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Dynamic acoustic-articulatory relations in back vowel fronting: Examining the effects of coda consonants in two dialects of British English

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ABSTRACT:
This study examines dynamic acoustic-articulatory relations in back vowels, focusing on the effect of different coda consonants on acoustic-articulatory dynamics in the production of vowel contrast. This paper specifically investigates the contribution of the tongue and the lips in modifying $F2$ in the FOOT-GOOSE contrast in English, using synchronized acoustic and electromagnetic articulography data collected from 16 speakers. The vowels FOOT and GOOSE were elicited in pre-coronal and pre-lateral contexts from two dialects that are reported to be at different stages of back vowel fronting: Southern Standard British English and West Yorkshire English. The results suggest similar acoustic and articulatory patterns in pre-coronal vowels, but there is stronger evidence of vowel contrast in articulation than acoustics for pre-lateral vowels. The lip protrusion data do not help to resolve these differences, suggesting that the complex gestural makeup of a vowel-lateral sequence problematizes straightforward accounts of acoustic-articulatory relations. Further analysis reveals greater between-speaker variability in lingual advancement than $F2$ in pre-lateral vowels. © *2020 Acoustical Society of America*. https://doi.org/10.1121/10.0001721

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I. INTRODUCTION

Understanding the relationship between movements of the vocal tract and the acoustic signal has formed a central concern of research in speech production for over 100 years (Atal *et al.*, 1978; Carignan, 2019; Fant, 1960; Mermelstein, 1967; Stevens, 1997). The ways in which acoustics and articulation specify one another is vital for understanding the nature of the information that is available in linguistic communication (Goldstein and Fowler, 2003; Iskarous, 2016), and lies at the heart of different theories of speech production (Guenther, 2016; Honda *et al.*, 2002). Acoustic-articulatory relations have even been invoked as a central explanation for how the vocal tract is modularized for the purposes of phonological contrast. For example, Stevens (1989) proposes a "quantal theory" of speech production, whereby a small number of vocal tract regions are exploited for phonological contrast. He proposes that these regions are relatively robust to the effect of articulatory perturbations on acoustics and that languages favour regions of articulatory space that yield stable acoustic outputs despite small variations in articulatory positions. This is one hypothesis behind some observed non-linearities in the acoustic-articulatory relationship, with movements in some vocal tract regions yielding larger acoustic changes than in others.

Despite the complex and multi-dimensional nature of the acoustic-articulatory relationship, there exist a number of relatively robust correspondences, such as the well-established correspondence between the second formant frequency and the advancement of the tongue body (TB) in unrounded vowels (Fant, 1960). However, a number of studies have also uncovered varying degrees of acoustic-articulatory mismatch in even relatively well-understood phenomena. For example, Blackwood Ximenes *et al.* (2017) report an electromagnetic articulography (EMA) study of vowels in dialects of North American English and Australian English and show that the relationship between $F2$ and tongue advancement is linear for some vowels, but non-linear for others, such as GOOSE. They suggest that such non-linearities may be accounted for by variation in lip rounding and tongue curvature.

A. Acoustic-articulatory relations and motor equivalence

While acoustic-articulatory relations are fundamentally grounded in the physics of resonance, the precise nature of the relationship may be shaped by factors such as phonological structure, language-specific factors, vocal tract anatomy, and speaker variation. A range of studies show speaker-specific patterns of articulation that have been widely studied in terms of motor equivalence. Motor equivalence refers to "the capacity to achieve the same motor task differently" (Perrier and Fuchs, 2015, p. 225) and, in speech, typically involves using different articulatory strategies in order to produce the same speech goal. Motor equivalence has been widely found in perturbed speech, with speakers adapting to a perturbation in order to produce a goal similar to their typical speech patterns (Honda *et al.*, 2002; Tremblay *et al.*,

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2003). However, motor equivalence also occurs in regular speech, with speakers exhibiting complementary covariation of different articulators in order to constrain acoustic variability for a particular phoneme (Perkell *et al.*, 1993).

