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Research Article

Evidence for active control of tongue lateralization in Australian English /l/

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ABSTRACT

Research on the temporal dynamics of /l/ production has focused primarily on mid-sagittal tongue movements. This study reports how known variations in the timing of mid-sagittal gestures are related to para-sagittal dynamics in /l/ formation in Australian English (AusE), using three-dimensional electromagnetic articulography (3D EMA). The articulatory analyses show (1) consistent with past work, the temporal lag between tongue tip and tongue body gestures identified in the mid-sagittal plane changes across different syllable positions and vowel contexts; (2) the lateral channel is largely formed by tilting the tongue to the left/right side of the oral cavity as opposed to curving the tongue within the coronal plane; and, (3) the timing of lateral channel formation relative to the tongue body gesture is consistent across syllable positions and vowel contexts, even as the temporal lag between tongue tip and tongue body gestures varies. This last result is particularly informative with respect to theoretical hypotheses regarding gestural control for /l/s, as it suggests that lateral channel formation is actively controlled as opposed to resulting as a passive consequence of tongue stretching. These results are interpreted as evidence that the formation of the lateral channel is a primary articulatory goal of /l/ production in AusE.

1. Introduction

The lingual kinematics associated with /l/ as observed in the mid-sagittal plane have been well-documented and show interesting patterns of variation in various dialects of English (e.g., Sproat & Fujimura, 1993; Browman & Goldstein, 1995; Ladefoged & Maddieson, 1996; Turton, 2017; Scobbie & Pouplier, 2010; Strycharczuk et al., 2020). In the present study, we investigated /l/ in Australian English. /l/ production typically involves the following characteristics: tongue tip raising, tongue middle lowering, tongue dorsum retraction, para-sagittal tongue blade lowering to facilitate lateral airflow, and jaw lowering to increase available space for lingual articulation (Mooshammer, Hoole, & Geumann, 2006; Tabain, 2009; Recasens, 2012). Whether and how these various movements are functionally related remains an open question.

Browman and Goldstein (1995) found that /l/ involves an apical extension of the tongue tip in a raising movement (coronal) and a tongue body[1] lowering/retraction (dorsal) movement. These movements were identified in the environment of the vowel /i/, e.g., words like *leap* and *peal*. The relative timing of these two movements varies according to syllable position as well as sentential context (Sproat & Fujimura 1993). Scobbie and Pouplier (2010) elaborated on this finding using electropalatography (EPG) data associated with the production of word-final /l/, varying the following context while keeping the preceding context constant (i.e. the high-front vowel /i/). They found that the realization of /l/s in various contexts all involve both tongue tip raising and tongue dorsum retraction movements. They also showed that both vocalized and syllable final /l/s have these two tongue movements. Using a corpus of ultrasound data,

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[1] Tongue body includes tongue middle and tongue dorsum.

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Strycharczuk and Scobbie (2019) found that /l/-vocalization primarily reflects a gradient weakening of the tongue tip movements (from full contact to full reduction) in Southern British English. These studies provide detailed description of contextual variation for /l/; however, they focused largely on kinematic movements observed in the mid-sagittal plane and/or did not consider the sides of the tongue to be under active control. The goals of the present study are (1) to extend empirical coverage of /l/ articulation to include the sides of the tongue, and (2) to assess whether such para-sagittal movements are under active control. Evidence of active control of para-sagittal movements would have implications for how we proceed in modelling high dimensional articulation in terms of low dimensional dynamics. In particular, it would necessitate further development of 3D models of vocal tract control so that we can compute the interaction between constrictions. On the other hand, if para-sagittal movements are not under active control, it may be possible to derive their movement from controlled constrictions in the mid-sagittal plane, simplifying the relation between articulatory kinematics and control structures.

A few authors have speculated that /l/ production requires active control of movements observable in the mid-sagittal plane as well as para-sagittal tongue movements not directly observable in the mid-sagittal plane (Sproat & Fujimura, 1993; Lindblad & Lundqvist, 2003; Proctor, 2011). According to Sproat and Fujimura (1993), /l/s are produced with a narrowed tongue blade, which causes the lateral channel(s) to be opened, although they were not able to observe this directly in their X-ray microbeam data (which was mid-sagittal only). Lindblad and Lundqvist (2003) proposed that the lateral transverse tongue compression makes the tongue longer. This is because the volume of the tongue is constant and the position of the tongue tip is relatively stable compared to other coronal consonants. The transverse compression thus causes the tongue to be expanded backwards, resulting in apparent tongue dorsum retraction.

In addition to these studies, Narayanan, Byrd and Kaun (1999) suggested that /l/ production goes beyond mid-sagittal constriction targets. On their account, 3D tongue shape and the dynamics of the underlying tongue shape formation are all playing a role in /l/ production. Their data included the use of multiple techniques: static palatography, structural magnetic resonance imaging (MRI) and electromagnetic articulography (EMA) in the mid-sagittal plane. Similarly, in the case of onset /l/s in English, and /l/s in other languages where the tongue dorsum movement does not result in lingual elongation, it has been proposed that the tongue blade movement might be actively controlled (Proctor, 2011). Alternatively it may be possible to obtain the lateral side channels characteristic of /l/ as a passive consequence of the active control of mid-sagittal gestures (Browman & Goldstein, 1995).

More recently, articulatory data tracking para-sagittal kinematics has allowed a more refined characterization of /l/ production. Katz, Mehta, Wood and Wang (2017) measured four alveolar consonants (/ɹ/, /l/, /z/ and /d/) using 3D electromagnetic articulography (EMA) with a tongue tip sensor, an anterior tongue dorsum sensor (4 cm from the tongue tip sensor), and a para-sagittal tongue sensor placed on the participant-left side of the tongue (2 cm from the tongue tip sensor and 1.5 cm left from the mid-line). Tongue shape information supplied by this left para-sagittal tongue sensor was used to improve description of consonant manner of articulation in American English (AmE). They devised a measure to assess the lateral positional change of the left para-sagittal tongue sensor relative to the change of the tongue tip sensor. Results showed that the left para-sagittal tongue sensor did not play an important role in differentiating consonants /d/, /l/ and /r/.

An EPG study by Gick, Allen, Roewer-Després, and Stavness (2017) provides a possible explanation for this result. They found that most consonants and vowels were produced with some degree of lateral bracing but that loss of lateral contact was observed in two contexts: in low vowel contexts and during /l/ production. They found that complete lateral contact loss is affected by syllable position. Overall, complete lateral loss was more likely to occur in syllable-coda /l/s than in syllable-onset /l/s. Also, they observed an asymmetrical release pattern for /l/ in cases of complete lateral contact loss and in cases of unilateral contact loss. In cases of complete lateral contact release, the release was sequential: that is, one side of the tongue released first, followed by the other side of the tongue. In cases of unilateral release, the lateral release occurred on either the speaker's left or right side of the tongue. This, together with the Katz et al. (2017), raises the possibility that instead of asymmetrical lowering of the sides of the tongue, the lateral channel is formed by tilting the tongue either to the left or to the right. The higher left para-sagittal tongue sensor observed in Katz et al. (2017) could have arisen if participants in that study happened to tilt the tongue to the right. Howson and Kochetov's (2015) 3D EMA data on Czech liquids lend further credence to this possibility. They placed para-sagittal tongue sensors on both the left and right sides of the tongue, as well as three sensors in the mid-sagittal plane (tongue tip, tongue middle, tongue dorsum). They observed that, in Czech /l/, a tongue dorsum retraction movement appears to be coordinated with a tongue tip raising movement, just as in English. In addition, there were differences in the height of the para-sagittal tongue sensors between /r/ and /l/: the left side of the tongue was lower for /l/ than for /r/ but on the right side there was no difference. On the basis of this data, it seems that, in Czech as well as English, lateralization may involve asymmetrical lowering of the sides of the tongue. Direct observation of para-sagittal tongue movements has improved characterization of the kinematics for /l/, but questions about the dynamics, including active para-sagittal control, still remain unanswered.

A fundamental issue in articulatory research is determining how the observed movements of the speech articulators (i.e., the articulatory kinematics) inform hypotheses about the dynamics of the gestures that control movements. We assume, following Articulatory Phonology (AP), that gestures are dynamic units that control coordinated, task-directed movements of articulators within the vocal tract (Browman & Goldstein, 1989) and are specified by tract variables (i.e., task goals) in the task dynamic (TD) model (Saltzman & Kelso, 1987; Saltzman, 1986). The AP/TD model uses explicit mathematical equations to provide a task dynamic characterization of articulation. The value of the tract variable changes over time, but the goal remains invariant. This is not to say that gestures and movements are the same. The gesture dynamics define a low dimensional control structure, whereas the kinematics are at the physical level of observable articulators. Although kinematics are not the same as dynamics, there can be little doubt that physical movements are the best substance from which to infer abstract gestures. Working from the task dynamics model enables a direct link between the temporal invariance of gestural units and the temporal continuity of their phonetic substance (Saltzman, 1986; Browman & Goldstein, 1989; Gafos & Benus, 2006).

Even as our understanding of the kinematics of /l/ has improved with several recent studies, questions about the dynamics remain. Using computational simulation, Browman and Goldstein (1995) showed that it is plausible that /l/ could be produced with active control of only mid-sagittal movements. That is, the para-sagittal kinematics of /l/ may follow from a dynamical control regime that only specifies mid-sagittal articulatory goals. According to this account, lateral channel formation is a passive consequence of longitudinal tongue stretching. Their viewpoint is in contrast to the hypothesis that lateral channel formation is under active control (Sproat & Fujimura, 1993; Proctor, 2011) and other proposals suggesting that tongue shape may be under active control. The proposals about tongue shape come from real-time (RT) MRI studies observing consistent tongue body lowering and retraction for /l/. Smith and Lammert (2013) investigated the production of vocalized syllabic /l/ in AmE using RT MRI. In contradiction to previous research (Hardcastle & Barry, 1989; Giles & Moll, 1975), the findings from their study suggest that the tongue blade lowering movement, which is hypothesized to be related to lateral channel formation, also occurs in vocalized /l/. In another study, Smith (2014) examined the sequence of achievement of both constriction formation and tongue shape (which may be seen as the true production goal) during /l/ production using RT MRI data. Two types of measures were used; one captured the constriction formation or tongue shape, and the other captured temporal achievements of these articulation events (e.g., time point for tongue tip closure, greatest tongue body retraction, and greatest degree of tongue curling). Edge tracking for the tongue contour was performed along the mid-sagittal plane with a view of the entire vocal tract including glottis, pharynx, and oral and nasal cavities. Smith (2014) found that the sequence for /l/ production appears to be tongue tip closure followed by tongue blade curvature, and then tongue body retraction in onset /l/s. In coda /l/s, the sequence appears to be tongue body retraction, followed by tongue blade curvature and tongue tip closure. Smith (2014) argued that tongue blade curling may be an active goal of /l/ production along with tongue body retraction, and tongue tip closure may be a form of tongue bracing that assists the real production goals. Unlike the proposals about a tongue shape target in terms of global vocal tract shape (Mattingly, 1990; Iskarous, 2005), the focus of the present study is on plausible gesture-based movements of the tongue, including possible gestural control of para-sagittal movement.

Some of the theoretical proposals for /l/ production in the studies reviewed above would require changes to the AP/TD model. In AP, gestures are currently specified by eight tract variables, which are a discrete set of parameters that describe the configuration of one or more vocal tract articulators: lip protrusion (upper and lower lips/jaw), lip aperture (upper and lower lips/jaw), tongue tip constriction degree (tongue tip/tongue body/jaw), tongue tip constriction location (tongue tip/tongue body/jaw), tongue body constriction degree (tongue body/jaw), tongue body constriction location (tongue body/jaw), velic aperture (velum), and glottal aperture (glottis). Gestures in AP are specified by two tract variables for each oral articulator: constriction degree (CD) and constriction location (CL). Notably absent from the list is a gesture for lateral channel formation. This is, in part, because early simulations showed that /l/ could be produced through the tongue stretching driven by antagonistic gestures without active control of the lateral channel. However, mounting empirical evidence suggests that it is appropriate to consider active lateral control within the AP framework.

1.1. The present study

The aim of the present study was to collect data that would bear on the production goals of /l/. This includes verifying what is already known about /l/ variation in the mid-sagittal plane, augmenting these findings with new direct articulographic data on para-sagittal movement during /l/ formation, and creating new metrics for quantifying changes in para-sagittal movements over time. To investigate the articulatory goals of /l/ production, we sought to determine the kinematic relationship between mid-sagittal and para-sagittal movements. To capitalize on known systematic contextual variations in the timing of mid-sagittal gesture movements, syllable position was manipulated. Specifically, syllable-onset and syllable-coda /l/s were examined in English words of the form /ˈCVb.lət/ and /ˈ(C)Vl.bət/. This manipulation is known to influence gestures in the mid-sagittal plane during production of /l/; our study examines whether there is also concomitant variation in the para-sagittal dynamics of lateral channel formation. Additionally, preceding vowel context was manipulated to be either /æ/ or /ɪ/. By varying the vowel in this way, we hoped to introduce variation in the starting position of the articulators that could aid in exposing gesture control (e.g., Shaw, Durvasula, & Kochetov, 2019; Shaw & Chen, 2019; Shaw, Gafos, Hoole, & Zeroual, 2011). To this end, the vowels were chosen because of the different constraints that they place on the shape of the tongue preceding /l/. In particular, /æ/ and /ɪ/ differ in the shape of the tongue blade within the coronal plane. According to a three-dimensional (3D) ultrasound study by Stone and Lundberg (1996), /æ/ has a medial groove tongue shape, such that the sides of the tongue are curved up (instead of curved down as in /l/) to form a spoon-shaped, concave configuration in the coronal plane, a shape which conflicts with lateral channel formation. In contrast, if we look in the coronal plane, a high front vowel such as /ɪ/ shows a convexity in tongue blade in the coronal plane (Stone & Lundberg, 1996), which does not conflict (i.e., is more compatible) with the tongue shape required for /l/.

The variation that syllable position and vowel context induce on the timing of mid-sagittal movements for /l/ is used in the present study to investigate articulatory control of para-sagittal tongue height in Australian English (AusE), using 3D electromagnetic articulography (EMA). Much of the past work described above focuses on AmE or varieties of British English. Although there are no articulatory studies on AusE /l/, there are some acoustic and impressionistic observations.

