Articulatory-acoustic relations in the production of alveolar and palatal lateral sounds in Brazilian Portuguese

Sherman Charles, and Steven M. Lulich

Citation: [The Journal of the Acoustical Society of America](#) **145**, 3269 (2019); doi: 10.1121/1.5109565

View online: <https://doi.org/10.1121/1.5109565>

View Table of Contents: <https://asa.scitation.org/toc/jas/145/6>

Published by the [Acoustical Society of America](#)

ARTICLES YOU MAY BE INTERESTED IN

[Specificity and generalization in perceptual adaptation to accented speech](#)

The Journal of the Acoustical Society of America **145**, 3382 (2019); <https://doi.org/10.1121/1.5110302>

[Acoustic correlates of female confidence: A production and comprehension study](#)

The Journal of the Acoustical Society of America **145**, 3410 (2019); <https://doi.org/10.1121/1.5109661>

[Structured phonetic variation facilitates talker identification](#)

The Journal of the Acoustical Society of America **145**, EL469 (2019); <https://doi.org/10.1121/1.5100166>

[Partial compensation to delayed auditory feedback: An analysis of syllable duration](#)

The Journal of the Acoustical Society of America **145**, 3531 (2019); <https://doi.org/10.1121/1.5111758>

[Masculine toughness and the categorical perception of onset sibilant clusters](#)

The Journal of the Acoustical Society of America **145**, EL574 (2019); <https://doi.org/10.1121/1.5113566>

[Neighborhood-conditioned phonetic enhancement of an allophonic vowel split](#)

The Journal of the Acoustical Society of America **145**, 3675 (2019); <https://doi.org/10.1121/1.5113582>

Articulatory-acoustic relations in the production of alveolar and palatal lateral sounds in Brazilian Portuguese

Sherman Charles and Steven M. Lulich^{a)}

Department of Speech and Hearing Sciences, Indiana University, Bloomington, Indiana 47405, USA

(Received 8 August 2018; revised 9 May 2019; accepted 9 May 2019; published online 5 June 2019)

Lateral approximant speech sounds are notoriously difficult to measure and describe due to their complex articulation and acoustics. This has prevented researchers from reaching a unifying description of the articulatory and acoustic characteristics of laterals. This paper examines articulatory and acoustic properties of Brazilian Portuguese alveolar and palatal lateral approximants (/l/ and /ʎ/) produced by six native speakers. The methodology for obtaining vocal tract area functions was based on three-dimensional/four-dimensional (3D/4D) ultrasound recordings and 3D digitized palatal impressions with simultaneously recorded audio signals. Area functions were used to calculate transfer function spectra, and predicted formant and anti-resonance frequencies were compared with the acoustic recordings. Mean absolute error in formant frequency prediction was 4% with a Pearson correlation of $r = 0.987$. Findings suggest anti-resonances from the interdental channels are less important than a prominent anti-resonance from the supralingual cavity but can become important in asymmetrical articulations. The use of 3D/4D ultrasound to study articulatory-acoustic relations is promising, but significant limitations remain and future work is needed to make better use of 3D/4D ultrasound data, e.g., by combining it with magnetic resonance imaging.

© 2019 Acoustical Society of America. <https://doi.org/10.1121/1.5109565>

[ZZ]

Pages: 3269–3288

I. INTRODUCTION

Lateral approximants are a class of speech sounds that have notoriously resisted articulatory and acoustic characterization. They are comprised of highly variable, complex, multifaceted, and often asymmetrical articulation that involves areas of the vocal tract on and away from the midline (Barberena *et al.*, 2014; Ladefoged and Maddieson, 1996; Narayanan *et al.*, 1997; Proctor, 2009, 2011). Lateral approximants are formed by asymmetrically raising one side of the tongue or symmetrically raising both sides of the tongue to contact the palate, while diverting airflow through one or two interdental channels. In symmetric articulations, two interdental channels are formed, and each is bounded by the side of the tongue, the inner surface of the cheek, and the upper and lower teeth. These channels originate posteriorly as side-branches from the main oral cavity at a point where the sides of the tongue are not in contact with the palate. They merge at the front to form an anterior cavity bounded by the upper and lower lips. Simultaneously, contact between the raised tongue blade and the palate (e.g., at the alveolar ridge) occludes the main oral cavity, which forms a supralingual cavity bounded by the raised tongue blade, the palate, and the sides of the tongue. Examples of symmetrical articulations have been reported in a variety of languages, including Tamil (McDonough and Johnson, 1997), American English (Zhou *et al.*, 2010), European Portuguese (Teixeira *et al.*, 2012b), Brazilian Portuguese (Charles and Lulich, 2018), and Korean (Hwang *et al.*, 2019). In asymmetric articulations, one interdental channel is formed in the

way described for symmetric articulations, while the other interdental channel remains connected to the oral cavity. This second interdental channel does not originate as a side-branch, but acts to extend and widen the oral cavity. With asymmetric articulations, the tongue blade is not raised to form a complete occlusion anteriorly. Asymmetric articulations have been less frequently reported, but examples have been found in American English (Recasens, 1996), Tamil (Narayanan *et al.*, 1999), and Korean (Hwang *et al.*, 2019), for instance.

The presence of interdental channels in parallel with the oral cavity gives rise to additional resonances and anti-resonances in the acoustic output of lateral speech sound production. These have been the subject of many studies in several languages such as American English (Bangayan *et al.*, 1996; Stevens, 1998; Zhang *et al.*, 2003; Zhang and Espy-Wilson, 2004; Zhou *et al.*, 2010), European Portuguese (Teixeira *et al.*, 2012b), Tamil (Narayanan and Kaun, 1999; Narayanan *et al.*, 1999), and Russian (Fant, 1960). It is frequently claimed that the additional resonances are clustered between the third and fifth formants (F_3 and F_5) and the anti-resonances, which vary in number depending on the specific geometry of the vocal tract, are located between approximately 2000 and 5000 Hz (Fant, 1960; Narayanan *et al.*, 1999; Stevens, 1998; Tabain *et al.*, 2016; Teixeira *et al.*, 2012b; Zhang and Espy-Wilson, 2004; Zhou *et al.*, 2010). It has been hypothesized that these additional resonances and anti-resonances result in raising the frequency of F_3 , which is possibly a primary acoustic correlate of laterality at the phonetics–phonology interface (Espy-Wilson, 1992; Fant, 1960; Ladefoged and Maddieson, 1996; Stevens, 1998).

^{a)}Electronic mail: slulich@indiana.edu

While it is generally accepted that lateral approximants are produced with (1) acoustic wave propagation through lateral interdental channels, (2) a side-branch formed by the occlusion of the tongue blade and palate (also called the supralingual cavity), (3) anti-resonances in the range of frequencies between approximately 2000 and 5000 Hz, and (4) a raised third formant frequency, these conclusions have been largely based on a small set of studies and an equally small set of speakers. In nearly 60 years since the publication of Fant's *Acoustic Theory of Speech Production*, the major studies of lateral articulatory-acoustic relations have been those by Zhang *et al.* (2003), Zhang and Espy-Wilson (2004), Zhou (2009), and Zhou *et al.* (2010). Important three-dimensional (3D) magnetic resonance imaging (MRI) studies of lateral articulations include Story *et al.* (1996), Narayanan *et al.* (1997), and Martins *et al.* (2008), although none of these studies attempted to determine how formants and anti-resonances might be related to specific vocal tract cavities. Stevens (1998; drawing principally on articulatory data from Fant, 1960, and Narayanan *et al.*, 1997) provided an analysis of lateral articulatory-acoustic relations that included both source and filter characteristics and placed upper and lower bounds on some vocal tract dimensions.

The two most important models of lateral articulatory-acoustic relationships have been those proposed by Fant (1960) and Stevens (1998). A third model described by Johnson (2012) has become popular, and all three models were recently compared and critically examined by Tabain *et al.* (2016). Fant and Stevens both propose that the first formant (F_1) is a Helmholtz resonance in lateral approximants, but they differ in their opinions about which cavities are most closely affiliated with F_2 and F_3 . Johnson, on the other hand, proposes a schwa-like model in which F_1 is not a Helmholtz resonance, and all three low formants (F_1, F_2, F_3) are nearly quarter-wavelength resonances of the entire vocal tract, which are subject to perturbations due to non-uniformities in the vocal tract area function. All three agree that anti-resonances are produced by the supralingual cavity near F_3 or higher, and Johnson proposes additional anti-resonances due to asymmetry between two interdental channels.

Detailed articulatory-acoustic analyses have been conducted for American English “dark” and “light” laterals in the paired studies of Zhang *et al.* (2003) and Zhang and Espy-Wilson (2004), and Zhou (2009) and Zhou *et al.* (2010). Each of these studies used 3D MRI data from one male speaker (Fant, 1960, also used data from one male speaker in his x-ray study). While Fant admitted that his area functions for the supralingual cavity and interdental channels were “pure guesswork” (Fant, 1960, p. 165) due to limitations of the articulatory data at his disposal, and Stevens’ model was based on general principles (rather than speaker-specific articulatory data), the studies by Zhang, Zhou, and colleagues provide the first detailed look at the acoustic consequences of individual speakers’ 3D vocal tract configurations in American English. These studies focus especially on anti-resonances, identifying both the supralingual cavity and asymmetrical interdental channels as the causes of anti-resonances in the frequency range between approximately 2000 and 5000 Hz. In addition,

Zhou (2009) and Zhou *et al.* (2010) identified an anti-resonance at approximately 4500 Hz due to a cross-mode just posterior to the split into three separate channels (the interdental channels and the supralingual cavity). None of these studies commented on formant-cavity affiliations.

Articulatory-acoustic analyses of dental and retroflex laterals in Tamil were presented in a series of studies by Narayanan and colleagues (Narayanan and Kaun, 1999; Narayanan *et al.*, 1996; Narayanan *et al.*, 1999). These studies used MRI, static palatography, and electromagnetic midsagittal articulography (EMMA) data from one male speaker. In their publications they commented on formant-cavity affiliations as well as an anti-resonance introduced by the supralingual cavity, but they did not consider anti-resonances due to the interdental channels.

A number of articulatory and acoustic studies of laterals in European Portuguese have been carried out in recent years, including Martins *et al.* (2008), Martins *et al.* (2010), Oliveira *et al.* (2011), Teixeira *et al.* (2012a), Teixeira *et al.* (2012b), and Silva *et al.* (2014). All of these studies used MRI data from between one and seven subjects. Only the study by Teixeira *et al.* (2012b) measured area functions and calculated transfer functions based on their MRI data. In that study, the alveolar and palatal laterals were investigated using data from four speakers (two males, two females). They did not comment on formant-cavity affiliations, but identified an anti-resonance due to the interdental channels as well as a second, more prominent resonance due to the supralingual cavity.

Additional phonetic studies of lateral approximants include the articulatory studies of Giles and Moll (1975); Narayanan *et al.* (1997); Sproat and Fujimura (1993), Stone *et al.* (1992), Story *et al.* (1996), and Proctor (2011), and the acoustic studies of Dalston (1975), Espy-Wilson (1989, 1992), Lisker (1957), Sproat and Fujimura (1993), and Tabain *et al.* (2016). Yet, articulatory and acoustic studies carried out in independence of each other cannot definitively identify formant-cavity affiliations, sources of anti-resonances, and other aspects of articulatory-acoustic relations.