While there is much evidence that acoustic-articulatory relations are often speaker-specific (e.g., Carignan, 2019), in some cases acoustic-articulatory relations can pattern with aspects of linguistic structure. For example, Kirkham and Nance (2017) show that acoustic-articulatory relations can subtly but consistently vary between a bilingual's two languages, even when there are strong phonological correspondences between languages. For this reason, our study adds an additional dimension of variability by examining acoustic-articulatory relations between two dialects of British English, which we review in greater detail below.

B. Back vowel fronting in British English

The fronting of back vowels in varieties of English is a well documented phenomenon, which involves vowels such as GOOSE /u/ and FOOT /ʊ/ undergoing fronting in apparent time (Ferragne and Pellegrino, 2010; Harrington *et al.*, 2011). Within the context of British English, back vowel fronting is reported to be most advanced in the south and least advanced in the north of England (Ferragne and Pellegrino, 2010; Lawson *et al.*, 2019). The fronting of GOOSE is typically limited before a coda lateral (Kleber *et al.*, 2011), due to the backing effect of the dorsal gesture in coda laterals. Despite this, recent research shows that some dialects do show fronting before /l/, which may represent a later stage of the sound change (Baranowski, 2017).

The primary acoustic correlate of back vowel fronting is $F2$ frequency, but a number of studies have sought to better understand the articulatory mechanisms behind back vowel fronting and whether predicted acoustic-articulatory relations hold in such contexts. For instance, Harrington *et al.* (2011) analyse the degree of lip protrusion and tongue advancement during the production of the GOOSE vowel in Southern Standard British English (SSBE), which is known to be undergoing fronting, and compare this to the KIT and THOUGHT vowels, which are not thought to be changing. Their results show that GOOSE is produced with tongue advancement comparable to that of KIT, while lip rounding in GOOSE is comparable to that of THOUGHT. This suggests that the high $F2$ in GOOSE is achieved via tongue advancement, rather than lip unrounding, at least in these SSBE speakers. Furthermore, a recent study by Lawson *et al.* (2019) used audio-synchronised ultrasound imaging, combined with a lip camera, to compare the articulatory strategies of GOOSE production in speakers from England, Ireland, and Scotland. Their results show that while varieties do not significantly differ in $F2$ of GOOSE, they do vary in articulatory strategies. Specifically, speakers from England and Ireland used an advanced tongue position with protruded lips, while Scottish speakers used less lip protrusion and a more retracted TB.

C. Coda consonant effects on vowel fronting

One of the strongest influences on back vowel fronting in English is the coda consonant that follows the vowel. A coda lateral typically inhibits vowel fronting due to the demands of tongue dorsum (TD) retraction involved in lateral velarization. Strycharczuk and Scobbie (2017) consider coarticulatory effects of the coda consonant on back vowel fronting in SSBE, using ultrasound tongue imaging and $F2$ measurements to analyse pre-coronal and pre-lateral FOOT-GOOSE contrasts. They find that acoustics and articulation pattern similarly pre-coronally, but the pre-lateral context shows acoustic-articulatory mismatches. In particular, FOOT and GOOSE are merged in $F2$ across their duration but remain distinct in tongue advancement. This suggests that a straightforward relationship between $F2$ and tongue advancement does not hold in pre-lateral contexts.

One possibility that Strycharczuk and Scobbie (2017) raise is the role of the lips, but they are unable to address this in their study due to the lack of lip data. Previous research shows that lip protrusion is a significant feature of GOOSE vowel production in English (Harrington *et al.*, 2011; Lawson *et al.*, 2019) and one hypothesis is that the non-linear patterns observed by Strycharczuk and Scobbie (2017) in pre-lateral vowels may be explained via covariation of tongue and lip movement. Indeed, previous research has examined covariation of the tongue and lips in /u/ production, finding that some speakers show a weak correlation between articulators (Perkell *et al.*, 1993). Such within-speaker covariation may be used to maintain some degree of acoustic consistency across multiple productions, but it may also be the case that different speakers weight the contribution of lingual and labial articulatory gestures differently, as in Lawson *et al.* (2019). In the present study, we aim to better understand these issues by investigating the contribution of dynamic tongue and lip movements to the production of back vowel contrasts.