Syllable-final /l/ in AusE has been described as more like the vowel /u/ than AmE, and AusE syllable-final /l/ may be more likely to be partially vocalized than AmE syllable-final /l/ (Borowsky & Horvath, 1997). For this reason, we only selected speakers who do not noticeably vocalize their final /l/s (see Section 2.1). Another difference between AusE and AmE is the quality of the context vowels. The two context vowels are realized differently in AusE than in AmE. Table 1 summarizes formant frequency of /ɪ/ and /æ/ for AusE and AmE female speakers from both older datasets and more recent datasets (Cox, 2006; Cox & Palethorpe, 2007; Peterson and Barney, 1952; Hillenbrand, Getty, Clark, & Wheeler, 1995). Articulatorily, /æ/ in AusE is lower and more retracted when compared to /æ/ in AmE, while /ɪ/ in AusE is slightly more advanced than /ɪ/ in AmE (Blackwood, Shaw, & Carignan, 2017). These differences are transparently reflected in the formant values. Compared to AmE, the distinction between the target vowels chosen for this study is somewhat larger in AusE, with regard to both frontness and height.

In the present study, sensors were located at key points on the midline to replicate past work, and on the sides of the tongue blade to track lateralization. To investigate the dynamics of lateralization during the production of /l/, both mid-sagittal and para-sagittal articulographic measures were used. The mid-sagittal analysis was designed to investigate the effects of syllable position on coordination of mid-sagittal gesture movements, while we created a para-sagittal analysis that was designed to index the stability of lateral channel formation relative to the mid-sagittal movements across our syllable manipulation.

1.2. Hypotheses and predictions

Since /l/ involves multiple articulatory movements, a natural theoretical question is how these movements are related. Phonological representation of /l/ has included characterization as [+coronal] and [+lateral] (Chomsky & Halle, 1968). According to Sproat and Fujimura (1993, p.304), the [+coronal] specification refers to the tongue tip raising gesture (which they refer to as an “apical gesture”). They assumed that /l/s are produced by actively controlling the tongue blade to form the lateral channel(s). This is the [+lateral] aspect of the representation. Since the tongue’s volume is incompressible, reducing tongue blade volume displaces some of the volume towards the anterior and posterior ends of the tongue. On their theoretical account, the tongue dorsum retraction observed in the mid-sagittal plane is a passive consequence of active control of tongue width which displaces tongue body volume rearward (retracted).

Browman and Goldstein (1995, p. 21) discussed a contrasting theoretical hypothesis to the one put forth by Sproat & Fujimura (1993). In the language of Articulatory Phonology, tongue movements are represented by articulatory gestures. Browman and Goldstein (1995) proposed that /l/ consists of two gestures: a tongue tip raising gesture and a tongue dorsum retraction gesture. They considered that any lateral channel could be a passive consequence of tongue stretching due to active control of mid-sagittal gestures.

Both Sproat and Fujimura (1993) and Browman and Goldstein (1995) present theoretical hypotheses that are consistent with observations about tongue kinematics in the mid-sagittal plane, using experimental tools that were available at the time. Scobbie and Pouplier (2010) took a step further; their investigation of English word-final /l/ using EPG has shown that tongue tip raising and tongue dorsum retraction movements in the mid-sagittal plane can also be observed in vocalized /l/s. The competing hypotheses can be differentiated by extending empirical coverage to include the relation between mid-sagittal and para-sagittal tongue kinematics.

The experimental design of the current study incorporates a factor known to influence the timing of the mid-sagittal movements observed for /l/: syllable position. We expect that, as observed in other varieties of English (Sproat & Fujimura, 1993; Browman & Goldstein, 1995; Krakow, 1989; Campbell & Gick, 2003; Gick, Campbell, Oh, & Tamburri-Watt, 2006; Strycharczuk & Scobbie, 2019; Proctor et al., 2019), syllable position will affect the relative timing of tongue tip (TT) and tongue body (TB) gestures. This expectation is schematized in Fig. 1. For onset /l/s, TT and TB gesture coordination should be nearly synchronous, whereas for coda /l/s, the TB gesture should start prior to the TT gesture (see Fig. 1). We refer to the measured timing of the onsets of the TT gesture relative to the TB gesture as “lag”. There should be a near-zero lag value or a very slight negative lag value in onset /l/s, and a positive lag value in coda /l/s. What is currently unknown is how the timing of lateral channel formation fits into the timing relationships illustrated in Fig. 1.

The competing hypotheses about lateral channel formation introduced above make different predictions for the timing of para-sagittal tongue (PT) movement (“lateralization”) relative to TB movements:

H1: Active control of lateral channel formation (as hypothesized in Sproat and Fujimura, 1993) predicts a consistent lag between the onset of lateralization and the onset of TB movement. This is because TB retraction is assumed in this hypothesis to be a passive side effect of lateralization.

H2: If lateralization is instead a passive consequence of the mid-sagittal tongue elongation (as hypothesized in Browman & Goldstein, 1995), we expect variations in the lateralization lag relative to TB movement, across syllable positions. The timing of lateral channel formation should vary with the timing of the antagonistic TT and TB gestures that condition passive lateral channel formation. Asynchrony between the TB and TT gestures in coda position should, according to this hypothesis, result in a delay in lateral channel formation relative to the TB gesture.

Fig. 2 shows conceptual plots of the competing hypotheses: active (left panel) and passive (right panel) lateralization for onset and coda /l/s. White bars represent gestures under direct control; gray bars represent indirect control, i.e., passive consequences of other gestures. The left panel illustrates the gesture scores of active lateralization, in which the para-sagittal tongue blade (PT) gesture and TT gesture act as independent active gestures in two different syllable positions (onset vs. coda). TB movement only occurs during the active PT gesture. This is to say that the PT gesture and the TB movement are time-locked (Sproat & Fujimura, 1993). The right panel shows passive lateralization, in which the PT movement is the consequence of TT and TB gestures (Browman & Goldstein, 1995). The duration of the passive PT movement should coincide with the temporal overlap of the active TT and TB gestures.

Table 1
Summary of formant frequency for AusE and AmE female speakers from old datasets and recent datasets. The AusE data reported below are from Cox (2006), Cox and Palethorpe (2007), and the AmE data are from Peterson and Barney (1952) and Hillenbrand, Getty, Clark, and Wheeler (1995). In the data column, C 2006 refers to Cox's (2006) study, C 2007 refers to Cox's (2007) study, PB refers to Peterson and Barney's (1952) study and HGCW refers to Hillenbrand, Getty, Clark, and Wheeler's (1995) study.

Vowel	Data	AusE		Data	AmE	
		F1	F2		F1	F2
æ	C 2006	850	2000	PB 1952	700	2300
	C 2007	1050	1900	HGCW 1995	900	2100
ɪ	C 2006	400	2500	PB 1952	450	2400
	C 2007	450	2500	HGCW 1995	500	2300

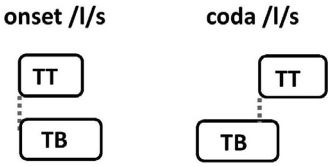

Fig. 1. Syllable position is expected to affect relative timing of coronal (TT) and dorsal (TB) gestures. In syllable-onset /l/, the TT and TB gestures are almost synchronized, or the TT slightly precedes TB. In syllable-coda /l/, the TB gesture is expected to precede the TT gesture.

Fig. 3 shows a schematic illustration of the kinematics predicted by the competing hypotheses schematized in Fig. 2. The horizontal axis shows time and the vertical axis shows articulator displacement. TT and PT movements are given with reference to vertical position; TB movements are with reference to horizontal position. The white bars represent gesture scores; they show the relative timing between the active gestures. The gray bars represent the duration of the passive movements. These schematic gesture scores are for visualization and illustration purposes only. They do not represent the actual length of temporal activation as estimated from data. Both gestural hypotheses predict similar kinematics for onset /l/ and similar kinematics for the movements in the midsagittal plane. The key difference is in the timing of parasagittal tongue blade movements (lateral channel formation) relative to the TB. The lag between these movements remains stable across onset and coda position on the active lateralization account (H1). In onset /l/s, TT movement and PT movements occur simultaneously (or PT movement occurs slightly later than TT movement), and these two movements are actively controlled, i.e., are gestures in AP terms. TB movement is linked to PT movement: once PT movement starts, TB movement also starts. The same timing relations between

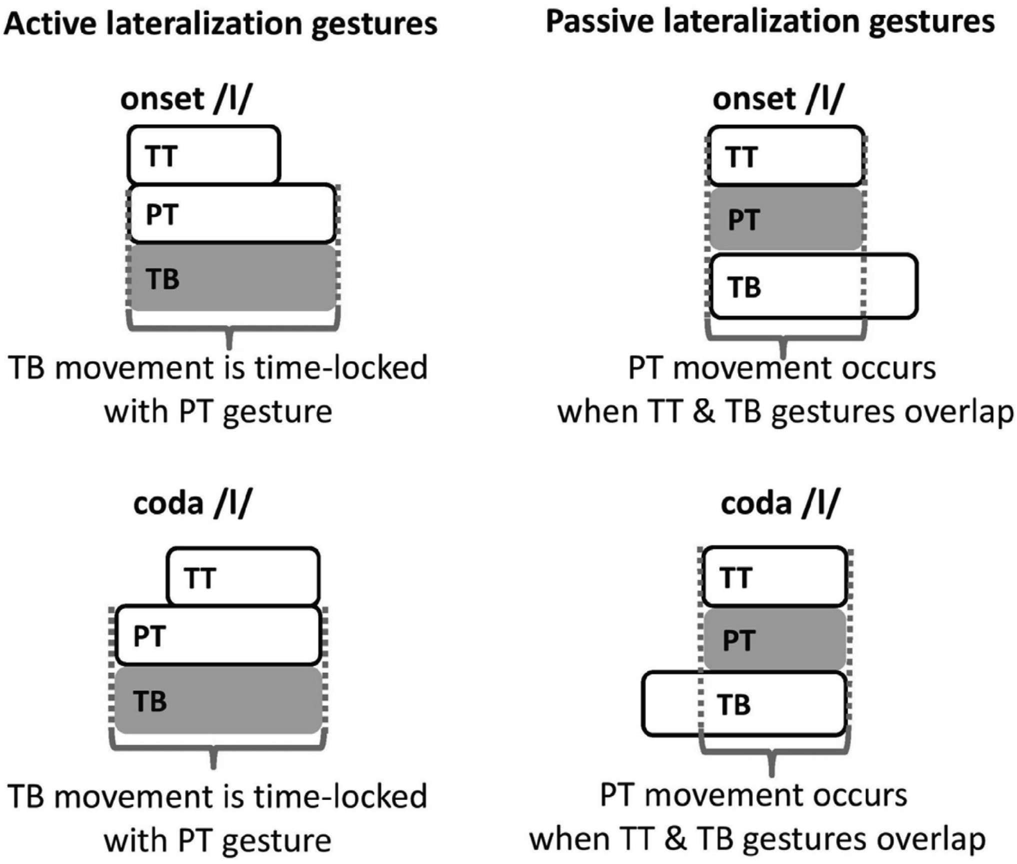

Fig. 2. Conceptual plots of temporal activation duration of active (left panel, H1) and passive (right panel, H2) lateralization for onset and coda /l/s. Active gestures are shown in white bars; passive movements are shown in gray bars. The length of the box in the horizontal dimension indicates the duration of temporal activation. In active lateralization, TT and PT gestures are active; the passive TB movement is time-locked with the PT gesture. In passive lateralization, TT and TB gestures are under direct control and passive PT movement occurs when the two active gestures overlap.

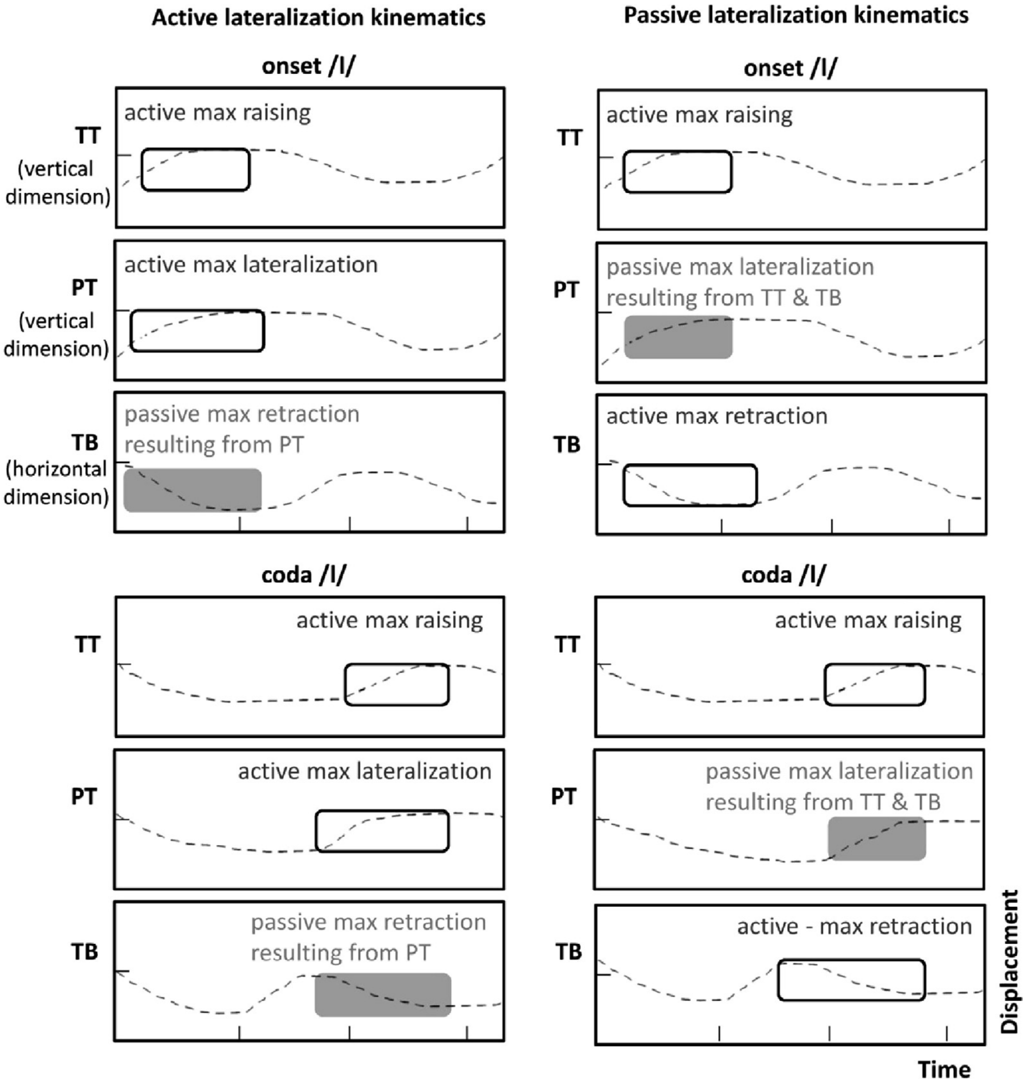

Fig. 3. Schematic illustration of tract variable motions of onset and coda /l/s as predicted by the two hypotheses: active lateralization (H1) on the left column, and passive lateralization (H2) on the right. These tract variable motions are schematic depictions of our hypotheses. The horizontal dimension shows time and the vertical dimension shows displacement. TT and PT movements are shown in the vertical dimension (raising/lowering); TB movements are shown in the horizontal position (advancement/ retraction). The white boxes represent gesture scores; they show the timing of activations for the hypothesized active gestures, relative to the predicted movement trajectories of each articulator (active or passive).