Considering all of these studies together, substantial attention has been given to articulatory-acoustic relations in American English light and dark laterals. Substantially less attention has been given to articulatory-acoustic relations in other kinds of laterals, including dental and retroflex laterals in Tamil, alveolar and palatal laterals in European Portuguese, and velarized and palatalized laterals in Russian. The present study adds to this list by investigating alveolar and palatal laterals in Brazilian Portuguese.

Brazilian Portuguese is spoken by approximately 200×10^6 people and represents the largest Portuguese-speaking population in the world. Several dialects exist within Brazil, and differ in lateral sound pronunciation. For instance, the historically palatal lateral has been vocalized to the glide [j] in some dialects, and the alveolar lateral is vocalized to the glide [w] in some contexts such as syllable final position. In non-vocalizing dialects, the laterals of Brazilian Portuguese are similar to those of European Portuguese. The articulatory properties of Brazilian Portuguese alveolar and palatal laterals were recently described in a study using

three-dimensional/four-dimensional (3D/4D) ultrasound and digitized palate impressions from one male speaker (Charles and Lulich, 2018).

The goal of the current study is to examine articulatory-acoustic relations in the production of phonologically contrastive alveolar [l] and palatal [ʎ] lateral sounds in Brazilian Portuguese (Azevedo, 2005; Barbosa and Albano, 2004). 3D articulatory data were acquired using 3D/4D ultrasound and digitized palate impressions. In contrast to prior studies using MRI, this allowed tongue surface shapes to be imaged during running speech produced in the upright position. The focus of this study is on (1) describing alveolar and palatal lateral articulations in a sample of six speakers (three males, three females), (2) describing the acoustic properties of these laterals, and (3) investigating articulatory-acoustic relations in each of the laterals produced by each of the speakers. With regard to articulatory-acoustic relations, we focus both on determining formant-cavity affiliations and identifying the sources of anti-resonances.

II. ARTICULATION OF BRAZILIAN PORTUGUESE LATERALS

A. Method

1. Subjects and stimuli

Seven subjects participated in this study, including the subject reported on in Charles and Lulich (2018; speaker 1) and an additional three males and three females. The ultrasound image quality for one of the male speakers was poor, and this subject (speaker 7) was therefore excluded from further analysis. The remaining six subjects (speakers 1–6; three males, three females) were all native speakers of the Paulistano dialect of Brazilian Portuguese from the state of São Paulo, Brazil.¹ All six subjects were fluent speakers of American English as a second language and reported no history of speech, language, or hearing disorders. The subjects were 23–31 years old (Table I), and speakers 1 and 2 are brothers.

The stimuli consisted of six target words,² together with a number of distracter words embedded within the carrier phrase “*Eu digo ____ para você*” “/ew dʒigu ____ parə vose/”³ “I say ____ for you.” In Brazilian Portuguese phonology, minimal pair (or near minimal pair) contrasts between these sounds are largely limited to syllable initial and intervocalic positions before non-front vowels (cf. Azevedo, 2005; de Oliveira, 1983; Ferreira, 1975).⁴ We

TABLE I. Demographic and recording information about the subjects. Ultrasound voxel dimensions are given in millimeters (mm) in the anterior-posterior (AP), medial-lateral (ML), and superior-inferior (SI) directions. Frame rates (FR) are given in frames per second (fps).

Speaker	Sex	Age	AP	ML	SI	FR
s1	M	25	1.01	0.96	0.48	14.82
s2	M	23	0.81	0.93	0.45	18.18
s3	M	23	0.82	0.79	0.39	14.40
s4	F	28	0.77	0.89	0.39	17.77
s5	F	28	0.67	0.74	0.34	16.81
s6	F	31	0.77	0.88	0.39	18.29

therefore included as stimuli only words with intervocalic laterals surrounded by non-front vowels. In addition, we included the distractor words *paia* /pajə/ “boring,” for comparison with the palatal lateral, and *barra* /bahə/ “bar,” to estimate vocal tract lengths (see details in Sec. III A 2). In Brazilian Portuguese the orthographic “rr” has a variety of pronunciations, but it is represented as /h/ here to reflect the pronunciation of the speakers in this study as a glottal fricative.

The stimuli were displayed one sentence at a time on a computer monitor from which the subjects read while seated in a double-walled sound attenuating booth. Stimulus order was randomized in each of three blocks, resulting in a total of three readings of each target word. Speakers 1, 2, 4, 5, and 6 completed the entire experiment, but speaker 3 withdrew from the experiment approximately halfway through the second block due to fatigue. The list of target words is provided in Table II.

2. Data collection

Lingual articulation data were recorded with a Philips EPIQ-7G ultrasound system and a Philips xMatrix x6–1 digital 3D/4D transducer (Bothell, WA; Lulich et al., 2018). The ultrasound probe was stabilized under the jaw with a headset from Articulate Instruments (Edinburgh, UK; Scobbie et al., 2008). Recordings consisted of a sequence of 3D wedge-shaped volumetric images of the tongue in a stable location relative to the head. Images captured the majority of the tongue surface at frame rates and voxel dimensions (resolution) reported in Table I. In addition, a palate impression was made with dental alginate and digitized using a NextEngine Desktop 3D laser scanner (Santa Monica, CA). The digitized palate object was manually registered with the ultrasound image data as described by Charles and Lulich (2018) and sketched in Appendix A.

Audio signals were recorded with a SHURE KSM32 directional dynamic microphone (Niles, IL) placed roughly one-half meter away from the subject. The sampling rate was 48 kHz and the recordings were made simultaneously with the ultrasound recordings. Profile video from the subject’s right side was recorded simultaneously with a Logitech C920HD Pro webcam (Lausanne, Switzerland). Audio and video recordings were synchronized with the ultrasound recordings using the method described by Lulich et al. (2018).

3. Analyses

Articulatory data were analyzed with a custom-made toolbox⁵ for MATLAB (The MathWorks, 2018). The toolbox facilitates 3D reconstruction of the tongue surface by manually segmenting coronal and sagittal slices at regular

TABLE II. Target stimuli written orthographically with phonemic transcription and English translation.

Alveolar lateral	Palatal lateral
<i>pala</i> [palə] “visor”	<i>palha</i> [paʎə] “straw”
<i>halo</i> [alu] “halo”	<i>alho</i> [aʎu] “garlic”
<i>galo</i> [galu] “rooster”	<i>galho</i> [gaʎu] “branch”

intervals to form a grid defined over the surface of the tongue. This process and the errors associated with it are sketched in [Appendix A](#), and described in greater detail in [Charles and Lulich \(2018\)](#) and references therein. The first author (S.C.) performed the manual segmentation. The grid is linearly interpolated to create the complete surface. This process was completed for the ultrasound image frame that coincided with the middle of the target lateral sound. Figure 1 shows example tongue surface reconstructions for both the alveolar lateral and palatal lateral produced by speaker 1, together with the registered digitized palate impression. (An example video of tongue surface movement relative to the palate is available for the word *pala* produced by speaker 1 in the supplementary material.⁶)

The articulatory data were visualized primarily in two ways: first, as a series of ultrasound images in the midsagittal plane and several coronal planes (Figs. 2 and 3); second, as a novel type of image that we refer to as “ultrasound-palatography” (or UPG, paralleling the abbreviation of electropalatography, EPG), in which a contour plot of the palate is superimposed on a color map that indicates the vertical distance from the palate to the tongue surface (Fig. 4). Although there were up to nine instances of the alveolar lateral and up to nine instances of the palatal lateral for each speaker (speaker 3 produced five rather than nine instances each), the articulatory results presented here are based primarily on only one alveolar lateral and one palatal lateral for each speaker in the words *pala* and *palha*. These representative tokens were selected on the basis of ultrasound image quality and how closely the ultrasound frame aligned with the temporal middle of the lateral.

Figures 5 and 6 show the variability of all the /l/ and /ʎ/ tokens in midsagittal, parasagittal, and coronal planes. The parasagittal planes were chosen to be just medial to the tooth that formed the posterior end of the longer interdental channel. The coronal plane was chosen to be just posterior to the same tooth. Inspection of Figs. 5 and 6 reveals the degree of consistency in the articulation of both lateral sounds for each speaker, and hence the degree to which any single /l/ or /ʎ/ token can be considered representative of the rest. For each speaker, the standard deviation of the tongue contours in each of the three planes was calculated, and the mean and maximum values are reported in Table III. The number of tokens produced symmetrically (i.e., with two interdental channels and a supralingual occlusion) and asymmetrically

(i.e., with one interdental channel and no supralingual occlusion) by each speaker are given in Table IV.

B. Results

1. Palatal laterals

Midsagittal and coronal images of the palatal lateral produced by each speaker are shown in Fig. 2. In each midsagittal image the tongue tip is to the right and the tongue root is to the left. The ultrasound image is displayed with the tongue surface outlined by a thin line, the palate surface shown as a thick line, and the locations of the five coronal images are shown as vertical lines. The tongue surface and palate surface are similarly indicated in each coronal image, along with a single vertical line indicating the location of the midsagittal plane. Each midsagittal and coronal image also includes a horizontal white bar in the lower left corner, indicating a distance of 1 cm. Among the coronal images, those near the top of Fig. 2 are more posterior, and those near the bottom of the figure are more anterior. Each column of images represents the palatal lateral produced by one speaker.

All six speakers produce the palatal lateral with the tongue body raised and fronted so that it nearly touches the hard palate in the midsagittal plane. The anteriority of tongue tip contact with the palate is variable with speaker 2 exhibiting relatively posterior contact and the remaining speakers exhibiting more anterior contact. Tongue-palate contact is clearly asymmetrical in speaker 5, and less clearly in speaker 6 with only one side of the tongue making contact with the palate anteriorly; for this reason, a lingual occlusion is not visible in the midsagittal plane. Tongue-palate contact is symmetrical for the remaining speakers, resulting in two interdental channels in addition to the supralingual cavity, which is closed by the anterior occlusion of the tongue tip against the palate.

Speakers 4–6 show a gap between the tongue surface and the palate at more posterior locations. At these locations the interdental spaces remain part of the main oral cavity, and become separate side-branches only at more anterior locations where the tongue and the palate come into contact. For speakers 1–3, tongue-palate contact even in the most posterior coronal images indicates that the interdental channels are disconnected from the main oral cavity here, and must connect more posteriorly. Speakers 1–3 must therefore have longer interdental channels than speakers 4–6. Speaker 5 never closes the gap on one

FIG. 1. 3D tongue (dark gray) and palate (transparent) surfaces for the alveolar lateral (left) and palatal lateral (right) as produced by speaker 1.

FIG. 2. Midsagittal and coronal images of the palatal lateral /k/ produced by six speakers. The top row displays a single midsagittal plane during a palatal lateral for each speaker. Rows 2–6 display coronal images at five locations of the same sound displayed in row 1. Thick black lines indicate the palate surface and thin dotted black lines indicate the traced tongue surface. Vertical lines in the midsagittal images indicate locations of coronal images, and vertical lines in the coronal images indicate the midsagittal plane. A white horizontal bar in the lower left corner of each image indicates a distance of 1 cm. Major articulatory features that are made visible in these images are the shape and size of the supralingual cavity, posterior openings of the interdental channels, and symmetric or asymmetric articulation of the palatal lateral.

side (a result of the asymmetrical articulation) and therefore has only one interdental channel in addition to the supralingual cavity, which is not closed anteriorly by an anterior occlusion.