D. The present study

In this study, we model dynamic acoustic and articulatory variation in the FOOT-GOOSE back vowel contrast in two dialects of British English using EMA. By exploiting EMA's ability to measure movements of multiple flesh points during speech, this study aims to build upon Strycharczuk and Scobbie (2017) in measuring the contribution of the tongue and the lips to the GOOSE-FOOT contrast in pre-coronal and pre-lateral contexts. Given the known effects of lip protrusion on $F2$ (Harrington *et al.*, 2011; Lawson *et al.*, 2019), we expect that a more integrated view of lingual and labial articulations will allow us to better understand the non-linear relationships previously found between $F2$ and tongue advancement within pre-lateral FOOT and GOOSE vowels (Strycharczuk and Scobbie, 2017). In addition to this, we compare two dialects of British English—SSBE and West Yorkshire English (WYE)—in order to test whether previously reported acoustic-articulatory patterns for SSBE also generalise to a dialect with a different vowel system, given previous findings for between-dialect variation in acoustics and articulation (Blackwood Ximenes *et al.*, 2017). Previous research suggests that GOOSE-fronting is most advanced in the south of England, and least advanced in the north of England (Ferragne and Pellegrino, 2010; Lawson *et al.*, 2019), with WYE being a robustly northern variety. Indeed, some studies have previously reported that WYE represents a much earlier stage of the change (e.g., Ferragne and Pellegrino, 2010; Watt and Tillotson, 2001). We anticipate that exploring acoustic-articulatory dynamics between these two dialects of English may reveal distinctive acoustic-articulatory strategies that allow us to test the nature of vowel contrasts across slightly different systems.

II. METHODS

A. Speakers

Simultaneous audio and EMA data were collected from 16 speakers, all of whom were native speakers of British English. Eight participants (three female, five male) spoke SSBE, while eight participants (five female, three male) spoke WYE. All speakers were aged between 18 to 27 years old at the time of data collection (2018–2019) and were born in the South East or West Yorkshire regions of England. Speakers were specifically recruited according to whether they self-reported to have an SSBE or WYE accent, which was subsequently verified by the authors based on salient features for each accent reported in the literature. For example, SSBE is characterised by distinctions between vowels such as FOOT and STRUT, which are indistinct in northern varieties of English such as WYE, while WYE is characterised by monophthongal realisations of canonical diphthongs such as GOAT and PRICE (Hughes *et al.*, 2005). All participants lived in Lancaster at the time of recording.

B. Stimuli

Stimuli were presented using PsychoPy in standard English orthography. Stimuli comprised the same four monosyllabic words as in Strycharczuk and Scobbie (2017), each of which was repeated five times in a randomized order in the carrier phrase "say X again," where X was the target word. The stimuli were designed to target the contrast between the GOOSE and FOOT vowel phonemes in fronting (pre-coronal) and non-fronting (pre-lateral) contexts. The specific word pairs used were *foot*/*food* and *full*/*fool*.

C. Experimental design and procedure

All recordings took place in Lancaster University Phonetics Lab. Audio data was recorded using a DPA 4006A microphone, preamplified and digitized using a Sound Devices USBPre2 audio interface, and recorded to a laptop computer at 44.1 kHz. EMA data were recorded at 1250 Hz using a Carstens AG501 electromagnetic articulograph that records sensor data on flesh points in the vocal tract across three dimensions (with two angular coordinates). Three sensors were attached to the midline of the tongue, including the tongue tip (TT), which was placed approximately 1 cm behind the TT; TD, which was placed around the velar constriction area; and TB, which was positioned equidistant between the TT and TD sensors. Sensors were also attached to the vermilion border of the upper and lower lips, as well as the lower gumline. The reference sensors used for head movement correction were attached to the upper incisors (maxilla), bridge of the nose, and on the right and left mastoids behind the ears. All sensors were attached midsagittally, except for the sensors behind the ears. The sensor locations on the midsagittal vocal tract are represented in Fig. 1.