PT and TB movements can be extended to coda /l/s, except that in coda /l/s, TT movement occurs later in time. On the passive lateralization account (H2), the lag between TB and PT is predicted to increase in coda position, owing to the increased lag between the TB and TT gestures. The delay of the onset of the TT movement relative to that of the TB movement also delays tongue elongation, which gives rise, on this hypothesis, to passive lateral channel formation.

The remainder of this paper presents an EMA experiment designed to evaluate the above hypotheses. Section 2 describes the methods, including details about sensor placement and the analytical methods used. Section 3 reports the results, starting with the effect of our experimental manipulations, syllable position and vowel context, on mid-sagittal gestures and then proceeding to para-sagittal movements. Section 4 provides discussion and conclusions, returning to our hypotheses in light of the results and offering a new proposal for the gestural characterization of /l/.

2. Methods

2.1. Participants

Six monolingual AusE speakers (three females and three males), mean age 22.2 years (range = 19–35 years) participated in the study. All were monolingual speakers of AusE. None of the participants were characterized as having atypical speech, and none had pervasive syllable-final lateral vocalization. Two procedures were used to select speakers. First, a trained phonetician listened to the /l/ tokens, who judged that none of our speakers produced vowel-like final /l/s. Then, the same phonetician visually inspected the articulatory data of the /l/ tokens. A vocalized /l/ is expected to exhibit the loss of coronal articulation (i.e. tongue tip raising). All the /l/s show clear tongue tip fronting and raising articulation.

All participants were living in Sydney at the time of data collection. They were paid for their participation and were naïve to the purpose of the experiment. Written consent was obtained from all participants and the study was conducted with approval from the ethics committee of Western Sydney University.

2.2. Experimental material

/l/s were elicited word-medially in disyllabic words of the form /ˈCVb.lət/ and /ˈ(C)Vl.bət/, allowing comparison of both syllable-onset and syllable-coda /l/s. Target words were read aloud in the carrier phrase "keep __ here", with adjacent /p/ and /h/ chosen to minimize lingual coarticulation effects; /b/ is used in both target forms for this purpose as well. In both syllable-onset and syllable-coda positions, /l/s were preceded by a stressed front vowel, either /æ/ or /ɪ/. The stimuli were presented in 10-word blocks (Table 2), with ten repetitions for each target word randomized across blocks for each participant. Each recording session took approximately 25 minutes for a participant to complete.

2.3. Procedure

Experiments were conducted at the MARCS Institute Analysis of Human Articulatory Actions (AHAA) Laboratory at Western Sydney University. Articulographic data were acquired at a rate of 100 Hz using an NDI Wave EMA system (Northern Digital Inc., Canada). Synchronized companion speech audio was recorded at a 22,050 Hz sampling rate using a Schoeps Colette Series supercardioid microphone and EURORACK UB802 preamplifier. Tongue movements were tracked using three EMA sensors affixed mid-sagittally at the tongue tip (TT; ~5 mm posterior to the apex), tongue middle (TM; ~20 mm posterior to the TT sensor) and tongue dorsum (TD; between 20 and 35 mm posterior to the TM sensor), and another two sensors affixed para-sagitally to the sides of the tongue blade (para-sagittal tongue left – PTL and para-sagittal tongue right – PTR; on the top surface ~5 mm from the edges of the tongue and ~15 mm from both the TT sensor and the TM sensor). The TD sensor was located 45 to 60 mm posterior to the TT sensor, depending on each speaker's comfort level. Fig. 4 provides a schematic of the tongue sensor placement: we developed this 'Southern Cross' configuration to allow measurement of para-sagittal kinematics.

Sensors were also attached to the lower jaw on the gum line between the two central incisors; to the upper lip and lower lip along the vermillion border in the mid-sagittal plane[2]; to the left mastoid (LM) and right mastoid (RM); and to the nasion (NA). The LM, RM and NA sensors were used for correction of head motion for post-collection data processing. Three sensors are required to account for the translation and rotation of the head using x, y, and z coordinates. The occlusal plane (i.e., the so-called "bite plane"; Fig. 4) was determined by having speakers clench a semi-circular protractor between their upper and lower teeth. Two sensors were attached to the corners of the protractor and the third sensor was attached to the center of the circular portion of the protractor to define a rigid occlusal plane.

Participants were familiarized with the target words before recording. Elicitation sentences were presented on a computer monitor placed approximately 120 cm in front of the participant, and participants were instructed to read the sentences at a comfortable speaking rate.

2.4. Data processing and measurements

Articulographic data were corrected for head movement in post-processing and rotated into a common coordinate system: x = front-back; y = left–right; z = up-down. Sensor displacement was expressed with respect to an origin located on the occlusal plane, along the midline and immediately behind the upper incisors. Displacement data from the lingual sensors were filtered and smoothed using a robust DCT-based penalized least squares algorithm (Garcia, 2010).

EMA data were first visualized using MVIEW, a MATLAB-based program developed by Mark Tiede at Haskins Laboratories (Tiede, 2005). MVIEW displays the positional signal of the sensors, time-aligned with the acoustic speech signal. Visualization of the data revealed that /l/ production primarily involved horizontal (x) motion of the TD sensor, and vertical (z) motion of the TM, TT and two para-sagittal tongue sensors.

A set of temporal landmarks was identified in the acoustic signal to define a window in which the articulatory data could be measured. Acoustic landmarks were identified by visual inspection of acoustic waveforms and spectrograms in PRAAT (Boersma & Weenink, 2015), and articulatory analysis was conducted in MATLAB. Inspection of the articulatory movement in MVIEW revealed that the local maximum in TTz typically occurred within the /b/ closure in /ˈ(C)Vl.bət/ (coda /l/) words. In /ˈCVb.lət/ (onset /l/) words, the local maximum in TTz was aligned well with the /ə/ onset. Based on these observations, Vl.b segment sequences for coda /l/ words and Vb.l segment sequences for onset /l/ words were demarcated for analysis using PRAAT. For both, the onset boundary of the target segment sequences was set at the onset of the stressed vowel preceding the /l/, and the offset boundary was set at the beginning of the unstressed vowel following the /l/. This segmentation protocol ensured that the TT gesture extremum (highest position, or peak) associated with /l/ production would occur within the segmentation boundaries for both coda and onset /l/ tokens. Fig. 5 shows two examples of acoustic landmarks in V-/l/ interval produced by female speaker F03.

Three analyses of the data were conducted, one based on mid-sagittal measures and the others on two para-sagittal measures. The mid-sagittal measures used Sproat and Fujimura's (1993) analytic approach, thus extending their investigation to two different vowel contexts and a new English dialect. The two para-sagittal measures were newly created for this study. They were designed to investigate tongue blade curvature in the coronal plane and tongue lateralization, and were used to examine the time course of lateral side-branch formation along the sides of the tongue blade.

2.4.1. Mid-sagittal articulatory measures

To examine the articulatory characteristics of onset and coda /l/s for comparison with the findings from previous studies, the temporal difference between the onset of TT raising (vertical dimension) and the onset of TM lowering (vertical dimension), and the onset of TD retraction (horizontal dimension) was measured. Earlier studies had observed TT raising in both onset and coda /l/s (Giles & Moll, 1975; Sproat &

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[2] The jaw and lip sensor data were not analyzed for the purpose of this study.

Table 2
Target words used to elicit Australian English /l/s. As AusE is a non-rhotic accent, final unstressed -bert is pronounced as [bət].

Tongue shape for preceding vowel	Concave		Convex	
Vowel	æ		ɪ	
Representations	Orthography	IPA	Orthography	IPA
CVC.lVC	*'tablet*	[ˈtæb.lət]	*'tiblet*	[ˈtɪb.lət]
	'cablet	[ˈkæb.lət]	*'kiblet*	[ˈkɪb.lət]
(C)Vl.CVC	*'talbot*	[ˈtæl.bət]	*'tilbert*	[ˈtɪl.bət]
	'calbert	[ˈkæl.bət]	*'kilbert*	[ˈkɪl.bət]
	'albert	[ˈæl.bət]	*'ilbert*	[ˈɪl.bət]

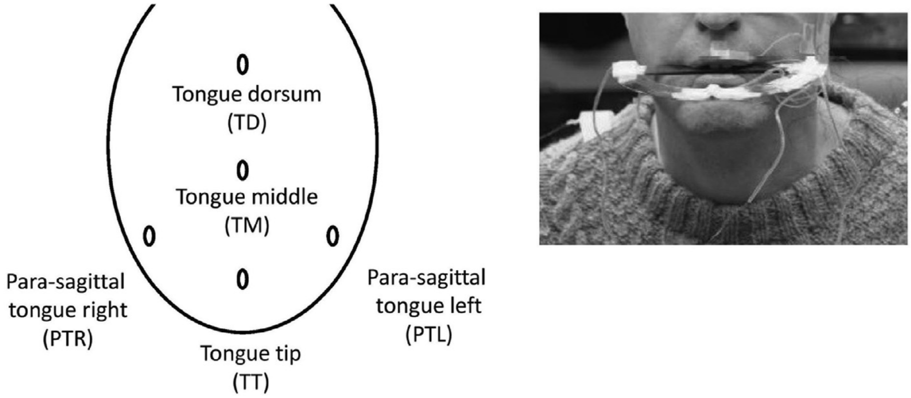

Fig. 4. Tongue sensor positions ('Southern Cross' configuration) for articulographic investigation of /l/ production in Australian English. Left panel: view of tongue from above; Right panel: front view of a participant with the protractor used to locate the occlusal plane held in the mouth; the three sensors taped to the protractor are visible (adapted from Derrick, 2017).

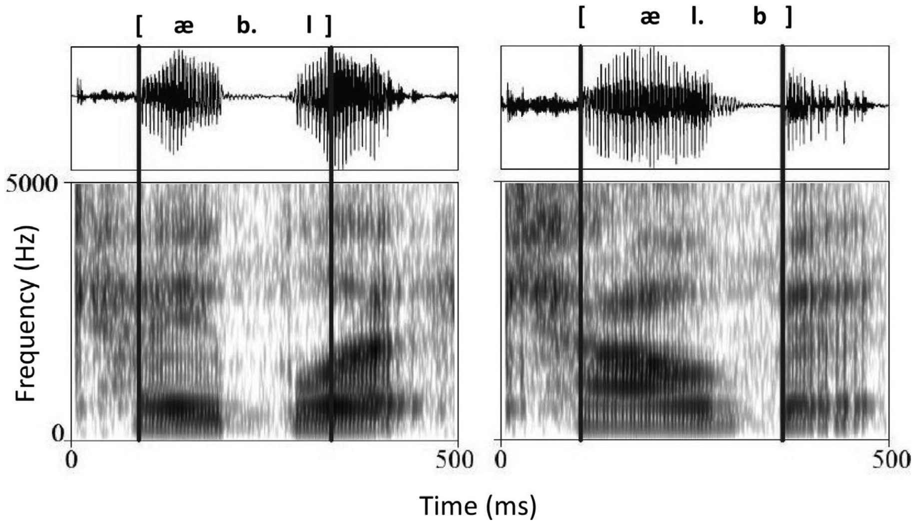

Fig. 5. Identification of analysis window. Acoustic waveform and spectrum of [æb.l] (left) and [æl.b] (right) produced by female speaker F03. Vertical lines indicate limits of analysis window. Left landmark: acoustic onset of stressed pre-lateral vowel; Right landmark: acoustic onset of unstressed post-lateral vowel.

Fujimura, 1993; Browman & Goldstein, 1995; Smith, 2014), along with TM lowering/TD retraction, reporting that TT reaches its extremum earlier in onset /l/s (relative to TM/TD) than in coda /l/s (Sproat & Fujimura, 1993). In the current study, therefore, /l/ production in each token was analyzed in terms of (1) TT advancing and raising, (2) TM lowering, and (3) TD retraction, verified by visual inspection of the sensor trajectories in the analysis window.

The current study focuses on the relative timing between different movements. Articulatory landmarks were determined according to the velocity signal in the movement trajectories of the V-/l/ interval. Then, the associated temporal landmarks were logged. The velocity signals were computed using the following steps. First, the first-order differential was used to calculate the velocity signal in the x and z dimensions. Second, the Euclidian distances of the velocity signals in the x and z dimensions were used to calculate the tangential velocity signals. Third, a 5-sample Boxcar filter was applied to remove any noise in the tangential velocity signals, using the filtfilt function in MATLAB to avoid re-phasing.

The TT extremum (in fronting/raising) was derived from the velocity profiles of the x and z dimensions (i.e., corresponding to the anterior-posterior and the superior-inferior dimensions of the TT sensor, respectively). The TM extremum (with regard to lowering) and the TD extremum were defined by the velocity minima.

Next, an interface script was developed in MATLAB to plot time-aligned TT/TM/TD trajectories from the EMA data within the analysis time-window defined by the acoustic landmarks identified in Sec. 2.4 (see Fig. 6). Then, we estimated specific locations of TT, TM and TD extrema. After that, the interface script would find the true extrema near those locations.