Speaker 6 produced a palate impression that extends more posterior than those of the remaining speakers. For this reason, the most posterior coronal images show part of the tongue root, which is deeply grooved; the most posterior coronal images for the remaining speakers show only the tongue dorsum rather than the root. The advanced tongue root during palatal lateral production evidenced by speaker 6 is consistent with the

proposal by Cavar *et al.* (2017) and Lulich *et al.* (2017a) that palatal articulations require tongue root advancement. These findings support the observation made by Tabain and Beare (2018) that palatal consonants in Arrernte have a more advanced position for the back portion of the tongue.

2. Alveolar laterals

Midsagittal and coronal images of the alveolar lateral are shown in Fig. 3. All six speakers produce the

FIG. 3. Midsagittal and coronal images of the alveolar lateral /l/ produced by six speakers. The top row displays a single midsagittal plane during an alveolar lateral for each speaker. Rows 2–6 display coronal images at five locations of the same sound displayed in row 1. Thick black lines indicate the palate surface and thin dotted black lines indicate the traced tongue surface. Vertical lines in the midsagittal images indicate locations of coronal images, and vertical lines in the coronal images indicate the midsagittal plane. A white horizontal bar in the lower left corner of each image indicates a distance of 1 cm. Major articulatory features that are made visible in these images are the shape and size of the supralingual cavity, posterior openings of the interdental channels, and symmetric or asymmetric articulation of the alveolar lateral.

alveolar lateral with the tongue body lowered and retracted and the tongue tip raised toward the palate. There is a mid-line groove in the tongue blade for speakers 1, 2, and 4, all of whom have symmetrical tongue-palate contact. Speakers 3, 5, and 6 have asymmetrical tongue-palate contact. Interestingly, the side of the tongue that is lowered is different in the alveolar and palatal laterals produced by speaker 5.

All six speakers show a gap between the tongue surface and the palate at more posterior locations, indicating generally shorter interdental channels in the alveolar lateral than

in the palatal lateral. While speaker 5 closes this gap on both sides in the most anterior coronal image, speakers 3 and 6 never close this gap on one side. Although speaker 5 is asymmetrical, there is a complete anterior occlusion and thus a closure of the gap between tongue and palate. Therefore, while speakers 1, 2, 4, and 5 have two interdental channels in addition to the supralingual cavity, which is closed by the anterior occlusion of the tongue tip against the palate, speakers 3 and 6 have only one interdental channel in addition to a supralingual cavity that is not closed by an anterior occlusion.

FIG. 4. UPG images of the palatal and alveolar laterals produced by six speakers. Similar to a topographic map, these images display the height of the palate with black lines, whereas height of the tongue relative to the palate is indicated by color. Dark blue indicates contact between the tongue and palate, and dark red indicates distance between the tongue and the palate (in mm). Horizontal black bars represent a distance of 1 cm.

3. UPG

UPG images for both palatal and alveolar laterals are shown in Fig. 4 for all six speakers. The black lines form a

contour map of the palate with each line separated vertically by 0.5 cm. The superimposed color map shows the vertical distance between the tongue surface and the palate. The color legend is not uniform across the 12 UPG images but,

FIG. 5. Midsagittal, coronal, and parasagittal images of the palatal lateral /k/ produced by six speakers. Vertical lines in the midsagittal and parasagittal images indicate the location of the coronal image plane, whereas vertical lines in the coronal plane indicate the locations of the midsagittal and parasagittal planes. The gray lines show the palate surface and the black lines show tongue contours for each token. The horizontal distance bar in each of the coronal images represents 1 cm.

in general, a more red color indicates a greater distance between the tongue and palate while a more blue color indicates a smaller distance or even an occlusion. A horizontal black line near the bottom of each UPG indicates a distance of 1 cm. Generally, the distance between the tongue and the palate is greater in the alveolar laterals than in the palatal laterals, and there is a higher rate of asymmetrical articulations in the alveolar laterals.

For the palatal laterals, contact between the sides of the tongue and the sides of the palate is relatively uniform in speakers 1 all the way to the most posterior reaches of the UPG data, indicating that the interdental channels connect with the main oral cavity even more posterior than this. Speakers 2 and 3 are similar, but with some evidence of a gap forming (indicated by a lighter color) between the tongue and palate at the most posterior reaches of the UPG data. In contrast, the symmetrical articulation by speaker 4 clearly shows a gap forming (indicated by a lighter color) between the tongue and palate, while the asymmetrical articulations of speakers 5 and 6 clearly show no occlusion along the right side of the oral cavity and a

FIG. 6. Midsagittal, coronal, and parasagittal images of the alveolar lateral /l/ produced by six speakers. Vertical lines in the midsagittal and parasagittal images indicate the location of the coronal image plane, whereas vertical lines in the coronal plane indicate the locations of the midsagittal and parasagittal planes. The gray lines show the palate surface, and the black lines show tongue contours for each token. The horizontal distance bar in each of the coronal images represents 1 cm.

gap forming between the tongue and palate on the left side at the posterior end of the oral cavity.

For the alveolar laterals, similar conclusions about tongue-palate contact can be drawn. Speaker 1 shows formation of a slight gap along the posterior half of the oral cavity, while symmetrical articulations by speakers 2 and 4 show clear posterior gap formations. Asymmetrical articulations by speakers 3 and 6 show a gap forming on the left side at the posterior end of the oral cavity, along with a clear lack of occlusion along the right side. The asymmetrical articulation by speaker 5 is more complex with a gap forming slightly more anteriorly on the left side than on the right side.

4. Within-speaker variability

The within-speaker variability is qualitatively small for all subjects. Table III displays the mean and maximum within-plane standard deviations of each token produced by each speaker in midsagittal, coronal, and parasagittal planes. The greatest amount of variability is in the position of the

TABLE III. Mean and maximum values (in cm) of the within-plane standard deviations of tongue contour height for alveolar and palatal laterals produced by six speakers in midsagittal, parasagittal, and coronal planes.

Speaker		Midsagittal		Parasagittal		Coronal	
		Mean	Max	Mean	Max	Mean	Max
s1	/l/	0.21	0.71	0.18	0.39	0.13	0.17
	/ʎ/	0.17	0.42	0.17	0.34	0.14	0.24
s2	/l/	0.16	0.26	0.13	0.22	0.18	0.41
	/ʎ/	0.22	0.39	0.16	0.45	0.13	0.19
s3	/l/	0.15	0.38	0.13	0.44	0.17	0.34
	/ʎ/	0.38	0.84	0.01	0.54	0.11	0.19
s4	/l/	0.17	0.4	0.17	0.33	0.28	0.4
	/ʎ/	0.13	0.23	0.12	0.34	0.15	0.56
s5	/l/	0.16	0.33	0.18	0.42	0.14	0.17
	/ʎ/	0.26	0.46	0.32	0.61	0.12	0.17
s6	/l/	0.24	0.44	0.17	0.27	0.27	0.41
	/ʎ/	0.24	0.44	0.11	0.26	0.10	0.17

back of the tongue, potentially caused by coarticulatory effects from the preceding and following sounds. This is visible in Fig. 5 for the palatal lateral and in Fig. 6 for the alveolar lateral. The consistency in the location of the posterior openings to the lateral channels and the location of the anterior occlusion between the tongue and the palate is also apparent from Figs. 5 and 6. The larger degree of variability seen in speaker 5 is probably due to movement of the probe relative to the skull.

C. Discussion and summary

Across six native speakers of the Paulistano dialect of Brazilian Portuguese, the palatal lateral articulations produced by speakers s1–s4 were always symmetric, and those produced by speakers s5 and s6 were always asymmetric. The alveolar laterals produced by speakers s1 and s2 were always symmetrical, those produced by speakers s3, s5, and s6 were always asymmetrical, and those produced by s4 were evenly split between symmetrical and asymmetrical articulations. Evidence of the interdental channels forming independent airways around the sides of the tongue is apparent in the UPG images, as well as the series of coronal

images, and these channels join the main oral cavity at variable locations behind the molars or premolars. The anterior ends of these channels join to form the lip cavity anterior to the tongue-palate occlusion. In cases of asymmetrical articulations, one of the interdental channels is merged with the main oral cavity and never forms a separate independent airway. In symmetrical cases, the two interdental channels are not necessarily of the same length.

The interdental channels are typically longer in the palatal laterals than in the alveolar laterals. The place of articulation for the anterior occlusion between the tongue blade and the palate is similar in both the palatal and alveolar laterals, while the position of the tongue body is raised in palatal lateral and lowered in the alveolar lateral, and the tongue root is advanced in the palatal lateral and retracted in the alveolar lateral. The supralingual cavity, bounded by tongue-palate contact on the sides and by the occlusion at the anterior end, is generally longer in the palatal laterals than in the alveolar laterals.

The articulatory characteristics of the Brazilian Portuguese palatal laterals produced by these six speakers are qualitatively similar to those reported for European Portuguese (Martins *et al.*, 2008; Teixeira *et al.*, 2012b). The articulatory characteristics of the Brazilian Portuguese alveolar laterals produced by these six speakers are qualitatively similar to those reported for European Portuguese (Martins *et al.*, 2008; Martins *et al.*, 2010; Oliveira *et al.*, 2011; Silva *et al.*, 2014).

III. ACOUSTICS OF BRAZILIAN PORTUGUESE LATERALS

A. Method

1. Stimuli and data collection

Acoustic data were recorded synchronously with the articulatory data described above and for the same speakers. Audio and video were recorded as described above, and were synchronized with the ultrasound recordings using the method described by Lulich *et al.* (2018). Due to investigator error, the audio signals for speakers 2 and 4 were frequently clipped during the stressed vowels preceding the lateral segments. This did not affect the measurement of formant frequencies within the lateral segments, but it did affect the appearance of the preceding vowel in spectrograms.

2. Analyses

Acoustic analyses were conducted with Praat (Boersma and Weenink, 2018) in two stages, as described by Charles and Lulich (2018). The automatic formant tracker was used for the first stage with a window length of 0.025 s, a dynamic range of 30 dB, and a maximum fourth formant frequency of 5000 Hz. The four formants were recorded in the middle of each target segment as well as in the middle of /j/ in the distractor word *paia* /pajə/ “boring.” In addition, spectrograms of the palatal glide were viewed for comparison with the palatal laterals, since Charles and Lulich (2018) found very little difference in the articulation of [j] and [ʎ] in speaker 1, except for the presence of the interdental channels in [ʎ]. Since there were three repetitions of each stimulus, there were $3 \times 3 = 9$ sets of formant measurements for the

TABLE IV. Number of symmetrical and asymmetrical articulations of /l/ and /ʎ/ tokens produced by six speakers.

Speaker		Symmetrical	Asymmetrical
s1	/l/	9	0
	/ʎ/	9	0
s2	/l/	9	0
	/ʎ/	9	0
s3	/l/	0	5
	/ʎ/	5	0
s4	/l/	5	4
	/ʎ/	9	0
s5	/l/	0	9
	/ʎ/	0	9
s6	/l/	0	9
	/ʎ/	0	9

alveolar laterals, $3 \times 3 = 9$ sets of measurements for the palatal laterals, and $3 \times 1 = 3$ sets of formant measurements for the palatal glides for speakers 1, 2, 4, 5, and 6. For speaker 3, only five sets of formant measurements were obtained for both the alveolar and palatal laterals, and one set of formant measurements was obtained for the palatal glide.