The EMA data were downsampled to 250 Hz and position calculation was carried out using the Carstens normpos procedure. Head-correction and bite plane rotation were applied so that the origin of each speaker's data is the occlusal plane. Reference sensors were filtered with a Kaiser-windowed low-pass filter at 5 Hz, while speech sensors were filtered with a Kaiser-windowed low-pass filter with 40 Hz pass and 50 Hz stopband edges (60 dB damping).

The lower lip sensor failed or fell-off during the experiment for two SSBE (SM4, SM5) and one WYE speaker (YF1), so our lip posture analyses only include data for six SSBE and seven WYE speakers. In addition to this, two speakers had some faulty TD data (SM2, YF5), and so this data was also excluded from analysis.

D. Acoustic and articulatory measurements

The acoustic data were automatically segmented using the Montreal Forced Aligner. The segmental boundaries for every token were manually checked and corrected where necessary. The first three formants were then extracted at 10% intervals between the onset and offset of each vowel.

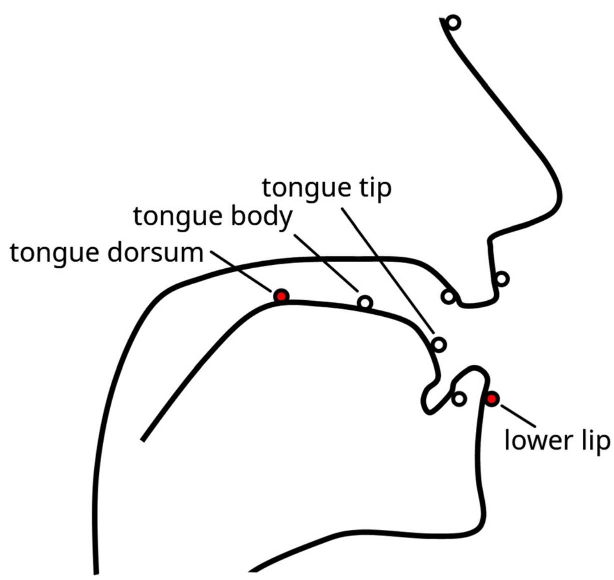

FIG. 1. (Color online) Midsagittal diagram of EMA sensor positions (excluding right/left mastoid sensors). The two key sensors used for this study are highlighted in red.

JASA
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Praat's LPC Burg algorithm was used, with speaker-specific maximum formant settings, which were verified by overlaying measurements with these settings on wide-band spectrograms.

We extracted measurements from the EMA data at 10% intervals between the acoustically-defined onset and offset of each vowel or vowel-lateral interval, which represents the same time-points as for the formant data. In the case of pre-lateral vowels, the lateral was included in the interval for both the articulatory and formant data due to the difficulty of identifying consistent segmental boundaries (Kirkham *et al.*, 2019; Strycharczuk and Scobbie, 2017). This meant that 11 measurements were taken across the vowel and the lateral for pre-lateral vowels, while for pre-coronal vowels, 11 measurements were taken across the vowel only. The EMA variables we consider in this study are TD horizontal position for the analysis of lingual advancement, and lower lip horizontal position as a proxy for lip protrusion (Harrington *et al.*, 2011).

All acoustic and articulatory measurements were *z*-scored by speaker in order to express acoustic and articulatory variables on a standardized scale. Note that all *z*-scoring was performed across the current stimuli plus a full set of hVd and sVd words for each speaker. Vowels used for normalization included vowels in the lexical sets DRESS, LOT, KIT, STRUT, TRAP, FOOT, GOOSE, START, FLEECE, NORTH, NURSE, GOAT, CHOICE, FACE, SQUARE, MOUTH, and PRICE, and were produced in the same experimental session within the same carrier phrase used for the main stimuli. Accordingly, the *z*-scores express all measurements relative to the mean of each speaker's acoustic or articulatory vowel space.

E. Statistics

In order to model dynamic acoustic and articulatory trajectories, we use Generalized Additive Mixed-Models (GAMMs) (Wood, 2017), which allow us to model non-linear acoustic and articulatory time series in a mixed-effects modelling framework (see Carignan *et al.*, 2020; Kirkham *et al.*, 2019; Sóskuthy, 2017; Strycharczuk and Scobbie, 2017; and Wieling, 2018 for examples of GAMMs applied to acoustic or articulatory phonetic data).