Lags were measured between the time points associated with the TT extremum and the TM extremum (1) of /l/, and between the time points associated with the TT extremum and the TD extremum (2) of /l/:

$$\mathit{TM\ lag} = \mathit{Time\ point\ of\ TT\ extremum} - \mathit{Time\ point\ of\ TM\ extremum} \tag{1}$$

$$\mathit{TD\ lag} = \mathit{Time\ point\ of\ TT\ extremum} - \mathit{Time\ point\ of\ TD\ extremum} \tag{2}$$

These two lag measures were calculated as closely as possible to the method used in Sproat and Fujimura (1993).

2.4.2. Para-sagittal articulatory measures

In order to characterize the relationship between lateral channel formation and midsagittal gestures of TT and TM/TD, we first needed to estimate both curvature and lateralization of the tongue blade in the coronal plane. In order to estimate both of those measures, a mid-sagittal tongue blade sensor is required. A tongue blade "pseudo" (virtual) sensor[3] was mathematically estimated in the mid-sagittal plane from relationships among the para-sagittal and mid-sagittal sensor data, instead of simply using the TT sensor data[4]. The advantage of this virtual sensor is that it is in the same coronal plane as the para-sagittal sensors. This is to say that the virtual sensor moves along the mid-sagittal plane as the para-sagittal sensors move (in relation to the mid-sagittal sensors).

The following steps were used to estimate the mid-sagittal tongue blade sensor. First, a second-order polynomial was fitted to the x (front-back) and z (up-down) dimensions of the three mid-sagittal sensors (TT, TM, TD), thus estimating the mid-sagittal shape of the tongue (concave, flat, or convex). The average of the positions of the para-sagittal tongue sensors (PTR and PTL) in the x dimension was then used to locate an intersection point along this mid-sagittal polynomial. The x, y and z dimension values of this intersection point served as the estimated midline location and height of the tongue blade sensor (virtual TB, or vTB). This virtual sensor represents the intersection of the fitted mid-sagittal (TT-TM-TD) curve in the sagittal plane and the coronal plane at a location between the two para-sagittal sensors (PTR-PTL). The reason we performed this estimation is because we observed that the front-back position (x) of the para-sagittal sensors can move somewhat independently of the mid-sagittal sensors. Because of this, we cannot assume that the angle between the TT (or TM) sensor and the para-sagittal sensors are all at the same coronal plane at different points in time. Our mathematically defined virtual tongue blade sensor effectively solves this problem.

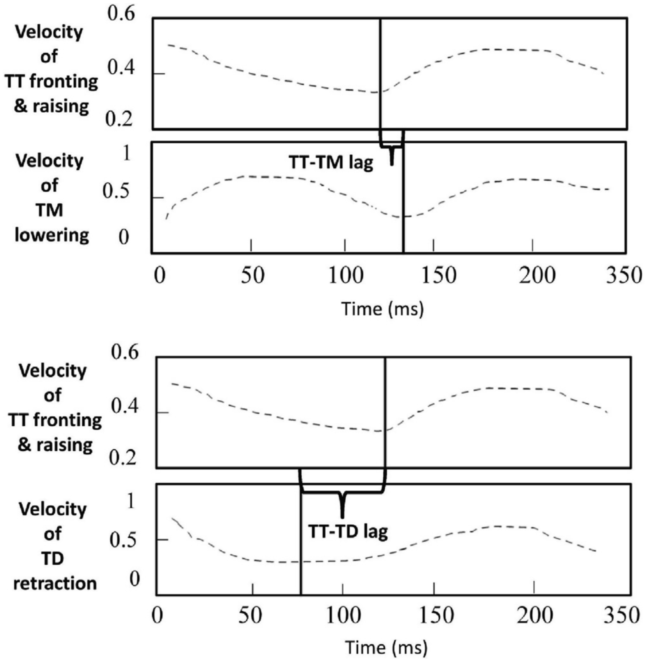

Fig. 6. Schematic illustration of the mid-sagittal articulatory analysis: TT-TM (top panel) and TT-TD lag (bottom panel), indicating the velocity minima of [ˈkæl.b]. Location of velocity minima (vertical black lines) in TT trajectories, TM trajectory, and TD trajectory of /l/, respectively.

In order to track tongue curvature over time, the quadratic term of a second-order polynomial fit to the para-sagittal sensors and the estimated mid-sagittal tongue blade sensor (vTB) was logged (Fig. 7); the quadratic term is used here as an indication of tongue curvature in the coronal plane. Smoothing spline analysis of variance (SSANOVA) was then applied to the temporal trajectories of the quadratic term. Spline smoothing is a technique used to connect discrete data points and find the best fit of a curved line to the data when the data are noisy (Davidson, 2006), and has been extensively employed in speech production research. In this analysis, the general smoothing splines (gss) package in R (Gu, 2002) was used. SSANOVA was used for data visualization and illustration. Linear mixed models (LMMs) were used for hypothesis tests.

In order to measure tongue lateralization in the coronal plane, we created an index of the difference in height (z) between the dominant (i.e., lower) side of the tongue blade (TL in the illustration in Fig. 7) and the mid-sagittal vTB sensor, called ΔHeight (indicated by the arrow next to the inset scale of values in Fig. 7). This measure captures the degree to which each side of the tongue was higher or lower than the estimated mid-sagittal vTB sensor at any given point in time. A value of zero for ΔHeight indicates that the line between the dominant para-sagittal sensor and the vTB sensor is completely horizontal (i.e. flat). A positive value indicates that the line is titled downwards (i.e. greater lateralization). A negative value indicates that the line is titled upwards (i.e. lesser lateralization). The following formula was used to calculate the difference between the estimated tongue blade sensor and the lower of the two para-sagittal sensors in the vertical dimension (3):

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[3] We did not place an additional sensor on the tongue blade, which would result in a crowded sensor configuration, potentially causing position estimation errors and participant discomfort.

[4] The differences in height among the two para-sagittal sensors and TT were also calculated. The analysis based on the TT sensor yielded the same results as that for the mid-sagittal tongue blade virtual sensor.

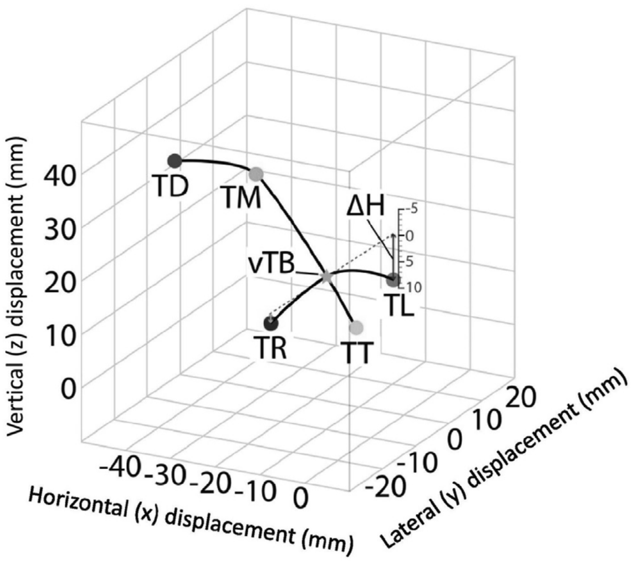

Fig. 7. Schematic illustration of a virtual tongue blade (vTB) sensor and the ΔHeight (tongue lateralization) measure projected in tongue ¾ overhead view. The origin is the center of the occlusal plane (which is about 1 cm below the tongue tip). The vTB sensor was mathematically estimated on the coronal plane perpendicular to the occlusal plane. The vTB sensor is located at the intersection of the coronal polynomial (TL and TR) curve with the sagittal polynomial (TT, TM, and TD) curve.

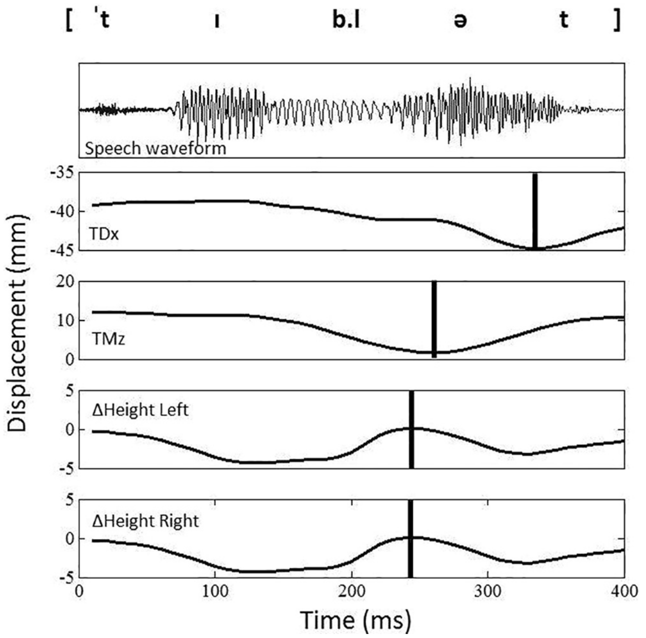

Fig. 8. Comparison of metrics derived from mid-sagittal and para-sagittal articulatory analyses. Example utterance ‘tiblet’ produced by male speaker M08. Top-to-bottom: phonetic transcription; acoustic signal; mid-sagittal front-back dorsal TDx (second row) and vertical medial displacement TMz (third row); ΔHeight right (fourth row); ΔHeight left (fifth row). All vertical axes: displacement (mm). Gestural targets (maximal displacement of relevant part of tongue) indicated with solid black vertical lines. Maximal TDx and TMz displacement correspond to retraction and lowering movements associated with the /l/ in the mid-sagittal articulatory analysis. The same landmarks are interpreted as the onset of tongue lateralization during /l/ production. The point of most extreme tongue lateralization was determined by the extremum of ΔHeight.

$$\begin{aligned} Height &= Estimated\ mid-sagittal\ tongue\ blade\ sensor\ height \\ &\quad - PTLz\ (or\ PTRz) \end{aligned} \tag{3}$$

Only one para-sagittal sensor (the lower of the two) was used in the statistical analyses; this lower sensor is considered the dominant side of tongue lateralization for both by-speaker average dominance analysis and by-token analysis. A summary of each participant’s dominant hand, dominant lateral channel formation and numbers of tokens produced with lowering of the left tongue blade and the right tongue blade is provided in Table I, Appendix A. The time course of lateralization during /l/ production was indexed as the temporal relationship between the mid-sagittal vTB and dominant para-sagittal sensor positions indexed by ΔHeight values over time. SSANOVA was also used to obtain the temporal trajectories of the tongue lateralization represented by ΔHeight.

In the mid-sagittal articulatory analysis, the minima of the velocity signal corresponded to the maxima of the positional signal (Fig. 8) and the positional extrema of TM and TD were interpreted as the onset of /l/. In the para-sagittal articulatory analysis below, the same extrema of TM and TD were instead interpreted as the onset of tongue lateralization during /l/ production. The point of most extreme tongue lateralization was determined by the extremum of ΔHeight. The para-sagittal analyses were conducted using by-token values.

2.4.3. Para-sagittal durational measures

The temporal interval during lateral channel formation is another parameter crucial to understanding the articulation of /l/. In terms of AP, this interval would correspond to the activation duration of the lateralization gestural movement. To estimate this, we identified the point in time when ΔHeight reached its minimum (which corresponds roughly to the vowel nucleus, i.e., the point when the sides of the tongue are highest relative to the midline) and the point in time when ΔHeight was in its maximum (which corresponds to the /l/, i.e., the point when the dominant side of the tongue blade is lowest relative to the midline). The interval between these two points was calculated as the duration of activation of tongue lateralization, which captures the para-sagittal movement in the formation of the vowel and the /l/. Fig. 9 illustrates an example of the activation duration of tongue lateralization for one token of ‘tiblet’. In the Results section, we show the log-transformed values of the activation duration for this analysis.

In order to identify how lateralization relates to the dorsal gesture in the mid-sagittal plane, we extracted the gestural maximum of TM (or TD) of the preceding vowel and the maximum of ΔHeight. For TM/TD, the maximum is the time point associated with the minimum velocity in the TM lowering gesture (z-dimension) and TD retraction gesture (x-dimension), respectively. For ΔHeight, the maximum is the time point associated with the greatest value in the lateralization index (maximum point of achievement of /l/). The temporal lag between achievements of mid- and para-sagittal targets was calculated using (4)[5]:

$$\begin{aligned} Parasagittal\ lateralization\ lag &= Time\ to\ Max\ TM\ (or\ TD) \\ &\quad - Time\ to\ Max\ Height \end{aligned} \tag{4}$$

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[5] We also measured the non-dominant side. The lateralization values (i.e, ΔHeight) were around zero (indicating a flat tongue shape along the coronal plane on the non-dominant side of the tongue) and showed low variability. Thus focusing specifically on the dominant side of the tongue in lateralization provides optimal opportunity for finding contextually conditioned variation.

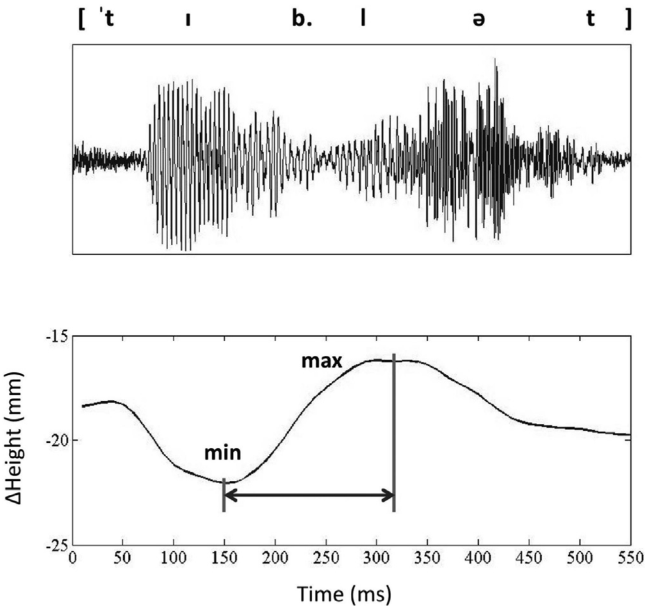

Fig. 9. Activation duration of tongue lateralization. Example utterance ‘tiblet’ produced by female speaker F05. Temporal origin located at syllable-onset consonant release, min point corresponds to onset of lateralization; and max point corresponds to maximal lateralization. The double-ended arrow indicates activation duration of tongue lateralization.