In the second stage, all formant measurements were manually checked and, when necessary, corrected. Corrections were made in approximately 10% of tokens, in which either $F1$ and $F2$ (in the alveolar laterals) or $F2$ and $F3$ (in the palatal laterals) were close enough together that the automatic formant tracker mistakenly reported only a single formant frequency rather than two. No corrections were needed for the palatal glide.

As a point of reference for comparisons across the speakers, the vocal tract length was estimated from measurements of $F3$ in the stressed vowel [a] of the distracter word *barra* /bahə/ “bar.”

B. Results

The means and standard deviations of the formant values for each lateral and each speaker are given in Table V, along with the number of tokens included in each mean. The estimated vocal tract length is also reported, as well as the formant means and standard deviations for the palatal glide. The first formant is generally lower in the palatal laterals than in the alveolar laterals, and in the palatal laterals it is specifically low enough to be unambiguously considered a Helmholtz resonance. The second formant is, unsurprisingly, relatively low in the alveolar lateral and relatively high in the palatal lateral. The third formant is rather variable as indicated by the large standard deviations, and is generally higher in the palatal laterals than in the alveolar laterals. The fourth formant is less variable than the third formant, and is generally higher in the palatal laterals than in the alveolar laterals.

TABLE V. Means (and standard deviations) of the first four formants frequencies ($F1, F2, F3, F4$) in Hz for alveolar and palatal laterals and the palatal glide produced by six speakers in different non-front vowel contexts. The number of tokens analyzed (n) and the estimated vocal tract length (VTL) are also given.

Speaker	VTL		n	$F1$	$F2$	$F3$	$F4$
s1	19.2	/j/	3	417 (36)	1989 (102)	2628 (151)	3506 (60)
		/k/	9	291 (44)	1797 (51)	2671 (274)	3556 (59)
		/l/	9	377 (80)	978 (137)	2615 (180)	3467 (130)
s2	18.5	/j/	3	378 (47)	2103 (123)	2800 (127)	3381 (81)
		/k/	9	309 (29)	1805 (51)	2676 (115)	3606 (36)
		/l/	9	423 (86)	1057 (57)	2443 (170)	3533 (55)
s3	18.6	/j/	1	262 (—)	2233 (—)	3272 (—)	3857 (—)
		/k/	5	304 (39)	1905 (55)	3006 (345)	3773 (55)
		/l/	5	420 (123)	1021 (57)	2829 (72)	3687 (130)
s4	16.6	/j/	3	421 (32)	2798 (66)	3427 (95)	4317 (163)
		/k/	9	349 (46)	2298 (64)	3475 (58)	4284 (115)
		/l/	9	478 (99)	1188 (92)	3006 (174)	3842 (294)
s5	15.5	/j/	3	436 (10)	2504 (60)	3009 (200)	4640 (137)
		/k/	9	423 (41)	2071 (183)	3031 (224)	4362 (492)
		/l/	9	519 (83)	1046 (150)	2860 (124)	4028 (276)
s6	15.9	/j/	3	465 (27)	2679 (95)	3245 (114)	4192 (24)
		/k/	9	408 (43)	2117 (191)	3142 (96)	4302 (64)
		/l/	9	547 (79)	1278 (75)	3063 (133)	4285 (434)

Spectrograms of *pala*, *palha*, and *paia* are displayed in Fig. 7. The distracter word *paia* is shown for comparison with the palatal lateral. Modeled transfer function spectra (described in Sec. IV) are overlaid on the spectrograms next to the lateral segments. Figure 8 shows spectra from the middle of each lateral token shown in Fig. 7, together with the modeled transfer function spectra (described in Sec. IV). Vertical dotted lines and shaded regions indicate mean formant frequencies, measured across all tokens, and the 95% confidence intervals.

The first three formants generally behave similarly in the palatal lateral and the palatal glide. In the glide, $F2$ reaches a higher frequency, while there is more dynamic formant movement during the lateral segment. The dynamic movement in $[\lambda]$ is especially noticeable in speaker 3, but was also commented on in Charles and Lulich (2018) for speaker 1. The first formant generally behaves similarly in the alveolar lateral, although it lowers to a less extreme degree. The second formant also lowers.

In both palatal and alveolar laterals across all six speakers, a low energy band above $F3$ or $F4$ cannot be identified with anti-resonances caused by the interdental channels or the supralingual cavity, since the same low energy band appears in the word *paia* and is probably due to anti-resonances of the piriform sinuses instead (Dang and Honda, 1997). Interestingly, there is no obvious observable difference between the spectrograms of asymmetrically produced laterals ($[\lambda]$ of speaker 5, and $[l]$ of speakers 3, 5, and 6) and symmetrically produced laterals.

C. Discussion and summary

The palatal and alveolar laterals of the Paulistano dialect of Brazilian Portuguese are characterized acoustically by a lowered $F1$. In addition, the alveolar lateral is characterized by a low $F2$ while the palatal lateral is characterized by a high $F2$. The palatal lateral differs from the palatal glide primarily in terms of $F2$ frequency ($F2$ is higher in the glide).

The $F1$ and $F2$ frequencies for the Brazilian Portuguese alveolar laterals are similar to those reported for European Portuguese (Oliveira et al., 2011), and the $F1$ – $F3$ frequencies for the Brazilian Portuguese palatal laterals are similar to those reported for European Portuguese (Teixeira et al., 2012b). For example, Oliveira et al. (2011) report $F1$ frequencies between 272 and 423.3 Hz for the alveolar lateral, and $F2$ frequencies between 869.3 and 1016.8 Hz (see their Table I; compare with our findings of $F1$ between 377 and 547 Hz, and $F2$ between 978 and 1278 Hz). Teixeira et al. (2012b) report $F1$ frequencies between 283 and 413 Hz for the palatal lateral, $F2$ frequencies between 1739 and 2442 Hz, and $F3$ frequencies between 2677 and 3658 Hz (see their Table II; compare with our findings of $F1$ between 291 and 423 Hz, $F2$ between 1797 and 2298 Hz, and $F3$ between 2671 and 3475 Hz).

IV. ARTICULATORY-ACOUSTIC RELATIONS IN BRAZILIAN PORTUGUESE LATERALS

In this section we examine the possibility of predicting the acoustic properties of Brazilian Portuguese laterals based

FIG. 7. Spectrograms of the words *paia*, *palha*, and *pala* by each of six speakers. Superimposed lines next to the lateral approximants are calculated transfer function spectra (described in Sec. IV).

on articulatory data acquired from 3D/4D ultrasound and digitized 3D palate impressions. Furthermore, through a sensitivity analysis we investigate the articulatory-acoustic relations involved in Brazilian Portuguese lateral productions with an aim to identify formant-cavity affiliations and the source of anti-resonances.

A. Methods

The first step is to derive area functions for the vocal tract, including the supralingual cavity and interdental channels. The kind of articulatory data at our disposal (namely, 3D/4D ultrasound and digitized palate impressions) places significant limits on our ability to derive area functions for

FIG. 8. Spectra of the words *palha* and *pala* by each of six speakers. Gray lines present the calculated transfer function spectra (described in Sec. IV), black lines present the measured spectra in the middle of the lateral. Vertical dotted lines and shaded regions present the mean formant measurements across all tokens and the 95% confidence intervals, respectively.

the entire vocal tract, and it is therefore necessary to proceed with caution. In particular, our data provide information about the area functions of the supralingual cavity and the lengths and locations of the interdental channels, but they do not furnish enough information to determine the variation in area along the interdental channels, or the pharyngeal and laryngeal cavities, or the lip cavity where the two interdental channels converge. On the other hand, it is possible to make some inferences about these other regions of the vocal tract

based on information that is available within our data set. For instance, advancement and retraction of the tongue root is visible in the ultrasound data and provide some information about the relative size of the pharyngeal cavity.

Furthermore, the lip cavity (including the sublingual cavity, if present) forms only a short section of the vocal tract and is not expected to have a large impact on low-frequency formants and anti-resonances. Thus, the lip cavity need not be specified to a high degree of accuracy. Finally,

length dimensions of individual cavities are more important than their cross-sectional areas as long as the formants affiliated with those cavities are not too close together and thus strongly coupled (Fant, 1960, p. 98). Thus, although our data are less than ideal for the purpose of modeling the entire vocal tract, we follow Fant's dictum that "[t]he existence of uncertainties in the mapping of vocal tract dimensions should not, however, discourage an investigator from making maximal use of his measurements. Errors due to local misjudgments are partially compensated for by the redundancies contained in a more precise evaluation of the remaining parts of the vocal tract" (Fant, 1960, p. 98). Moreover, the most interesting parts of the vocal tract for lateral sounds are exactly those for which we have articulatory data, namely, the supralingual cavity and the interdental channels. For the pharyngeal cavity, we substituted a uniform tube whose length and cross-sectional area were roughly tuned (without a systematic grid search) in order to create a better fit with the measured acoustic data. This is the only part of the vocal tract that was tuned in any way for the model calculations.

Due to the limitations of our data, we do not attempt to model vocal tract acoustics with methods, which in this instance would be overly specified, such as might be possible with a 3D finite-element model. Instead, we restrict ourselves to considering two-dimensional plane wave propagation modeled by an electric circuit analog. The "T-network" circuit characteristics and equations defining the lumped inertance, compliance, resistance, and conductance of each T-segment are familiar from many vocal tract modeling studies and summarized by Fant (1960), Flanagan (1972), and Stevens (1998). In this study the "inexact" equations defining the lumped elements are used, as presented by Flanagan (1972). To calculate the vocal tract transfer functions for each of the 12 laterals (2 laterals produced by each of the 6 speakers), the circuit was solved using standard numerical methods (e.g., Fant, 1960; Maeda, 1982; Zhang and Espy-Wilson, 2004; Lulich, 2006). Details of the model are sketched in Appendix B.

Area functions were directly measured for the supralingual cavity by (1) selecting a series of coronal slices, (2) identifying the pixels bounded by the tongue surface and the palate for each slice, and (3) multiplying the number of pixels by the pixel dimensions for each slice. The spacing between consecutive slices was chosen independently for each of the 12 lateral sounds such that the length of each T-segment was smaller than 0.4 cm or $\approx 1/16$ of the wavelength of a 5600 Hz tone (assuming the speed of sound in the vocal tract is 35 900 cm/s; Lulich *et al.*, 2011). Transfer functions were calculated up to 5000 Hz, ensuring the accuracy of the lumped element approximations and the T-network model in the frequency range under investigation.

The length of each interdental channels was determined by (1) identifying the posterior point where it joined the main oral cavity, (2) identifying the anterior point where it joined the lip cavity, and (3) measuring the curvilinear distance between the two points along an arc outlined by the upper teeth from the palatal impression. The cross-sectional area of each interdental channel could not be measured

directly with our dataset, which does not show the locations of the lower teeth or the inner wall of the cheek. We therefore (1) assumed that the cross-sectional area of each interdental channel was uniform and circular, (2) measured the width of the first molar from speaker 1, and (3) assumed that this was the diameter of the interdental channel in each of the 12 laterals. Each interdental channel was therefore approximated as a uniform circular tube with an area of 0.79 cm^2 . For asymmetrically articulated laterals, only one interdental channel was modeled.

