossus medial and posterior activity. Suppression of hyoglossus activity in combination with some styloglossus activity may help with posterior tongue body raising (towards the uvula), but the inferior longitudinal muscle may also play a role here, causing the tongue body to bulge hydrostatically in its transverse dimensions as it undergoes axial shortening.

The ultrasound data confirmed that the onset lateral undergoes secondary palatalization when an /i/ vowel follows it. This involved fronting and raising of the tongue body for some speakers and for other speakers, it involved only fronting with little or no tongue body raising. The biomechanical model revealed substantially higher activation of the medial and posterior genioglossus muscle in the /i/ context and indicates that activation is a key difference between vowel contexts. In coda position, we observed an absent tongue tip gesture and a more retracted and raised tongue body. However, we did observe some degree of tongue tip advancement in the ultrasound. The biomechanical models further implicated reduced genioglossus medial and posterior muscle activation and increased inferior longitudinal muscle activation as critical for the observed differences. Retraction towards the velum is most probably due to increased styloglossus activation in the vocalized lateral. The findings support Proctor's (2011) generalization that laterals are composed of a tongue body and tongue tip gesture (although there may be coupling between the two articulators) and that the process of vocalization is the product of lenition of the tongue tip gesture. However, the lenition is more of an active movement away from the palate, rather than a weakening of the movement towards the palate. This would suggest that lenition, while conceived as a weakening or loss of a gesture, can be implemented actively. However, given the limitations of the model, we suggest a cautious interpretation of this possibility.

We hypothesize that a series of positional phonetic effects work in conjunction to facilitate vocalization. Increased antagonistic muscle activation (i.e., activation of muscle responsible for retraction and raising) and reduced activation of muscles implicated in tongue tip/blade advancement, coupled with the phasing of the gestures with the preceding vowel, results in more tongue body movement and reduced tongue tip/blade movement. In essence, the apical gesture is weakened by the phonetic effects of lenition in the coda position, which is, somewhat ironically, biomechanically implemented by the strengthening of intrinsic muscle action (especially of the inferior longitudinal muscle), while additional muscular load is put on the styloglossus resulting in a vocalized lateral. This explanation can also account for differences across speakers and languages in lateral vocalization. For example, Morén (2006) describes the vocalized lateral in Serbian as phonetically similar to [ɔ], which contrasts other languages where vocalized laterals are often described as [w], [u], or [u̯]. Our research suggests that phonetic differences in the realization of the lateral may play a significant role in how patterns of lenition interact with the muscular activation and as such, produce a phonetically different vocalized lateral. However, this is a direction for further research.

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[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0012186 for individual GAMM plots and statistical results of the onset and coda laterals for BP1–BP6.

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