A negative value indicates that the maximum mid-sagittal gestural target (i.e. TM lowering/TD retraction) occurs first, while a positive value indicates that the maximum para-sagittal gestural target occurs first. The para-sagittal lateralization lag offers an important advantage over a single time-point measure of para-sagittal lateralization: the lag identifies both the order and time-course of para-sagittal lateralization, whereas a single time point of peak lateralization does not capture any information before or after the peak of lateralization.

3. Results

This study investigated how known variations in timing of mid-sagittal gestures are related to para-sagittal dynamics in /l/ in AusE. We predicted that syllable position would have an effect on the temporal coordination of /l/. To track lateral channel formation, we used the tongue curvature and lateralization measurements we developed to characterize para-sagittal tongue activities. As described earlier, we formulated two alternative hypotheses based on past work, which make different predictions for the time course of tongue lateralization dependent on whether it is actively controlled or a passive consequence of other active gestures. If lateralization is actively controlled, then the lateralization lag should remain stable across different syllable positions. Alternatively, if tongue lateralization is a passive consequence of mid-sagittal tongue elongation, then the lateralization lag should vary with factors that influence the lag between TT and TM gestures.

3.1. Mid-sagittal articulatory measure analyses

Lag values between TT and TM (TT–TM lag) for /l/s produced in syllable-onset and -coda positions, and in /æ/ and /ɪ/ contexts, are compared in Fig. 10. The (positive) lag is greater for the /l/s produced in /æ/ context than for the /l/s produced in /ɪ/ context. Across both vowels, the (positive) lag is longer for syllable-coda /l/ than for syllable-onset /l/. This indicates that TB retraction precedes TT raising in syllable-coda position. In syllable-onset position, TT and TM gestural movements are almost synchronous following /ɪ/. For onset /æ/, there is a slightly longer (positive) TT-TM lag (compared to the vowel /ɪ/) for both syllable positions, although the lag in onset is shorter than the lag in coda position.

TT-TM lag was modelled as a linear function of syllable position and vowel context, using linear mixed effects models constructed with the lme4 package (Bates et al. 2014) in R (version 3.0.2). The fixed effects were vowel (/æ/ and /ɪ/) and syllable position (onset and coda). The models contained a random slope and intercept for the effect of vowel and syllable for each speaker. Table 3 compares the two-factor model and the full model, including the interaction between vowel and syllable position. The full model shows significant improvement ($p < .05$) over the simpler model (the two-factor model), therefore we report results of the full model below.

Table 4 shows a summary of the fixed effects in the full model. Both syllable position and vowel show significant effects. The negative estimate for vowel (-44.641) indicates that the TT-TM lag was shorter for /ɪ/ than for /æ/. The negative estimate for syllable position (-70.784) indicates that the TT-TM lag was shorter for onset than for coda /l/. In addition to these, the significant vowel-syllable interaction in the full model indicates that the vowel effect on the TT-TM lag is conditioned by syllable position (28.493). We found that the vowel-syllable interaction varies across participants and is most robust for speaker F03 (see Appendix A – Fig. I). For this speaker, the median of the TT-TM lag is shorter for onset /l/s adjacent to /æ/ than for onset /l/s adjacent to /ɪ/. The other five speakers show the opposite trend with longer TT-TM lag for onset /l/s adjacent to /æ/ compared to onset /l/s adjacent to /ɪ/. These results support the effect of syllable position on lag found in past work. The TT-TD lag is similar to the TT-TM lag, so we only report the TT-TM lag here. For complete results on TT-TD lag (see Appendix B – Fig. II and Fig. III, Table II and Table III).

3.2. Para-sagittal articulatory analyses

Fig. 11 shows the temporal dynamics of tongue curvature in the coronal plane over a time window of 800 ms from the onset of V1. This time window captures the entire V-/l/ interval across all syllable and vowel combinations, and speaker variations. The value on the y-axis is an indication of the magnitude of coronal tongue curvature. A negative value indicates a concave tongue shape in the coronal plane, and a positive value indicates a convex tongue shape. The x-axis shows time in milliseconds. The results suggest a convex tongue shape in the coronal plane throughout the interval, i.e., the sides of the tongue are slightly lowered relative to the midline. The values on the y-axis throughout the time course are very close to zero (from ~0.00 to 0.02) which means that temporal change in the magnitude of the convex shape (an indication of curvature in the coronal plane) is actually quite subtle. During the /l/ portion of the frame, prior to 200 ms for onset /l/s and later (around 300 ms) for coda /l/s, the tongue shows the lowest degree of

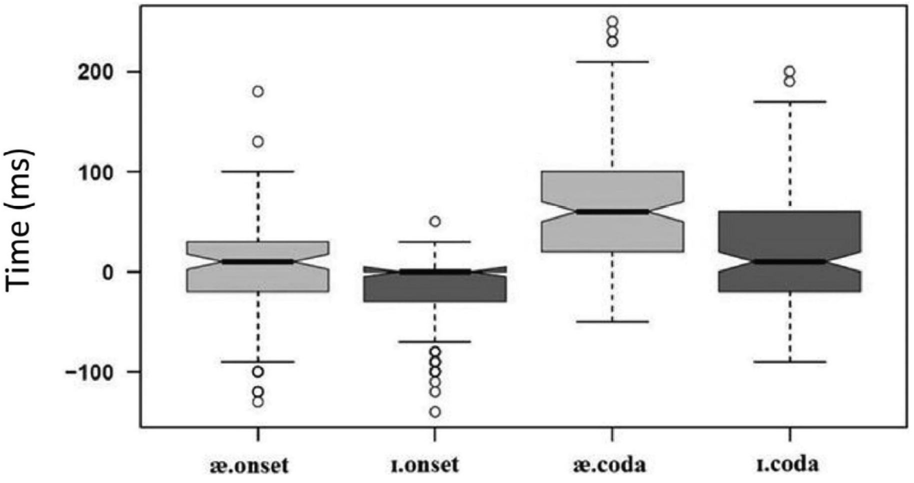

Fig. 10. Intergestural timing (TT-TM lag) in onset and coda /l/s in /æ/ and /ɪ/ context. The mean is shown as the medial black line, the whiskers show 95% confidence intervals around the mean, and the dots are outliers. The average TT-TM lag for the speakers in this study was 22 ms with a standard deviation of 64 ms.

Table 3
Model comparison showing the effects of vowel and syllable on TT-TM lag. The two-factor model has both vowel and syllable as fixed effects. The full model has an interaction term.

	Model of TD lag	Df	AIC	BIC	logLik	Chisq	Pr(>Chisq)
Two-factor model	vowel + syllable + (1+(vowel + syllable)|speaker)	10	5574.8	5617.3	−2777.4	–	–
Full model	vowel * syllable + (1+(vowel + syllable)|speaker)	11	5567.4	5614.1	−2772.7	9.4648	0.002

Table 4
Summary of the mixed effects model of TT-TM lag.

	β	S.E.	*t* value	Pr (>|t|)
Intercept	67.510	8.820	7.655	0.000
Vowel	−44.641	10.209	−4.373	0.001
Syllable position	−70.784	9.573	−7.394	0.000
Vowel * syllable position	28.493	9.204	3.096	0.01

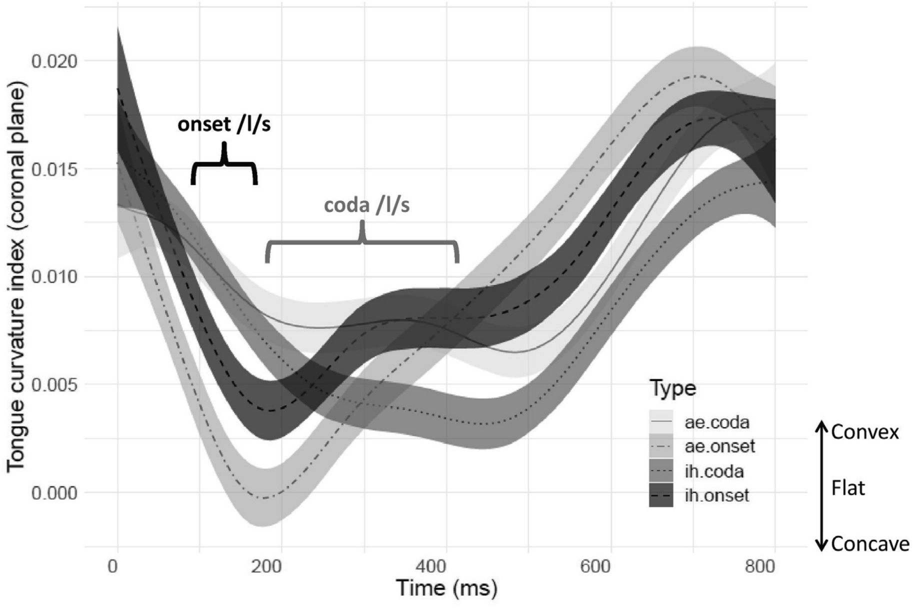

Fig. 11. Temporal dynamics of tongue curvature in the coronal plane over the entire V-/l/ interval. The brackets indicate onset (black) and coda (-gray) /l/ intervals. Each bracket extends from the /l/ onset to its peak. For onset /l/s, the peak occurs earlier (at about 200 ms) than coda /l/s (at about 450 ms). A time of zero indicates the vowel onset. The 800-interval window captures the entire V-/l/ articulation in every token.

convexity. In the onset /æ/ condition, the tongue curvature value reaches 0 near 200 ms, indicating a flat (neither concave nor convex) tongue shape for /l/. The trend towards approaching a flat tongue in the coronal plane in the region of the /l/ is apparent across conditions.

Fig. 12 shows the change over time in tongue lateralization (ΔHeight) on the dominant side (by-token analysis) over the same 800 ms interval. All participants showed a dominant side of lateralization in this study. A higher (positive) lateralization index indicates a greater degree of para-sagittal lowering (i.e. on the side of the tongue that lowers more). The curve in Fig. 12 starts (V1) with negative values for all tokens, indicating that the midline is higher than the side of the tongue during the stressed vowel. This is consistent with the previous figure (Fig. 11), both showing a convex tongue shape in the coronal plane at this time point. The lateralization values are negative for both vowels. The lateralization index (y-axis) increases over time (x-axis) as articulation moves from V1 to /l/ at about 200 ms for both onset /l/s and coda /l/s. This indicates that side of the tongue started higher than the midline for the stressed vowel preceding /l/, and then gradually lowered for the following /l/. After lowering for /l/, the side of the tongue raises relative to the midline again for the unstressed vowel following /l/. Graphs of each participant's data can be found in the Appendices (Fig. IV & Fig. V).

The comparison between the two figures is instructive because it allows us to see how the coronal plane curvature of the tongue, which reflects both para-sagittal sensors relative to tongue midline, varies with the change in height of the dominant side of the tongue. For example, note that the ΔHeight peak occurs around 200 ms in Fig. 12. In Fig. 11, it shows that the value of tongue curvature at this point of time is near zero, which indicates a flat tongue in the coronal plane. By comparing the measures from Fig. 11 and Fig. 12, we can deduce that the tongue is tilted toward one side in order to form the lateral channel: at about 200 ms, the tongue is flat in the coronal plane (Fig. 11) and yet the dominant side of the tongue is maximally lateralized (Fig. 12). The only way to keep the tongue blade flat (near zero curvature in the coronal plane) while still having one side lower than the middle is to tilt the tongue toward the dominant side.

3.3. Para-sagittal durational analyses

Log-transformed activation duration values are shown in box plots in Fig. 13, with outliers denoted by circles. Log-transformation was performed because duration values are inherently expected to exhibit a right-skewed distribution (i.e., given that duration values can only be zero or positive; Gahl & Baayen, 2019; Rosen, 2005). The activation duration remains relatively stable and consistent across syllable position. The median log-transformed activation duration value for most conditions was around 2.1. The long whiskers in the coda lateral adjacent to /æ/ means that the activation duration of tongue lateralization is more variable for this context compared to the other three contexts. The inter-quartile range is less variable for onset laterals compared to coda laterals.

A series of linear mixed effects models were fitted to the log-transformed activation duration of lateralization values (Table 5). As with the temporal lag measures (3.4.1), a two factor model was compared to an interaction model. There is no significant difference between the two models, so the simpler model is retained. The fixed effects were vowel (/æ/ and /ɪ/) and syllable position (onset and coda). Random slopes and intercepts were included for all speakers. There were no significant effects of syllable position or vowel context.

Our final result is a measure of the temporal lag between the formation of the lateral channel and tongue body lowering/retraction (Fig. 14). This measure is important as it can help to resolve the relationship between lateral channel formation and tongue body retraction. The timing difference between maximum tongue body retraction and ΔHeight are mostly positive across all environments. This indicates that the maximum of the para-sagittal tongue blade gesture occurs prior to the

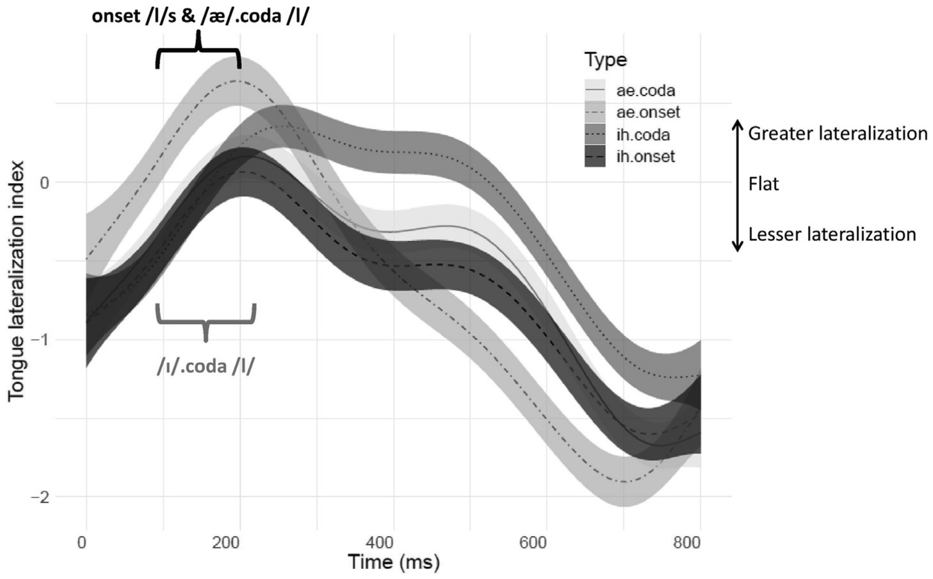

Fig. 12. Temporal dynamics of tongue lateralization over the entire V-/l/ interval on the dominant side in the coronal plane. The data displayed are from the by-token dominance analysis. The black bracket indicates onset /l/s and /æ/.coda /l/ interval range, and the gray bracket indicates /ɪ/.coda /l/ range. Each bracket extends from the /l/ onset to its peak.