The length dimensions of the different cavities in the model were systematically manipulated in a sensitivity analysis in order to determine the cavity affiliations of the various resonances and prominent anti-resonances. The percentage changes in the resonance frequencies (represented here as Δ) were calculated for each 1% increase in cavity length. For instance, lengthening the pharyngeal cavity by 1% for the palatal lateral produced by speaker 2 resulted in a $\Delta = 0.71\%$ decrease in R2, from 1699 to 1687 Hz. Changes in the lengths of the remaining cavities resulted in less than $\Delta = 0.12\%$ change in R2. Thus, R2 in the palatal lateral produced by speaker 2 is primarily affiliated with the pharyngeal cavity. As another example, R1 in the palatal lateral produced by speaker 1 underwent a $\Delta = 0.35\%$ change in response to increases in the lengths of the pharynx and both interdental channels. R1, in this instance, is not primarily affiliated with any single cavity, but is instead a Helmholtz resonance of the pharyngeal cavity and its interdental channel outlets. In this way, cavity affiliations can be determined for each of the modeled resonances. Note that the ability to relate resonances to specific cavities is not dependent on the details of the model (e.g., whether concatenated tubes, T-networks, or finite elements models are used). The correspondence between the modeled resonances and the measured formant frequencies was determined by proximity in frequency to one another, i.e., the modeled resonance peak frequencies that were closest to the measured formant frequencies were determined to correspond to one another.

B. Results

Tables VI and VII present the lengths ("L") and cross-sectional areas ("A") of each model segment within the pharynx and oral cavity, excluding the interdental channels. Each segment is numbered ("N") starting from the larynx. The lengths of the interdental channels are presented in Table VIII. Because the difference in interdental channel lengths was less than 0.5 cm and the location of the posterior openings were similar, the interdental channels were connected to the main oral cavity together between T-segments 46 and 47.

The transfer function magnitude spectra for each lateral produced by each speaker are plotted and overlaid on the spectrograms in Fig. 7. These spectra are drawn with frequency along the vertical axis and amplitude along the horizontal axis. In this way, the positive spectral peaks (peaks pointing to the left) appear at frequencies that are directly comparable with the formants in the spectrogram. The transfer function magnitude spectra are also overlaid on the spectra in Fig. 8. Qualitatively, the modeled spectra reproduce

TABLE VI. Lengths (L) and cross-sectional areas (A) associated with each of N T -segments used to model the acoustic transfer functions of the alveolar and palatal laterals produced by three male speakers.

s1						s2						s3					
[l]			[ʌ]			[l]			[ʌ]			[l]			[ʌ]		
N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A
1–32	0.35	4.9	1–46	0.20	7.35	1–44	0.31	4.9	1–40	0.23	8.56	1–46	0.22	1.23	1–46	0.26	8.58
33	0.13	4.59	47	0.36	1.37	45	0.3	8.36	41–46	0.23	2.45	47	0.22	6.63	47	0.29	2.43
34	0.13	4.71	48	0.36	1.45	46	0.21	7.55	47	0.21	3.23	48	0.22	6.53	48	0.29	2.24
35	0.13	4.85	49	0.36	1.34	47	0.17	6.68	48	0.21	3.04	49	0.22	6.45	49	0.29	2.15
36	0.13	4.98	50	0.36	1.36	48	0.17	6.11	49	0.21	2.90	50	0.22	6.32	50	0.29	2.13
37	0.13	5.04	51	0.34	1.41	49	0.17	5.22	50	0.21	2.76	51	0.22	6.14	51	0.29	2.24
38	0.13	5.10	52	0.36	1.36	50	0.17	4.02	51	0.21	2.73	52	0.22	6.02	52	0.29	2.51
39	0.13	5.16	53	0.36	1.51	51	0.17	3.27	52	0.21	2.54	53	0.22	5.95	53	0.29	2.68
40	0.13	5.19	54	0.36	1.73	52	0.17	2.67	53	0.21	2.13	54	0.22	5.87	54	0.29	2.59
41	0.13	5.22	55	0.36	1.72	53	0.17	2.32	54	0.21	1.57	55	0.22	5.52	55	0.29	2.15
42	0.13	5.26	56	0.36	1.52	54	0.17	1.92	55	0.21	1.14	56	0.22	4.88	56	0.29	1.63
43	0.13	5.27	57	0.36	1.33	55	0.17	1.49	56	0.21	0.89	57	0.22	4.27	57	0.29	1.11
44	0.13	5.30	58	0.36	0.78	56	0.17	1.14	57	0.21	0.60	58	0.22	3.65	58	0.29	0.63
45	0.13	5.32	59	0.36	0.51	57	0.17	0.95	58	0.21	0.42	59	0.22	2.69	59	0.29	0.34
46	0.13	5.29	60	0.36	0.18	58	0.17	0.63	59	0.21	0.25	60	0.22	1.92	60	0.29	0.15
47	0.24	5.24	61–63	0.25	3.7	59	0.17	0.49	60	0.21	0.10	61	0.22	1.29	61–63	0.25	3.7
48	0.24	5.23				60	0.17	0.43	61–63	0.25	3.7	62	0.22	0.82			
49	0.24	5.26				61–63		0.25	3.7			63	0.22	0.45			
50	0.24	5.33										64	0.22	0.22			
51	0.24	5.38										65	0.22	0.10			
52	0.24	5.24										66	0.22	0.02			
53	0.24	4.89										67–69		0.25	3.7		
54	0.24	4.52															
55	0.24	3.95															
56	0.24	2.89															
57	0.24	1.70															
58	0.24	0.68															
59	0.24	0.28															
60	0.24	0.33															
61–63	0.25	3.7															

the formant structure of the lateral sounds well. The calculated spectra have a low $F1$, especially for the palatal laterals, a high $F2$ for the palatal lateral, a low $F2$ for the alveolar lateral, and in most cases evidence of a single prominent anti-resonance. The frequencies of the resonances and the prominent anti-resonance are presented in Table IX. The resonances that correspond with formants in the spectrograms are marked by an asterisk. The mean absolute error in formant prediction ranged from 4% ([l] for speaker 3, [ʌ] for speaker 2) to 14% ([l] for speaker 5). The mean absolute error across speakers and both laterals was 8%. The Pearson correlation between measured and calculated formant frequencies across all speakers and both laterals was $r = 0.987$.

In response to a 1% increase in cavity length, the mean decrease in any resonance across all speakers and both laterals was 0.2%, and the maximum decrease was 0.98%. A threshold of 0.2% was chosen for determining which cavities were substantially affiliated with a resonance. Complete results for the sensitivity analysis are found in Appendix C. A summary of the main findings from this section is provided in Table X.

The first resonance (which always corresponded with the first formant) was usually affiliated with the pharyngeal

cavity ($0.229\% \leq \Delta \leq 0.725\%$) and the interdental channels ($0.206\% \leq \Delta \leq 0.496\%$). In most of these cases, the pharyngeal cavity itself was most strongly affiliated with the first resonance. For speaker 3, the interdental channels in [l] were more strongly affiliated with the first resonance, while for speakers 2 and 5 in [ʌ], only the pharyngeal cavity was affiliated with the first resonance.

The second resonance (which always corresponded with the second formant) was always affiliated most strongly with the pharyngeal cavity ($0.549\% \leq \Delta \leq 0.810\%$). For the palatal lateral, the pharyngeal cavity was the only portion of the vocal tract affiliated with the second resonance in speakers 2–5. In speakers 1 and 6, the supralingual cavity was also affiliated with the second resonance ($0.267\% \leq \Delta \leq 0.314\%$). (Note that the supralingual cavity in speaker 6 is not occluded anteriorly because of the asymmetrical articulation.) For the alveolar lateral, the pharyngeal cavity was the only portion of the vocal tract affiliated with the second resonance in speakers 1–4. In speakers 5 and 6, both of whom had asymmetrical articulations, the non-occluded supralingual cavity was also affiliated with the second resonance ($0.210\% \leq \Delta \leq 0.260\%$).

TABLE VII. Lengths (L) and cross-sectional areas (A) associated with each of N T -segments used to model the acoustic transfer functions of the alveolar and palatal laterals produced by three female speakers.

s4						s5						s6					
[l]			[ɤ]			[l]			[ɤ]			[l]			[ɤ]		
N	L	A	N	L	A	N	L	A	N	L	A	N	L	A	N	L	A
1–36	0.26	4.9	1–36	0.23	7.35	1–46	0.22	4.9	1–46	0.23	4.9	1–46	0.21	2.45	1–46	0.16	7.35
37	0.25	9.12	37	0.10	8.66	47	0.15	4.26	47	0.15	1.69	47	0.25	6.90	47	0.27	11.13
38	0.25	9.05	38	0.10	8.25	48	0.15	4.28	48	0.15	1.60	48	0.25	7.29	48	0.27	9.92
39	0.25	9.87	39	0.10	7.60	49	0.15	4.28	49	0.15	1.72	49	0.25	7.04	49	0.27	8.26
40	0.25	9.02	40	0.10	6.89	50	0.15	4.32	50	0.15	1.78	50	0.25	6.98	50	0.27	7.06
41	0.25	9.16	41	0.10	6.33	51	0.15	4.41	51	0.15	1.89	51	0.25	6.95	51	0.27	6.00
42	0.25	9.02	42	0.10	5.73	52	0.15	4.45	52	0.15	1.91	52	0.25	7.13	52	0.27	5.12
43	0.25	8.83	43	0.10	5.36	53	0.15	4.36	53	0.15	1.90	53	0.25	7.26	53	0.27	4.62
44	0.25	8.47	44	0.10	4.84	54	0.15	4.30	54	0.15	2.03	54	0.25	7.39	54	0.27	4.18
45	0.25	8.12	45	0.10	4.53	55	0.15	4.16	55	0.15	2.15	55	0.25	7.29	55	0.27	3.69
46	0.25	7.76	46	0.10	4.25	56	0.15	4.04	56	0.15	2.22	56	0.25	7.18	56	0.27	3.31
47	0.16	7.49	47	0.2	3.99	57	0.15	3.82	57	0.15	2.33	57	0.25	7.12	57	0.27	3.32
48	0.16	7.26	48	0.2	3.81	58	0.15	3.36	58	0.15	2.34	58	0.25	6.82	58	0.27	2.99
49	0.16	6.74	49	0.2	3.60	59	0.15	2.56	59	0.15	2.43	59	0.25	6.29	59	0.27	2.73
50	0.16	6.18	50	0.2	3.41	60	0.15	1.67	60	0.15	2.35	60	0.25	5.35	60	0.27	2.50
51	0.16	5.66	51	0.2	3.13	61	0.15	0.87	61	0.15	2.34	61	0.25	4.27	61	0.27	2.39
52	0.16	4.96	52	0.2	2.82	62	0.15	0.44	62	0.15	2.17	62	0.25	3.35	62	0.27	2.53
53	0.16	4.25	53	0.2	2.70	63	0.15	0.10	63	0.15	1.77	63	0.25	2.51	63	0.27	2.10
54	0.16	3.31	54	0.2	2.48	64	0.15	0.10	64	0.15	0.90	64	0.25	1.18	64	0.27	1.53
55	0.16	2.38	55	0.2	2.23	65	0.15	0.09	65	0.15	0.32	65	0.25	0.37	65	0.27	1.07
56	0.16	1.74	56	0.2	1.93	66	0.15	0.04	66	0.15	0.09	66	0.25	0.05	66	0.27	0.43
57	0.16	1.36	57	0.2	1.61	67–69	0.25	3.7	67–69	0.25	3.7	67–69	0.25	3.7	67–69	0.25	3.7
58	0.16	1.01	58	0.2	1.28												
59	0.16	0.48	59	0.2	1.01												
60	0.16	0.10	60	0.2	0.36												
61–63	0.25	3.7	61–63	0.25	3.7												

At frequencies higher than the second resonance, the correspondence with formants became more variable. For [ɤ], the resonance corresponding with the third formant was affiliated with the pharyngeal cavity alone in speakers 1 and 2 ($0.355\% \leq \Delta \leq 0.686\%$), the combined supralingual cavity

and long interdental channel in speakers 5 and 6 ($0.267\% \leq \Delta \leq 0.667\%$), the combined pharyngeal cavity and long interdental channel in speaker 4 ($0.210\% \leq \Delta \leq 0.260\%$), and the two interdental channels alone in speaker 3 ($0.323\% \leq \Delta \leq 0.581\%$). For [l], the resonance corresponding with

TABLE VIII. Lengths of the interdental channels for six speakers. The cross-sectional area was assumed to be 0.79 cm^2 in all symmetric cases. In the case of asymmetric articulation, the length of the single interdental channel is provided in the second column labeled “Long length” (cross-sectional area is 0.79 cm^2), and the length of the unoccluded supralingual cavity is provided in the first column labeled “Short length” and marked with an asterisk (“*”); cross-sectional areas are reported in Tables VI and VII.

	Short length	Long length
s1	/l/	4.75
	/ɤ/	7.25
s2	/l/	4.00
	/ɤ/	4.85
s3	/l/	4.40*
	/ɤ/	5.00
s4	/l/	3.35
	/ɤ/	4.85
s5	/l/	3.00*
	/ɤ/	3.00*
s6	/l/	4.25*
	/ɤ/	3.00*

TABLE IX. Calculated frequencies of resonances (R1–R8) and the prominent anti-resonance (A1) of the entire resonating system below 5000 Hz. Asterisks (“*”) mark resonances that correspond with measured formants. Correspondence between modeled resonance peaks and measured formant frequencies was determined by proximity in frequency.

Speaker	R1	R2	R3	R4	R5	R6	R7	R8	A1
s1	[l] 398*	1092*	2330*	3470*	3625	3708	4619		3872
	[ɤ] 283*	1591*	2201	2423	2536*	3886*	4660	4890	2026
s2	[l] 414*	1146*	2165*	3353*	3932	4399	4663		4217
	[ɤ] 297*	1699*	2622*	3597	3710*	4125			4817
s3	[l] 437*	1111*	2734*	3717*	4406				3456
	[ɤ] 269*	1401*	2523	3097*	3389	3543*	4612		2878
s4	[l] 452*	1194*	2795*	4180*	4629				
	[ɤ] 346*	1829*	3269*	3604	3688	4812*			4356
s5	[l] 446*	1427*	2823*	3904*	4400				4490
	[ɤ] 453*	1692*	3000*	4045*	4950				4420
s6	[l] 403*	1152*	2696*	3734	4281*	4954			2750
	[ɤ] 485*	1875*	3410*	4454*					

TABLE X. Summary of findings of formant-cavity affiliations. The “lat” entries refer to the interdental (lateral) channels, and “sym” and “asym” refer to symmetrical and asymmetrical articulations, respectively.

Formant	Alveolar lateral	Palatal lateral
<i>F1</i>	Helmholtz resonance	Helmholtz resonance
<i>F2</i>	Pharynx (s1,s2,s3,s4), or pharynx and supralingual (s5,s6)	Pharynx (s2,s3,s4,s5), or pharynx and supralingual (s1,s6)
<i>F3</i>	Pharynx	Pharynx (s1,s2), or supralingual and long lat (s5,s6), or pharynx and long lat (s4), or long lat and short lat (s3)
<i>F4</i>	Pharynx (s2), or short lat (s1,s3,s5), or pharynx and short lat (s4,s6)	Pharynx (s1,s2), or pharynx and supralingual (s4,s5,s6), or short lat (s3)
Anti-resonance	Supralingual (sym) (s1,s2,s4), or one lat (asym) (s3,s5,s6)	Supralingual (sym) (s1,s2,s3,s4), or one lat (asym) (s5,s6)

the third formant was always affiliated only with the pharyngeal cavity ($0.815\% \leq \Delta \leq 0.951\%$).

For [Λ], the resonance corresponding with the fourth formant was always affiliated with the pharyngeal cavity ($0.254\% \leq \Delta \leq 0.848\%$). For [λ], in speakers 1 and 2, the pharyngeal cavity was the only portion of the vocal tract affiliated with the fourth formant. In speakers 4–6, the resonance was also affiliated with the supralingual cavity ($0.291\% \leq \Delta \leq 0.420\%$). In speaker 3, the resonance was primarily affiliated with the short interdental channel ($\Delta = 0.649\%$). For [l], the fourth formant was variously affiliated with the pharyngeal cavity and the shorter interdental channel. In speaker 2, it was affiliated only with the pharyngeal cavity ($\Delta = 0.895\%$). In speakers 1, 3 and 5, it was affiliated only with the short interdental channel ($0.834\% \leq \Delta \leq 0.980\%$). For speakers 4 and 6, it was affiliated with the combined pharyngeal cavity and short interdental channel ($0.239\% \leq \Delta \leq 0.467\%$).

The prominent anti-resonance was always affiliated with the supralingual cavity when this cavity was articulated symmetrically with an occlusion anteriorly. In cases of asymmetrical articulation, the interdental channels were affiliated with the prominent anti-resonance.

C. Discussion and summary

Transfer functions calculated from 3D/4D ultrasound images of the tongue combined with digitized palate impressions were capable of distinguishing palatal and alveolar laterals in each of six native speakers of the Paulistano dialect of Brazilian Portuguese with relatively close correspondence between the calculated resonances and the measured formants. The pharyngeal and interdental channels were affiliated with the first formant, indicating either a Helmholtz resonance or a perturbed quarter-wavelength resonance of a roughly uniform vocal tract area function. The pharyngeal

cavity was affiliated with the second formant in both alveolar and palatal laterals and, usually, with the third formant in alveolar laterals and the fourth formant in palatal laterals. The interdental channels were usually affiliated with the third formant in palatal laterals and the fourth formant in alveolar laterals. A single prominent zero was usually observed, which was always affiliated with the supralingual cavity in cases of symmetric articulation and the interdental channel in cases of asymmetric articulation.

The area functions and transfer function spectra for the alveolar and palatal laterals of Brazilian Portuguese are broadly similar to those reported for European Portuguese (Teixeira *et al.*, 2012b). For example, data from Martins *et al.* (2008) show that the palatal lateral is produced with a more advanced tongue root in comparison with the alveolar lateral (see Fig. 19 from Martins *et al.*, 2008). Furthermore, data from Teixeira *et al.* (2012b) indicate back cavity lengths between 8.10 and 8.70 cm for females (compare with our 7.36–10.58 cm lengths for *T*-segments 1–46) and 11.40 cm for males (compare with our 9.20–11.96 cm lengths); anterior cavity lengths between 0.6 and 0.9 cm (compare with our 0.75 cm lengths); supralingual cavity lengths between 3.0 and 3.9 cm for both males and females (compare with our 2.8–5.8 cm for both males and females); and interdental channel lengths between 4.5 and 6.3 cm (compare with our 3.0–7.5 cm lengths).

Some differences between our findings and those found for European Portuguese include a less prominent anti-resonance affiliated with the interdental channels in symmetric articulations of Brazilian Portuguese laterals, and longer measured interdental channels and supralingual cavity in Brazilian Portuguese. Another important difference is that Teixeira *et al.* (2012b) modeled the entire vocal tract with a set of five concatenated uniform tubes (back, front, and supralingual cavities plus two interdental channels), whereas our models used more detailed area functions for the part of the vocal tract that our data covered, namely, the oral cavity. On the other hand, their model for the back cavity was based on MRI data that included the pharyngeal cavity, whereas our model of the pharyngeal cavity was roughly tuned (not optimized with a grid search) to generate better fits with the acoustic data.

Our results suggest that anti-resonances from the interdental channels do not have a substantial effect on the transfer function spectrum when the articulation is symmetric (i.e., there are two interdental channels) and a supralingual cavity is present. This is consistent with the studies by Zhang and Espy-Wilson (2004) and Zhou *et al.* (2010), although there were differences in how the interdental channels were modeled. Zhang and Espy-Wilson (2004) modeled the interdental channels as lossless uniform tubes, and while Zhou *et al.* (2010) appear to have included losses throughout their model (cf. Zhou, 2009, and Zhou *et al.*, 2008), the sharply defined transitions between anti-resonances and resonances in their transfer function spectra suggest that these losses were minimal. Smaller losses and greater differences in interdental channel lengths and cross-sectional areas have the effect of creating more prominent anti-resonances (Zhang and Espy-Wilson, 2004; Zhou *et al.*, 2010) in contrast to the acoustic and modeling results reported in this paper.

V. GENERAL DISCUSSION AND CONCLUSIONS

This study investigated Brazilian Portuguese lateral sounds produced by six native speakers (three males, three females). One of the innovations of this investigation was in the methods employed, namely, the use of 3D/4D ultrasound combined with digitized palate impressions to derive area functions and predict spectral resonances and anti-resonances. These articulatory data showed that some speakers produce both laterals symmetrically, some alternate between symmetrical and asymmetrical articulations, and some produce both laterals asymmetrically.

In general, the interdental channels are longer in the palatal lateral than in the alveolar lateral. This is probably a consequence of the raised tongue body and advanced tongue root in the palatal lateral. In contrast, the tongue body is lower and the tongue root retracted in the alveolar lateral. The location of the anterior occlusion of the supralingual cavity is similar in both laterals, so that an increase in interdental channel length in palatal laterals also corresponds to an increase in supralingual cavity length and a lower frequency cluster of resonances and anti-resonances affiliated with these anterior airways. Thus, the anterior airways were more likely to be affiliated with $F3$ in the palatal laterals and with $F4$ in the alveolar laterals.

The lengthened interdental channels in the palatal laterals also resulted in a lower frequency anti-resonance, which was affiliated with the supralingual cavity in symmetric articulations and the interdental channel in asymmetric articulations. There was no evidence that the two interdental channels were strongly asymmetrical. Strongly asymmetrical interdental channels may result in the introduction of a second prominent anti-resonance (Zhou *et al.*, 2010). The prominent anti-resonance appears above $F3$ in most cases. Potential anti-resonances around 4000 Hz are likely to be present and due to the piriform sinuses regardless of the presence of additional anti-resonances from the supralingual cavity or interdental channels. The role of anti-resonances in defining lateral acoustics or articulatory-acoustic relations is therefore questionable given the observed inconsistency in anti-resonance frequencies and the lack of strong evidence for their impact on spectrograms of recorded speech.