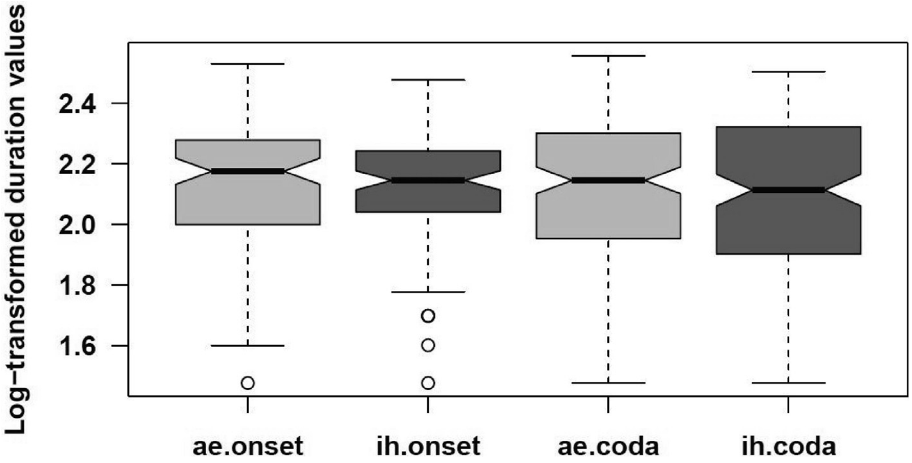

Fig. 13. The log-transformed duration values of tongue lateralization. Error bars show 95% confidence intervals. The mean is shown as the medial black line, the dots are outliers.

Table 5
Model comparison showing the effects of vowels and syllable positions on the log-transformed activation duration of tongue lateralization. The two-factor model has both vowel and syllable as fixed effects. The full model has an interaction term.

	Models of the activation duration of tongue lateralization	Df	AIC	BIC	logLik	Chisq	Pr (>Chisq)
Two-factor model	vowel + syllable + (1+(vowel + syllable)|speaker)	10	−334.69	−292.23	177.34	–	–
Full model	vowel * syllable + (1+(vowel + syllable)|speaker)	11	−332.93	−286.22	177.46	0.24	0.63

maximum of the tongue body retraction movement. To evaluate the statistical reliability of these results, a series of linear mixed effects models were fitted to the para-sagittal lateralization lag. The fixed effects were vowel (/æ/ and /ɪ/) and syllable position (onset and coda). By-speaker random slopes and intercepts were included for both fixed factors. Table 6 compares the two-factor model and the full model, including the interaction between vowel and syllable position. There were no significant effects of syllable position or vowel context. This means that the temporal sequencing of the lateralization and TD gestures is consistent with the proposition that lateralization is an active gesture, for which tongue elongation is the consequence (H1), rather than the cause (H2).

4. Discussion and conclusion

In this study, several complementary analyses of /l/ production were conducted. Each analysis taken in isolation provides an incomplete picture, but, when taken together, they deepen our understanding of /l/ production beyond what could be deduced from past work. We formulated two hypotheses at the outset of the paper: Lateralization is actively controlled (H1), or alternatively lateralization is a passive consequence of mid-sagittal tongue elongation (H2). We argue here that the totality of our findings suggest that the formation of the lateral channel is under active phonological control, rather than being a passive or secondary result of an active TB gesture in tandem with an active TT gesture, thus supporting H1 over H2.

Our mid-sagittal analyses revealed a relative timing difference between onset and coda /l/s in AusE. In onset /l/s, the TT advancing and raising movements slightly precede TM/TD lowering/retracting movements in the mid-sagittal plane, or are nearly synchronous with them. In coda /l/s, the TM/TD lowering/retracting movements instead precede TT advancing and raising movements. These results are consistent with past work on the production of /l/s in American English (AmE) (Sproat & Fujimura, 1993). We also found that these syllable-based timing differences interact with vowel quality. Onset and coda /l/s following /æ/ have longer TT-TM lag than /l/s following /ɪ/. Additionally, we found that tongue shape is not concave for /æ/ as one might have expected from Stone and Lundberg's (1996) 3D tongue surface reconstructed data. Our data show slightly convex tongue shapes for both /æ/ and /ɪ/ when they precede /l/.

The mid-sagittal results by themselves are compatible with both hypotheses. Some past work has argued and provided evidence that lateral channel formation is actively controlled (Sproat & Fujimura, 1993), consistent with H1. Others have assumed that the main articulatory properties of /l/ arise from the mid-sagittal gestures (Ladefoged & Maddieson, 1996), and computational simulations have shown that this is plausible (Browman & Goldstein, 1995), consistent with H2. Besides replicating Sproat and Fujimura's (1993) finding of syllable position effects on mid-sagittal movements in another accent of English, we sought to use this variation in mid-sagittal timing along with para-sagittal articulatory data to adjudicate between the competing hypotheses on how lateral channel formation is controlled.

The tongue curvature and lateralization analyses developed with the para-sagittal data collected in this study offer insights into the change in tongue configuration over time for /l/. These analyses required 3D data. Our index of tongue curvature in the coronal plane returned values of approximately zero during maximal lateralization, suggesting that the tongue was almost flat rather than convex or concave in the coronal plane at the tongue blade. Moreover, the coronal plane tongue shape was flattest around the achievement of the /l/ target. Our tongue lateralization measure revealed that one side of the tongue blade was lower than the tongue midline in most tokens.

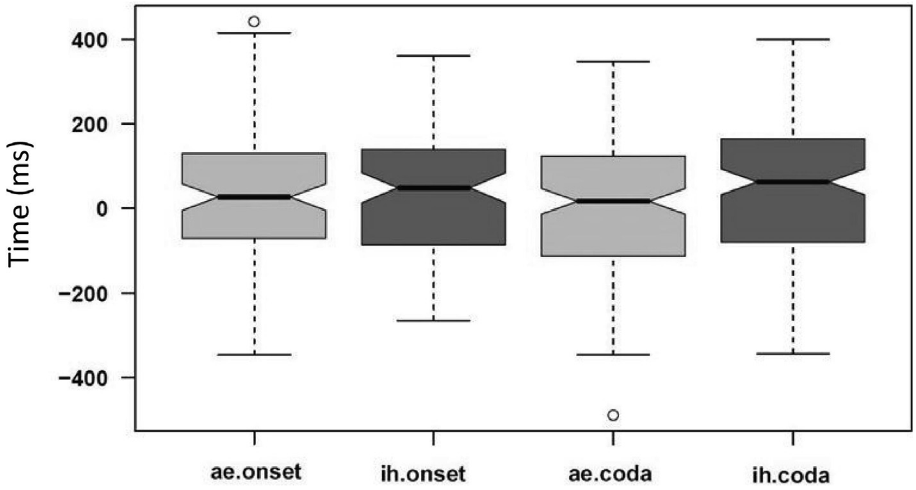

Fig. 14. The para-sagittal lateralization lag of the TM sensor maximum to the ΔHeight maximum of /l/ in onset and coda position in /ɹ/ and /æ/ context. The mean is shown as the medial black line, the whiskers show 95% confidence intervals around the mean, and the dots are outliers.

Table 6
Model comparison showing the effects of vowels and syllable positions on the para-sagittal lateralization lag of the TM sensor maximum to the ΔHeight maximum. The two-factor model has both vowel and syllable as the fixed effect. The full model has an interaction term.

	Models of the para-sagittal lateralization lag of the maximum TM sensor to the maximum ΔHeight	Df	AIC	BIC	logLik	Chisq	Pr(>Chisq)
Two-factor model	vowel + syllable + (1+(vowel + syllable)|speaker)	10	6569.7	6612.2	−3274.8	–	–
Full model	vowel * syllable + (1+(vowel + syllable)|speaker)	11	6570.6	6617.3	−3274.3	1.1285	0.2881

For this to occur while the tongue blade remains flat in the coronal plane rather than convex or concave, the tongue would need to be configured such that one side is lower than the midline while the other side is higher, resulting in a tilt of the coronally-flat tongue through the midline, as in a child's seesaw. This suggests that asymmetrical lateralization[6] (i.e., only one side of the tongue is lowered) played an important role in lateral channel formation within the data presented in this study. We speculate that tongue-tilting as the movement that creates the lateral channel is consistent with the asymmetrical loss of lateral contact found in other studies (Gick et al., 2017; Howson & Kochetov, 2015).

The tongue-tilting mechanism helps to explain some otherwise puzzling results in Katz et al. (2017). In that study, a single para-sagittal tongue sensor was placed on the coronal plane, i.e., on one side of the tongue. The aim of the study was to examine whether or not tongue information picked up by the para-sagittal sensor would facilitate classification for the American English alveolar consonants (/ɹ/, /l/, /z/ and /d/). They found that the TT sensor provides the highest amount of information for distinguishing these alveolar consonants. The para-sagittal sensor helps to classify /z/, but not the other three alveolar consonants (/ɹ/, /l/, /d/). In light of our results, it is easy to see why the spatial position of a single para-sagittal sensor might not be generally informative for characterizing lateralization in /l/. If tongue tilting is the primary mechanism and some speakers or tokens show tongue tilt to the left while others show tilt to the right, a single para-sagittal sensor will sometimes be high for /l/ and sometimes low, providing little consistent information. Our para-sagittal analyses further inform the characterization of the three-dimensional temporal dynamics of lateralization. Changes over time in ΔHeight varied in ways that are consistent with gestural control of lateralization (H1) and not with passive lateralization (H2). Lateral channel formation showed temporal stability across syllable positions and vowel contexts. For starters, we found that the duration of lateral channel formation, defined as the temporal interval from the minimum lateralization index to the maximum lateralization index, was consistent across conditions. Context-independent control is the hallmark of gestures as phonological units (Fowler, 1980). We believe this finding supports lateral channel formation as a primary rather than secondary gestural goal.

We also evaluated how para-sagittal tongue movement was coordinated with the tongue body gesture, a measure we referred to as para-sagittal lateralization lag. The para-sagittal lateralization lag was largely unperturbed by syllable position or vowel context, indicating that the relative timing between lateral channel formation and tongue body lowering/retraction remains relatively stable across syllable position. This also supports H1: tongue lateralization is under task-directed control during /l/ production rather than being a secondary result of tongue elongation. Comparing Figs. 10 and 13, the TT-TM lag varies with syllable position, while the temporal lag between the formation of the lateral channel and tongue body lowering/retraction remains constant. Even in the coda /æ/ condition (Fig. 10), the TT movement happens well after the TM movement, and yet we still observe lateralization with the same timing relative to TM, as shown in Fig. 14. This indicates that tongue elongation is not required to induce lateral channel formation. Further evidence comes again from our measure of para-sagittal lag (Fig. 14). In all environments, the tongue body

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[6] We actually ran a tongue width analysis with our data; the results show that it did not play a predominant role in /l/ production.

movement followed rather than preceded the lateralization movement. This is not possible if lateral channel formation is a passive consequence of tongue body movement. Rather, our findings imply that lateralization may displace the tongue body, as suggested by Sproat and Fujimura (1993).

As discussed in the introduction, Sproat and Fujimura (1993) assumed that /l/s are produced by actively controlling the tongue blade to form the lateral channel(s). On the contrary, Browman and Goldstein (1995) argued that lateralization could be a purely secondary consequence of coordinated antagonistic coronal and dorsal gestures. Their mid-sagittal findings (e.g., Browman & Goldstein, 1995) might appear to support the proposal that the goal of coda /l/s in AmE is the coordination of two gestures (coronal and dorsal) in the mid-sagittal plane, since the coronal and dorsal portions of the tongue are maximally distant from one another for a fully elongated tongue. However, it remained unclear whether the coordination of two such gestures would always result in a lingual configuration that will to give rise to lateralization in syllable onsets, especially in languages with 'clear' /l/s such as German and Spanish, where the relative proximity of the coronal and dorsal gestural targets means that the tongue is less elongated (Proctor, 2009). Our study provides further evidence that the sides of the tongue may instead be under active control, which would allow for the formation of one or more para-sagittal airways even when the tongue is insufficiently stretched in the mid-sagittal plane. The activation duration of a lateral gesture remained fairly constant across contexts. It thus appears that the mid-sagittal gestures, which have attracted the bulk of the empirical focus on /l/, may vary in ways that are independent of lateral channel formation, behavior which is captured elegantly by the addition of a lateral channel tract variable.

Accounting for this in Articulatory Phonology (AP) requires augmenting the theory to include an additional tract variable. Therefore, we conclude with a recommendation for further development of AP. On the assumption that our current findings are representative of /l/s more generally, tongue blade (i.e., tongue lateralization in the case of English /l/s) should be added to the framework as an actively controlled tract variable, to augment the set of variables which have so far been used to describe articulatory gestures in speech (LP, LA, TTCL, TTCD, TBCL, TBCD, VEL, and GLO). These data suggest that the relevant tasks might be described using Tongue Blade Constriction Degree (TBL-CD) and Tongue Blade Constriction Location (TBL-CL) variables, where CL could refer to lateral (or para-sagittal, in the case of lateral consonants such as English /l/). Other potential TBL-CL settings could be dental, post-alveolar, and palatal in the mid-sagittal plane. The inclusion of this additional tract variable would allow more accurate modelling of a wider range of languages that have laterals including other manner types (e.g., lateral clicks and lateral fricatives). An extension of the set of tract variables to include tongue blade specifications will have broader phonological relevance beyond the analysis of laterals. For example, it may help describe contrastive apical-laminal distinctions in the phonologies of many languages (e.g., see Best et al., 2014). Articulatory gestures can be differentiated by CD and CL within the same articulatory organ (Goldstein et al., 2006). Some languages have a bimodal distribution of TT-CL. For example, Malayalam (a Dravidian language) has a three-way distinction between laminal dental, apical alveolar and subapical retroflexes in voiceless oral stops. Incorporating active control of the tongue blade and a lateral constriction location could make it straight-forward for AP to account for these inventories.