A. Limitations

The use of 3D/4D ultrasound to investigate articulatory-acoustic relations, including the development of area functions for acoustic modeling, has shown promise in this study. However, significant limitations remain. With regard to methodology, the fact that ultrasound technology does not image the posterior pharyngeal wall, the palate, or the interdental channels well places a significant limitation on the ability to define area functions for the whole vocal tract. In this paper, we modeled the pharynx as a uniform tube with length and cross-sectional area tuned to give a reasonable match between the modeled and measured formant frequencies, and we modeled the interdental channels as uniform tubes with cross-sectional area equal to 0.79 cm^2 . In the future, it could be of great benefit to combine 3D/4D ultrasound with other imaging modalities such as MRI (Lulich, 2018).

With regard to the corpus analyzed in this paper, we examined a limited number of tokens in non-front vowel

contexts, produced by speakers of a single dialect in São Paulo, Brazil. In the future, it would be interesting to examine dialectal variability in the production of alveolar and palatal laterals, as well as the effects of front vowel contexts on the articulation of both laterals.

The creation of area functions from 3D/4D ultrasound images required us to manually register the digitized palate impressions with the ultrasound images, and to segment the tongue surface in three dimensions. Errors associated with palate registration and tongue surface segmentation have been reported to be less than 2.5 mm (for registration; Lulich *et al.*, 2017b) and less than the size of a pixel (for segmentation), which in the present study was less than 0.48 mm (Charles and Lulich, 2018). Although manual registration and segmentation is currently the gold standard for ultrasound analyses of speech sound articulations, they are onerous and would benefit from further development of computational tools that automate, or semi-automate, these processes.

ACKNOWLEDGMENTS

We would like to thank the editor and three anonymous reviewers for their helpful comments.

APPENDIX A: VALIDITY OF ARTICULATION MEASUREMENTS

The position of the palate within the volumetric ultrasound image was determined in two ways: (1) using ultrasound images collected while the subject swallowed water, and (2) using ultrasound images of speech sounds that are produced with linguo-palatal contact. Water allows the ultrasound waves to continue beyond the surface of the tongue and come in contact with the surface of the palate. The result is a bright outline of where the palate is located relative to the stabilized ultrasound probe. Similarly, during linguo-palatal contact the ultrasound waves continue through the tongue and come into contact with the surface of the palate. Palate position was verified across several ultrasound image frames during the swallow and during linguo-palatal contact of consonants throughout the recordings. As reported in Lulich *et al.* (2017b), the expected error for palate registration is no more than 2.5 mm.

The tongue surface images were segmented by manually tracing every fifth sagittal plane and every tenth coronal plane. This formed a 3D grid that was then linearly interpolated to complete the entire surface. As described in Charles and Lulich (2018) and the citations therein, the expected error is approximately the size of a single voxel. In the case of the corpus used in this study, the voxel height ranged between 0.34 and 0.48 mm.

APPENDIX B: MODEL DETAILS

Figure 9 shows a simple acoustical circuit for a two-section vocal tract. The circuit is composed of a volume velocity source (U_s) and two T -networks. The impedances within each T -network are defined as in Flanagan (1972). Kirchhoff's current law and Kirchhoff's voltage law are

FIG. 9. Simple acoustical circuit diagram of a two-section vocal tract with volume velocity source, U_s . Arrows indicate the direction in which flow (U) through corresponding impedances (Z) is positive.

used to derive a set of “node” and “loop” equations as described by Fant (1960). These equations are written using the matrix formulation as illustrated in the following equation representing the circuit in Fig. 9:

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & -1 & 0 & -1 \\ (Z1 + Z2) & 0 & Z3 & Z4 \\ 0 & Z2 & 0 & -Z4 \end{bmatrix} \times \begin{bmatrix} U1 \\ U2 \\ U3 \\ U4 \end{bmatrix} = \begin{bmatrix} U_s \\ 0 \\ 0 \\ 0 \end{bmatrix}.$$

TABLE XI. Sensitivity analysis for palatal and alveolar laterals: Resonance frequencies. Note that the supralingual cavity is not present for speakers s5 and s6 because all of their articulations were asymmetrical.

Speaker	Condition	Palatal								Alveolar						
		R1	R2	R3	R4	R5	R6	R7	R8	R1	R2	R3	R4	R5	R6	R7
s1	Measurement	291	1797	—	—	2671	3556	—	—	377	978	2615	3467	—	—	—
	Baseline	283	1591	2201	2423	2536	3886	4660	4890	398	1092	2330	3470	3625	3708	4619
	Pharynx	282	1582	2199	2420	2526	3857	4652	4890	397	1086	2311	—	3600	3711	4592
	Short lat	282	1590	2198	—	2527	3883	4655	4854	397	1092	2330	3465	3624	—	4618
	Long lat	282	1590	2195	2408	2534	3882	4628	4880	397	1092	2330	3436	3623	3699	4618
	Supralingual	283	1586	2190	2421	2534	3883	4660	4890	398	1091	2328	3468	3619	3707	4608
	Anterior	283	1591	2201	2423	2536	3885	4659	4890	398	1092	2330	3467	3625	3708	4619
s2	Measurement	309	1805	2676	—	3606	—	—	—	423	1057	2443	3533	—	—	—
	Baseline	297	1699	2622	3597	3710	4125	—	—	414	1146	2165	3353	3932	4399	4663
	Pharynx	295	1687	2604	3596	3708	4090	—	—	411	1139	2146	3323	3930	4398	4623
	Short lat	297	1698	2619	3595	3681	4124	—	—	413	1145	2165	3353	3931	4361	4661
	Long lat	297	1698	2619	3569	3709	4124	—	—	413	1145	2165	3352	3899	4396	4663
	Supralingual	297	1697	2618	3595	3707	4120	—	—	414	1145	2164	3353	3931	4399	4660
	Anterior	297	1699	2621	3596	3709	4125	—	—	414	1146	2165	3353	3930	4398	4663
s3	Measurement	304	1905	—	3006	—	3773	—	—	420	1021	2829	3687	—	—	—
	Baseline	269	1401	2523	3097	3389	3543	4612	—	437	1111	2734	3717	4406	—	—
	Pharynx	268	1390	2508	3096	3377	3534	4574	—	436	1102	2708	3718	4370	—	—
	Short lat	268	1401	2523	3095	3383	3520	4611	—	435	1110	2734	3686	4405	—	—
	Long lat	268	1401	2523	3079	3380	3541	4611	—	435	1109	2733	3713	4400	—	—
	Supralingual	269	1400	2515	3087	3384	3542	4609	—	—	—	—	—	—	—	—
	Anterior	269	1401	2523	3096	3389	3542	4612	—	437	1111	2734	3716	4406	—	—
s4	Measurement	349	2298	3475	—	—	4248	—	—	478	1188	3006	3842	—	—	—
	Baseline	346	1829	3269	3604	3688	4812	—	—	452	1194	2795	4180	4629	—	—
	Pharynx	344	1816	3254	3599	3686	4782	—	—	450	1186	2770	4163	4616	—	—
	Short lat	345	1828	3264	3601	3663	4812	—	—	451	1194	2795	4178	4627	—	—
	Long lat	345	1828	3260	3583	3687	4812	—	—	451	1194	2794	4172	4603	—	—
	Supralingual	346	1827	3268	3599	3684	4798	—	—	452	1193	2794	4177	4627	—	—
	Anterior	346	1829	3268	3604	3688	4812	—	—	452	1194	2795	4179	4627	—	—
s5	Measurement	423	2071	3031	4362	—	—	—	—	519	1046	2860	4028	—	—	—
	Baseline	453	1692	3000	4045	4950	—	—	—	446	1427	2823	3904	4400	—	—
	Pharynx	451	1679	2980	4022	4934	—	—	—	443	1417	2798	3905	4363	—	—
	Short lat	453	1691	3000	4045	4924	—	—	—	444	1426	2822	3870	4399	—	—
	Long lat	453	1690	2992	4028	4944	—	—	—	445	1424	2820	3902	4393	—	—
	Anterior	453	1692	3000	4045	4949	—	—	—	445	1427	2823	3903	4400	—	—
s6	Measurement	408	2117	3142	4302	—	—	—	—	547	1278	3063	—	4285	—	—
	Baseline	485	1875	3410	4454	—	—	—	—	403	1152	2696	3734	4281	4954	—
	Pharynx	483	1863	3393	4431	—	—	—	—	401	1144	2674	3726	4265	4925	—
	Short lat	484	1875	3409	4453	—	—	—	—	402	1152	2696	3718	4261	4952	—
	Long lat	483	1870	3393	4436	—	—	—	—	401	1149	2693	3721	4274	4938	—
	Anterior	485	1875	3409	4454	—	—	—	—	402	1152	2696	3733	4280	4954	—

The first matrix is inverted and solved to find the flow (U_2) that represents volume velocity at the lips. The ratio U_2/U_s provides the transfer function. In this paper, the circuit was divided into 63 T -segments if the articulation was symmetrical, and it was divided into 69 T -segments if the articulation was asymmetrical. The number of T -segments was able to be maintained at a constant value (either 63 or 69) across all speakers and for each lateral consonant because the lengths of the vocal tract sections represented by each T -network were variable. This is equivalent to the method used by Story *et al.* (2018) to warp the length dimensions of a single model to those of individual speakers. Segments 1–46 represented the part of the vocal tract behind the posterior openings of the interdental channels. The supralingual cavity was represented by segments 47–60 if the articulation was symmetrical and by segments 47–66 if the articulation was asymmetrical. The anterior cavity was represented by segments 61–63 if the articulation was symmetrical and by segments 67–69 if the articulation was asymmetrical. The interdental channels were represented by an additional 19 segments (for the short channel) and 20 segments (for the long channel). Note that the long channel was merged with the supralingual cavity for asymmetrical articulations.

APPENDIX C: SENSITIVITY ANALYSIS

Complete results of the sensitivity analysis are presented in Table XI. For each speaker and each lateral (/l/ and /ʎ/) the resonance frequencies ($R1$ – $R8$) were measured from transfer function spectra calculated under several conditions. The “baseline” condition represents the unperturbed model whose transfer function spectra are shown in Figs. 7 and 8, and whose area functions are given in Tables VI and VII. Subsequent conditions (e.g., “pharynx,” “short lat,” “anterior”) indicate which part of the area function was manipulated. The abbreviation “lat” stands for “interdental (lateral) channel.” The “measurement” condition presents the acoustically measured formant frequencies in the columns of their corresponding calculated resonances. Percentage changes in resonance frequencies described in Sec. IV B are derived from the resonance frequencies presented in Table XI.

¹Five of the speakers were from São Paulo City. The sixth speaker was from Ribeirão Preto in São Paulo State. Technically, Paulistano refers to the dialect spoken in São Paulo City. The dialect of the speaker from Ribeirão Preto is technically Interior Paulista. The main differences between these dialects are the stronger sounding approximant rhotic and a slower rhythm outside of São Paulo City. These differences do not affect the present study.

²Speaker 1 produced the word *calo* [kalu] 1.SG “shut up” instead of *galo*.

³While there are differing opinions on exactly how to transcribe Brazilian Portuguese, the transcriptions presented here are based on information provided in Azevedo (2005). Another common transcription system is presented in Barbosa and Albano (2004).

⁴Charles and Lulich (2018) suggest that the contrast between /l/ and /ʎ/ before front vowels is largely neutralized.

⁵The toolbox, called “WASL,” is available for free download at <http://www.indiana.edu/~spliu/WASL.html> (Last viewed May 21, 2019).

⁶See supplementary material at <https://doi.org/10.1121/1.5109565> for a video of tongue surface movement relative to the palate for the word *pala* produced by speaker 1.

- Azevedo, M. M. (2005). *Portuguese: A Linguistic Introduction* (Cambridge University Press, New York).
- Bangayan, P., Alwan, A., and Narayanan, S. (1996). “From MRI and acoustic data to articulatory synthesis: A case study of the lateral approximants in American English,” in *International Conference on Spoken Language Processing*, pp. 793–796.
- Barberena, L. d. S., Keske-Soares, M., and Berti, L. C. (2014). “Description of the articulatory gestures concerned in the production of the sounds /r/ and /l/,” *Audiol. Commun. Res.* **19**(4), 338–344.
- Barbosa, P. A., and Albano, E. C. (2004). “Brazilian Portuguese,” *J. Int. Phonetic Assoc.* **34**(2), 227–232.
- Boersma, P., and Weenink, D. (2018). “Praat: Doing phonetics by computer (version 6.0.27) [computer program],” <http://www.praat.org> (Last viewed March 18, 2017).
- Cavar, M. E., Lulich, S. M., and Nelson, M. (2017). “Allophonic variation of Polish vowels in the context of prepalatal consonants,” *Proc. Mtgs. Acoust.* **30**, 060007.
- Charles, S., and Lulich, S. M. (2018). “Case study of Brazilian Portuguese laterals using a novel articulatory-acoustic methodology with 3D/4D ultrasound,” *Speech Commun.* **103**, 37–48.
- Dalston, R. (1975). “Acoustic characteristics of English /w,r,l/ spoken correctly by young children and adults,” *J. Acoust. Soc. Am.* **57**, 462–469.
- Dang, J., and Honda, K. (1997). “Acoustic characteristics of the piriform fossa in models and humans,” *J. Acoust. Soc. Am.* **101**, 456–465.
- de Oliveira, M. A. (1983). “Phonological variation and change in Brazilian Portuguese: The case of the liquids,” Ph.D. thesis, University of Pennsylvania, Philadelphia.
- Espy-Wilson, C. Y. (1989). “The influence of selected acoustic cues on the perception of /l/ and /w/,” *J. Acoust. Soc. Am.* **86**, S49–S52.
- Espy-Wilson, C. Y. (1992). “Acoustic measures for linguistic features distinguishing the semivowels /w j r l/ in American English,” *J. Acoust. Soc. Am.* **92**(2), 736–757.
- Fant, G. (1960). *Acoustic Theory of Speech Production* (Mouton, The Hague), pp. 1–328.
- Ferreira, A. B. d. H. (1975). *Novo Dicionário da Língua Portuguesa (New Dictionary of the Portuguese Language)* (Editora Nova Fronteira, Rio de Janeiro).
- Flanagan, J. L. (1972). *Speech Analysis, Synthesis and Perception*, 2nd ed. (Springer, Berlin).
- Giles, S. B., and Moll, K. L. (1975). “Cinefluorographic study of selected allophones of English /l/,” *Phonetica* **31**(3–4), 206–227.
- Hwang, Y., Charles, S., and Lulich, S. M. (2019). “Articulatory characteristics and variation of Korean laterals,” *Phonetics Speech Sci.* **11**(1), 19–27.
- Johnson, K. (2012). *Acoustic and Auditory Phonetics* (Wiley-Blackwell, Malden, MA).
- Ladefoged, P., and Maddieson, I. (1996). *The Sounds of the World's Languages* (Blackwell, Malden, MA).
- Lisker, L. (1957). “Minimal cues for separating /w, r, l, y/ in intervocalic position,” *WORD* **13**, 257–267.
- Lulich, S. M. (2006). “The role of lower airway resonances in defining vowel feature contrasts,” Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA.
- Lulich, S. M. (2018). “Registration and fusion of 3D head-neck MRI and 3D/4D tongue ultrasound,” *J. Acoust. Soc. Am.* **144**, 1904–1904.
- Lulich, S. M., Alwan, A., Arsikere, H., Morton, J. R., and Sommers, M. S. (2011). “Resonances and wave propagation velocity in the subglottal airways,” *J. Acoust. Soc. Am.* **130**, 2108–2115.
- Lulich, S. M., Berkson, K. H., and de Jong, K. (2018). “Acquiring and visualizing 3D/4D ultrasound recordings of tongue motion,” *J. Phonetics* **71**, 410–424.
- Lulich, S. M., Cavar, M. E., and Nelson, M. (2017a). “Three-dimensional ultrasound images of Polish high front vowels,” *Proc. Mtgs. Acoust.* **30**, 060006.
- Lulich, S. M., Charles, S., and Lulich, B. (2017b). “The relation between tongue shape and pitch in clarinet playing using ultrasound measurements,” *J. Acoust. Soc. Am.* **141**(3), 1759–1768.
- Maeda, S. (1982). “A digital simulation method of the vocal-tract system,” *Speech Commun.* **1**, 199–229.
- Martins, P., Carbone, I., Pinto, A., Silva, A., and Teixeira, A. (2008). “European Portuguese MRI based speech production studies,” *Speech Commun.* **50**, 925–952.

- Martins, P., Oliveira, C., Silva, A., and Teixeira, A. (2010). "Articulatory characteristics of European Portuguese laterals: A 2D and 3D MRI study," in *FALA2010: VI Jornadas en Tecnología del Habla and II Iberian SLTech Workshop*, pp. 1–4.
- McDonough, J., and Johnson, K. (1997). "Tamil liquids: An investigation into the basis of the contrast among five liquids in a dialect of Tamil," *J. Int. Phonetic Assoc.* **27**, 1–26.
- Narayanan, S., and Kaun, A. (1999). "Acoustic modeling of Tamil retroflex liquids," in *International Congress on Phonetic Sciences*, pp. 2097–2101.
- Narayanan, S. S., Alwan, A. A., and Haker, K. (1997). "Toward articulatory-acoustic models for liquid approximants based on MRI and EPG data. Part I. The laterals," *J. Acoust. Soc. Am.* **101**(2), 1064–1077.
- Narayanan, S. S., Byrd, D., and Kaun, A. (1999). "Geometry, kinematics, and acoustics of Tamil liquid consonants," *J. Acoust. Soc. Am.* **106**, 1993–2007.
- Narayanan, S., Kaun, A., Byrd, D., Ladefoged, P., and Alwan, A. (1996). "Liquids in Tamil," in *International Conference on Spoken Language Processing*, pp. 797–800.
- Oliveira, C., Martins, P., Teixeira, A., Marques, I., and Couto, P. (2011). "An articulatory and acoustic study of the European Portuguese /l/," in *International Congress of Phonetic Sciences*, pp. 1–4.
- Proctor, M. I. (2009). "Gestural characterization of a phonological class: The liquids," Ph.D. thesis, Yale University, New Haven, CT.
- Proctor, M. (2011). "Towards a gestural characterization of liquids: Evidence from Spanish and Russian," *Lab. Phonol.* **2**(2), 451–485.
- Recasens, D. (1996). "An articulatory-perceptual account of vocalization and elision of dark /l/ in the Romance languages," *Lang. Speech* **39**, 63–89.
- Scobbie, J. M., Wrench, A. A., and van der Linden, M. L. (2008). "Head-probe stabilisation in ultrasound tongue imaging using a headset to permit natural head movement," in *8th International Seminar on Speech Production*, pp. 373–376.
- Silva, A., Martins, P., Oliveira, C., and Teixeira, A. (2014). "Quantitative analysis of /l/ production from RT-MRI: First results," in *Advances in Speech and Language Technologies for Iberian Languages* (Springer, Cham, Switzerland), pp. 30–39.
- Sproat, R., and Fujimura, O. (1993). "Allophonic variation in American English /l/ and its implications for phonetic implementation," *J. Phonetics* **21**(21), 291–311.
- Stevens, K. N. (1998). *Acoustic Phonetics* (MIT Press, Cambridge, MA).
- Stone, M., Faber, A., Raphael, L. J., and Shawker, T. H. (1992). "Cross-sectional tongue shape and linguopalatal contact patterns in [s], [ʃ], and [l]," *J. Phonetics* **20**(2), 253–270.
- Story, B. H., Titze, I. R., and Hoffman, E. A. (1996). "Vocal tract area functions from magnetic resonance imaging," *J. Acoust. Soc. Am.* **100**(1), 537–554.
- Story, B. H., Vorperian, H. K., Bunton, K., and Durtschi, R. B. (2018). "An age-dependent vocal tract model for males and females based on anatomic measurements," *J. Acoust. Soc. Am.* **143**(5), 3079–3102.
- Tabain, M., and Beare, R. (2018). "An ultrasound study of coronal places of articulation in Central Arrernte: Apicals, laminals and rhotics," *J. Phonetics* **66**, 63–81.
- Tabain, M., Butcher, A., Breen, G., and Beare, R. (2016). "An acoustic study of multiple lateral consonants in three Central Australian languages," *J. Acoust. Soc. Am.* **139**(2), 890–903.
- Teixeira, A., Martins, P., Oliveira, C., Ferreira, C., Silva, A., and Shosted, R. (2012a). "Real-time MRI for Portuguese," in *International Conference on Computational Processing of the Portuguese Language*, pp. 306–317.
- Teixeira, A., Martins, P., Oliveira, C., and Silva, A. (2012b). "Production and modeling of the European Portuguese palatal lateral," in *International Conference on Computational Processing of the Portuguese Language*, pp. 318–328.
- The MathWorks. (2018). "MATLAB" (version 9.2) [computer program], Natick, MA, available at <https://www.mathworks.com> (Last viewed May 2018).
- Zhang, Z., and Espy-Wilson, C. Y. (2004). "A vocal-tract model of American English /l/," *J. Acoust. Soc. Am.* **115**(3), 1274–1280.
- Zhang, Z., Espy-Wilson, C., and Tiede, M. (2003). "Acoustic modeling of American English lateral approximants," in *EUROSPEECH-2003*, Geneva, Switzerland, pp. 2393–2396.
- Zhou, X. (2009). "An MRI-based articulatory and acoustic study of American English liquid sounds /r/ and /l/," Ph.D. thesis, University of Maryland, College Park.
- Zhou, X., Espy-Wilson, C., Boyce, S., Tiede, M., Holland, C., and Choe, A. (2008). "A magnetic resonance imaging-based articulatory and acoustic study of 'retroflex' and 'bunched' American English /r/," *J. Acoust. Soc. Am.* **123**, 4466–4481.
- Zhou, X., Espy-Wilson, C. Y., Tiede, M., and Boyce, S. (2010). "An MRI-based articulatory and acoustic study of lateral sound in American English," in *International Conference on Acoustics, Speech, and Signal Processing* (Institute of Electrical and Electronics Engineers, Dallas, TX), pp. 4182–4185.