Our focus in this study was narrowly aimed at adjudicating between two competing hypotheses. The results observed in this study are not fully consistent with Browman and Goldstein's (1995) hypothesis for /l/, because the timing of lateral channel formation does not appear to be dependent on tongue elongation. Instead, our findings are consistent with Sproat and Fujimura's (1993) hypothesis that lateral channel formation is under active control.

However, there were other hypotheses about the production goals for /l/ and other aspects of Sproat and Fujimura's proposal that we were not able to test in our current data. We were not able to test the hypothesis, for example, that 3D tongue shape is a production goal for /l/. This idea can be traced to Narayanan, Byrd and Kaun (1999), who used combined methods (MRI, EMA, static palatography, acoustic analysis and modeling) to examine production of multiple liquids (/l/, /ɭ/, /r/, /r̠/, /ɻ/) in Tamil. The articulatory results from their study show that /l/ production involves TT contact in the dental region, high posterior tongue body position, tongue root retraction to the pharyngeal wall, flat anterior surface (but generally in a convex coronal plane tongue shape), and curved sides of posterior tongue. They suggested that 3D tongue shape and dynamics underlying tongue shape formation are critical to our understanding of natural linguistic classes (e.g., laterals and rhotics) and phonological phenomena (e.g., phonological merger and substitution). They also compared the articulatory and acoustic characteristics of /l/ in Tamil and in AmE, and found that the two /l/s are very similar.

Other research has lent additional credence to the idea that tongue shape is under control for /l/. In Smith and Lammert's (2013) RT MRI study, they observed that the tongue body retraction and tongue blade lowering/curling were always present for /l/ while tongue tip raising was not, particularly in vocalized syllabic /l/ in AmE. In their non-vocalized /l/ data (/l/ in onset position and ambisyllabic position), the tongue body retraction, tongue tip raising and tongue blade lowering/curling were all present. These observations made them question the true goals of /l/ production. These studies provide very comprehensive information on the tongue shape (in the mid-sagittal plane) during /l/ production. However, their data cannot answer the question of whether or not /l/ involves active para-sagittal control. Conceivably, active para-sagittal control is related to tongue shape goals, although this is not something that we can test in our data.

While we presented evidence for active para-sagittal control, which supports an aspect of Sproat and Fujimura's proposal, they also proposed that the TB gesture is a consequence of the lateral channel formation. Unfortunately, our data cannot directly address this proposal, for a similar reason that we cannot evaluate tongue shape. 3D EMA is not ideally suited to defining mid-sagittal tongue curvature. Imaging techniques that do not rely on flesh-point tracking, such as magnetic resonance imaging or 3D ultrasound, may provide more complete information about how lateral channel formation relates to the dynamics of mid-sagittal tongue shape, including tongue body retraction. Using EMA in conjunction with ultrasound to investigate timing of lateralization and tongue curvature during /l/ production might also be an appropriate way forward, following e.g., Strycharczuk et al. (2020). The role of jaw lowering is another interesting avenue for future study, since it is likely to be a major determinant of whether tongue elongation is linked to lateralization.

In summary, this study used EMA to investigate the role of para-sagittal dynamics in the production of syllable-onset and -coda /l/ in maximally different vowel contexts in AusE. The timing of tongue lateralization remains consistent across the different syllable positions and vowels we examined. We conclude that tongue lateralization is actively controlled in our data. However, we do not think we can draw a firm conclusion as to whether this characteristic of tongue lateralization is speaker-dependent or universal. More data are required to address this issue. In addition, it is also important to examine the role of tongue body retraction relative to lateralization (Sproat & Fujimura, 1993), as this might provide us a better understanding of articulatory configurations during /l/ production and theories of speech production.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Open practices statement

All data and analyses reported here are available at: https://github.com/JY-JiaYING/JPhon-Paper.

Appendix A. The mid-sagittal articulation analysis: TT-TM lag (individual)

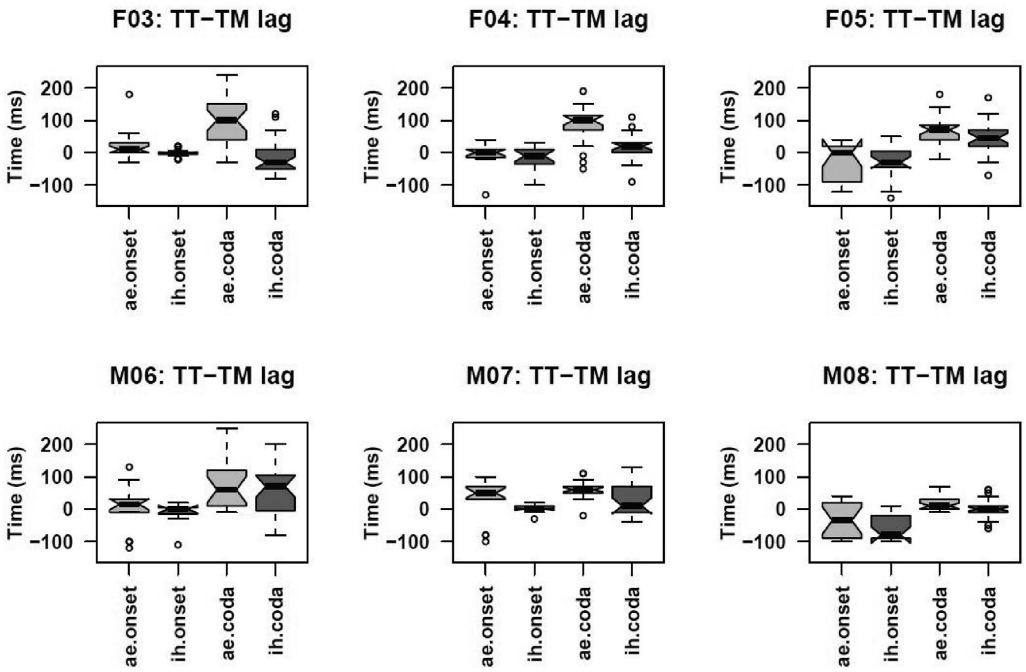

Fig. I. Intergestural timing (TT-TM lag) in onset and coda laterals in /ɪ/ and /æ/ context for each speaker.

Table I
Summary of each participant's dominant hand, dominant tongue lateralization side and numbers of tokens produced with lowering of the left tongue blade (LTB) and of the right tongue blade (RTB). The data on handedness were obtained in a questionnaire.

ID	Sex	Handed	Dominant tongue lateralization side	No. of tokens produced with LTB lowering	No. of tokens produced with RTB lowering
F03	Female	Right	Right	0	99
F04	Female	Right	Right	13	69
F05	Female	Right	Left	55	33
M06	Male	Right	Right (marginally)	29	37
M07	Male	Right	Left	87	2
M08	Male	Right	Right	10	87

Appendix B. The mid-sagittal articulation analysis: TT-TD lag

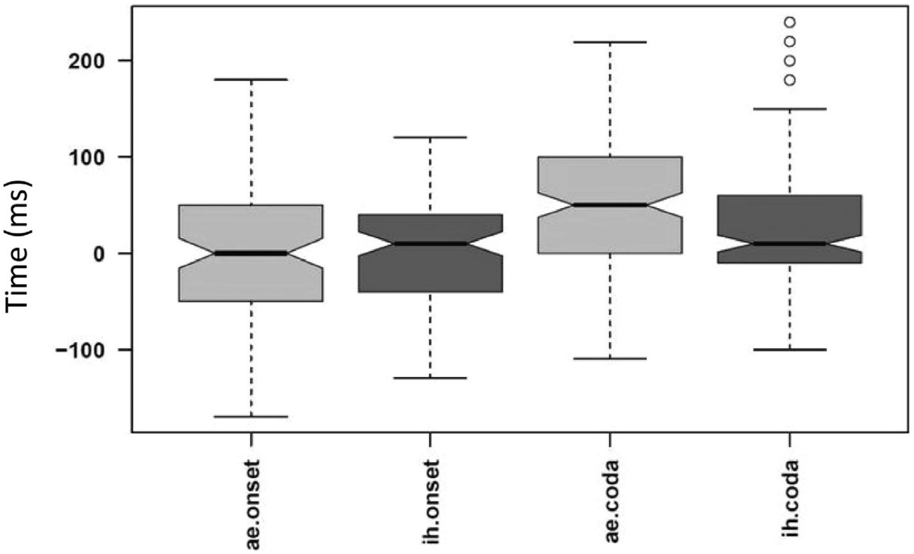

Fig. II. Intergestural timing (TT-TD lag) in onset and coda laterals in /ɪ/ and /æ/ context.

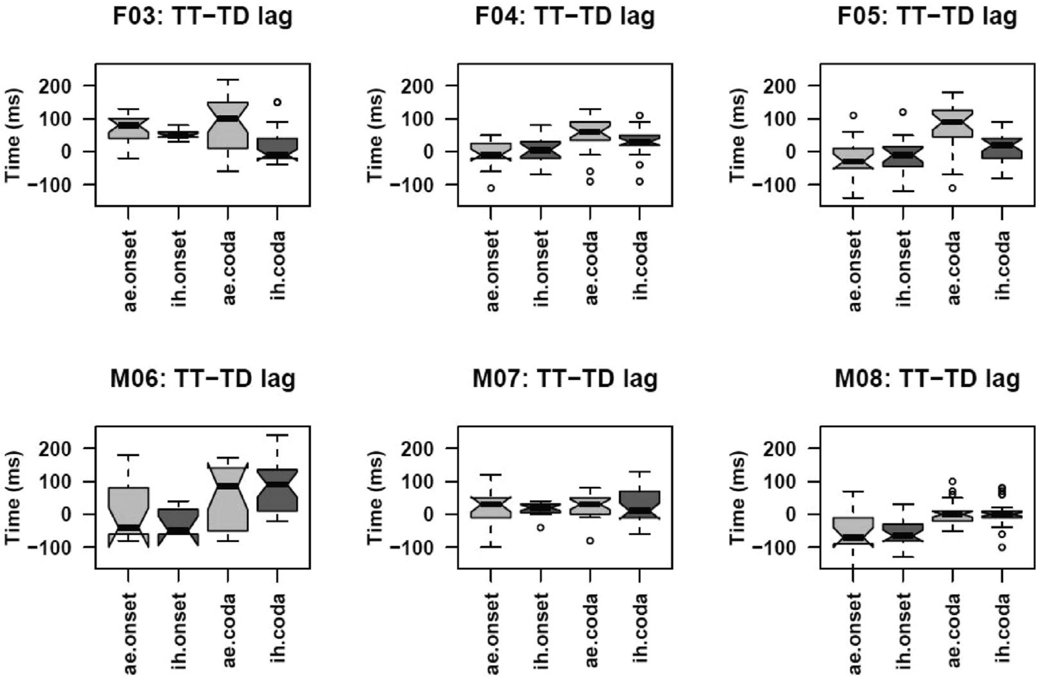

Fig. III. Intergestural timing (TT-TD lag) in onset and coda laterals in /ɪ/ and /æ/ context for each speaker.

Table II
Model comparison showing the effects of vowel and syllable on TT-TD lag. The two-factor model has both vowel and syllable as the fixed effect. The full model has an interaction term. The full model shows significant improvement (p > .05) over the simpler model (the two-factor model), therefore we report results of the interaction model in Table II.

	Model of TD lag	Df	AIC	BIC	logLik	Chisq	Pr(>Chisq)
Two-factor model	vowel + syllable + (1 + (vowel + syllable)|speaker)	10	5676.7	5719.2	−2828.4	–	–
Full model	vowel * syllable + (1 + (vowel + syllable)|speaker)	11	5673.6	5720.3	−2825.8	5.1889	0.02273

Table III
Summary of the mixed effects model of TT-TD lag.

	β	S.E.	*t* value	Pr (>|t|)
Intercept	50.138	10.357	4.841	0.000
Vowel (/ɪ/)	−22.437	9.838	−2.281	0.04
Syllable position (onset)	−50.606	13.762	−3.677	0.003
Vowel /ɪ/ : syllable onset	23.283	10.168	2.290	0.04

Appendix C Individual data of temporal dynamics of tongue curvature

Appendix D Individual data of temporal dynamics of tongue lateralization

Fig. V

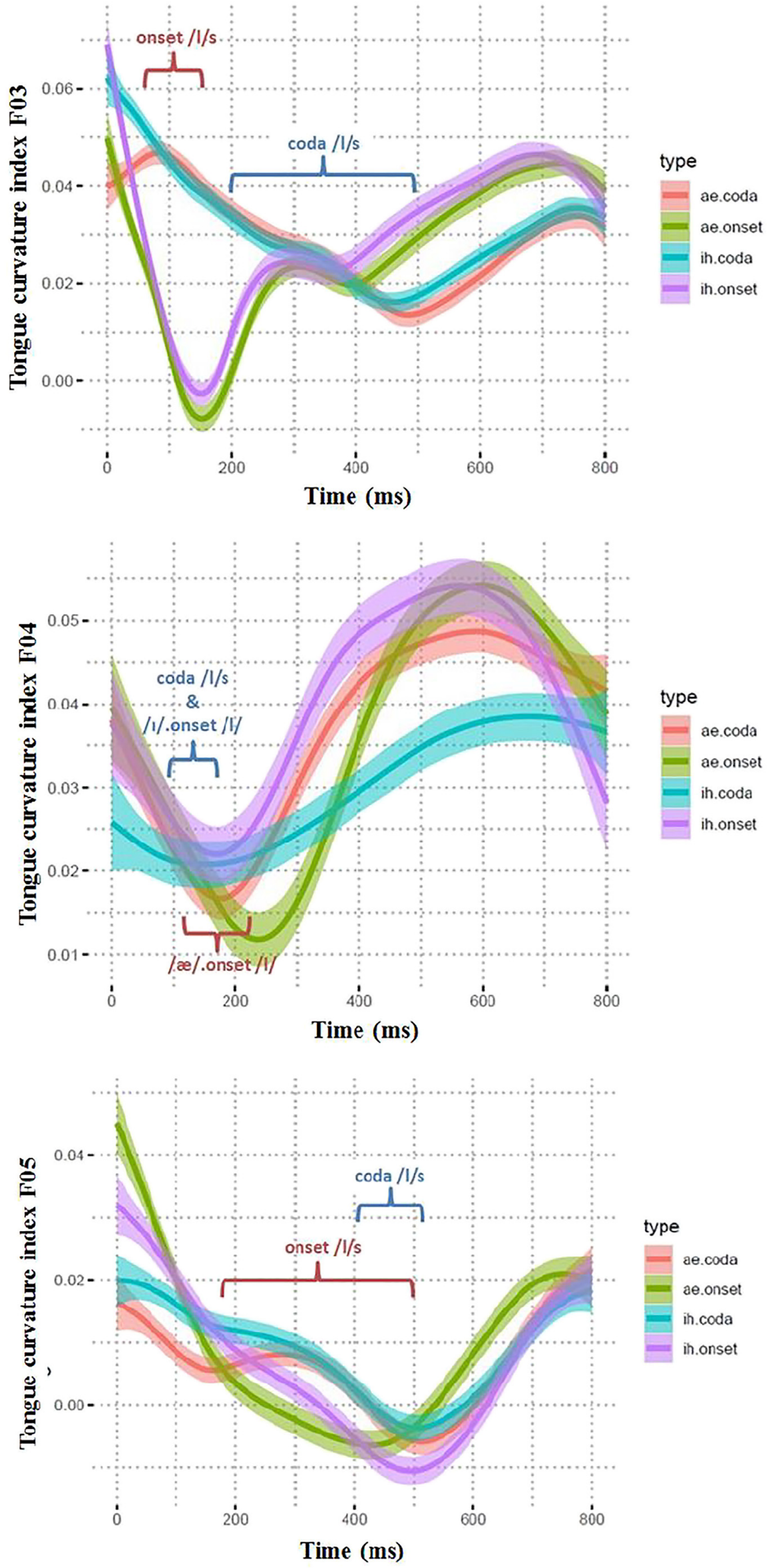

Fig. IV. Individual data of temporal dynamics of tongue curvature over the entire V-/l/ interval in the mid-sagittal plane. A value of zero in the y-axis indicates a flat tongue shape in the coronal plane. A negative value indicates a concave tongue shape, and a positive value indicates a convex tongue shape in the coronal plane. The time window covers 800 ms from the onset of V1, which incorporates the entire V-/l/ interval in every case. The bracket indicates the onset of /l/ and its peak. Speakers show different production patterns for onset and coda /l/s.

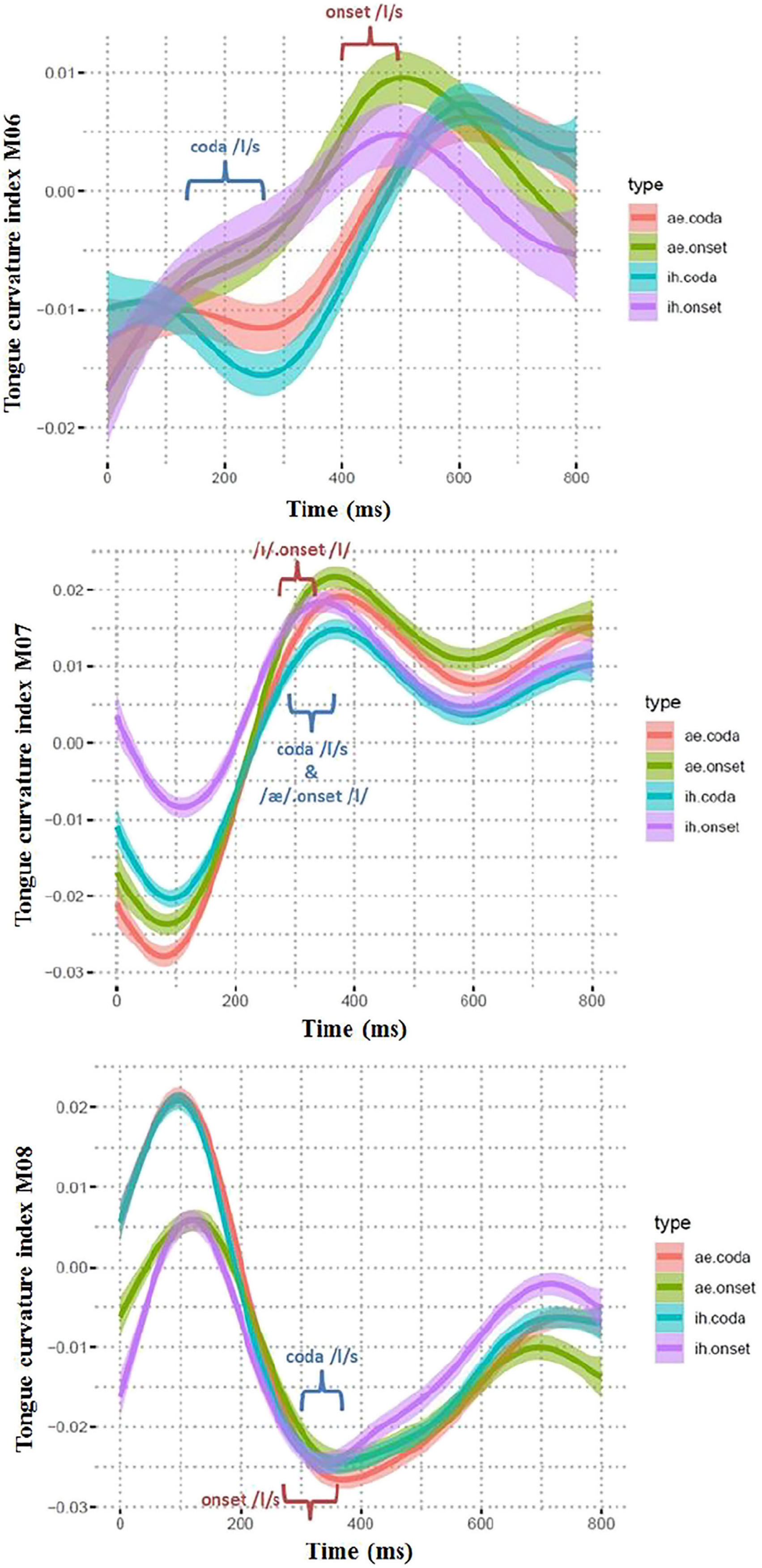

Fig. IV (*continued*)

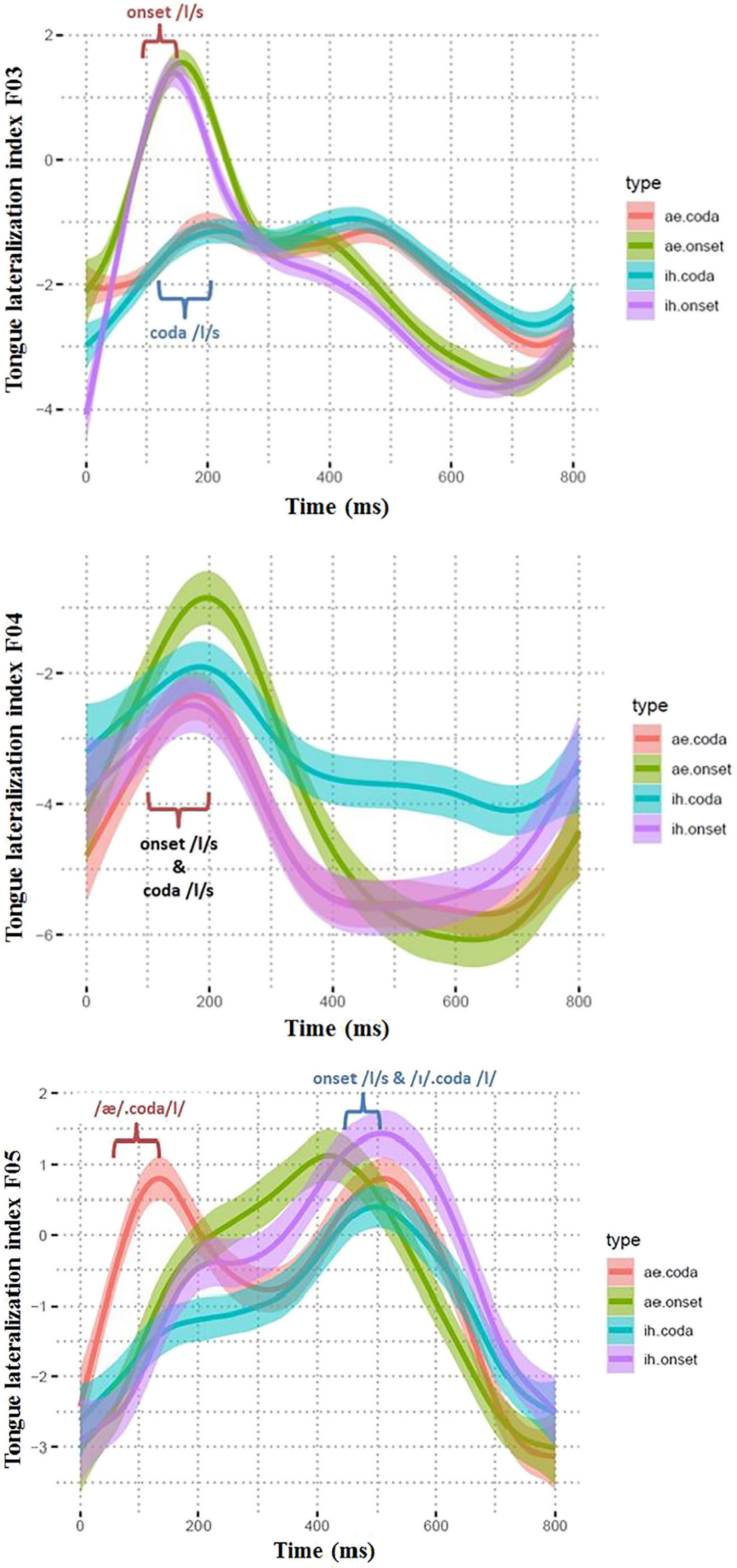

Fig. V. Individual data of temporal dynamics of tongue lateralization over the entire V-/l/ interval in the dominant side in the coronal plane. The data displayed are from the by-token dominance analysis. The dominant side of tongue lateralization is defined by the lower side of the tongue blade (i.e. greater tongue lateralization index). A lateralization value of zero indicates a flat tongue shape along the coronal plane between the dominant-side para-sagittal sensor and the estimated mid-sagittal tongue blade sensor. The bracket indicates the onset of /l/ to its peak. Speakers show different production patterns for onset and coda /l/s.

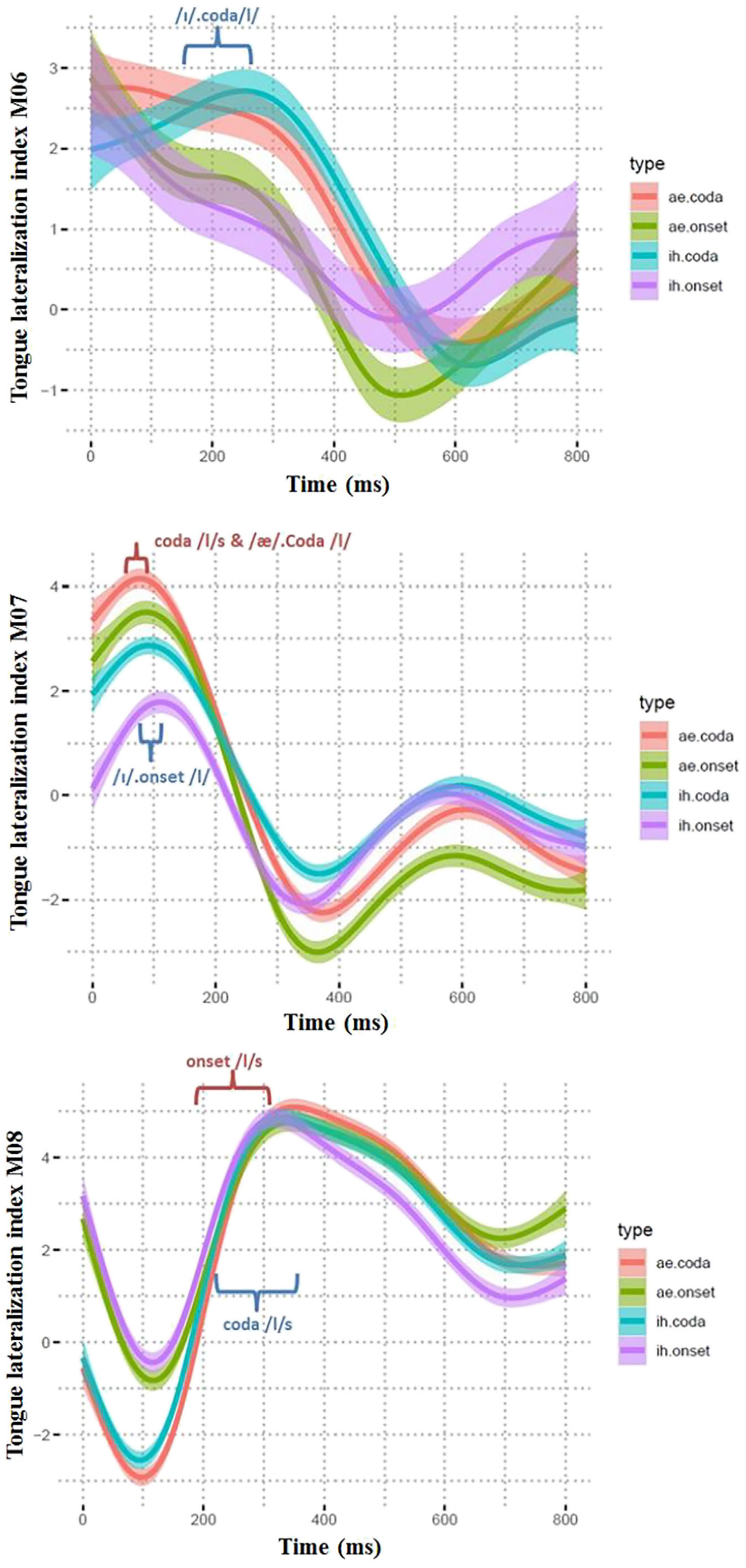

Fig. V (*continued*)

Appendix E. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wocn.2021.101039.

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