We fitted three separate GAMMs to each dialect in order to observe within-dialect effects of vowel phoneme and following context. Each model targeted one of our three outcome variables: *F*2 frequency, TD horizontal position, or lip protrusion. In all models, predictor variables included parametric terms of vowel phoneme (GOOSE/FOOT), following context (coronal/lateral), and the interaction between vowel phoneme and following context. Smooth terms included normalised time, and smooth terms for time-by-vowel phoneme, time-by-following context, and an interaction between time, vowel phoneme, and following context. We also fitted random smooths of time-by-speaker and time-by-token, the latter of which was used to account for token variability and autocorrelation in trajectories.

In order to evaluate the significance of each predictor variable, we adopted the following procedure based on Sóskuthy *et al.* (2018):

(1) We compare a full model to a nested model that excludes the smooth and parametric terms for the predictor being tested. If this difference is significant, it suggests an overall effect of that predictor variable. In order to test main effects, our full model excluded any interactions between vowel phoneme and following context.

(2) If (1) is significant, we then specifically test for differences in the shape of the trajectory by comparing the full model to a nested model that excludes only the smooth term for the predictor of interest. If there is a significant difference between models, we conclude that there is specifically a difference in shape of the trajectories. If there is not a significant difference between models but there is a significant difference in (1), then we conclude that there are only differences in the height of the trajectories.

All models were fitted using the mgcv::bam function in R (Wood, 2017) and model comparisons were performed via likelihood ratio tests using the itsadug::compareML function.

III. RESULTS

Tables I and II show GAMM model comparison outputs for SSBE and WYE speakers, respectively. We find that every effect is significant in both dialects, with the exception of the interaction between vowel phoneme and following context for the lower lip shape term in WYE. This suggests that all other predictor variables significantly influence the height and shape of the trajectory for *F*2, TD advancement, and lip protrusion in both dialects. In summary, GOOSE and FOOT differ in all acoustic and articulatory trajectories; pre-lateral and pre-coronal vowels also differ in acoustic and articulatory trajectories; and the effect of following context varies between vowels across time (except for the WYE lower lip shape term). As we find significant effects of almost every predictor variable, the rest of this section focuses on visualization of models in order to better understand the specific nature of these differences.

A. *F*2 frequency

Figure 2 shows the time-varying *F*2 trajectories for FOOT and GOOSE vowels for each dialect. Pre-coronal FOOT and GOOSE are distinct in their *F*2 trajectories for speakers of both dialects, but the magnitude of this difference between vowels is larger in WYE, suggesting a slightly fronter GOOSE and much backer FOOT in this dialect. Pre-lateral vowels do show significant height and shape effects in the model comparison, but the visual representation of the model shows these differences to be much smaller. These height and shape effects are likely to be caused by the higher *F*2 onset in GOOSE tokens, which gives the overall trajectories a

TABLE I. Results of model comparisons for SSBE data.

Comparison	χ^2	*df*	$p(\chi^2)$
*F*2			
Overall: vowel phoneme	37.28	5	<0.0001
Shape: vowel phoneme	7.87	4	0.003
Overall: following	139.91	5	<0.0001
Shape: following	37.62	4	<0.0001
Overall: vowel phoneme × following	76.53	11	<0.0001
Shape: vowel phoneme × following	68.9	8	<0.0001
TD advancement			
Overall: vowel phoneme	57.21	5	<0.0001
Shape: vowel phoneme	50.75	4	<0.0001
Overall: following	63.43	5	<0.0001
Shape: following	60.97	4	<0.0001
Overall: vowel phoneme × following	50.87	11	<0.0001
Shape: vowel phoneme × following	32.96	8	<0.0001
Lower lip protrusion			
Overall: vowel phoneme	19.30	5	<0.0001
Shape: vowel phoneme	11.96	4	<0.0001
Overall: following	90.76	5	<0.0001
Shape: following	63.29	4	<0.0001
Overall: vowel phoneme × following	15.87	11	<0.0001
Shape: vowel phoneme × following	13.91	8	<0.0001

different shape and different overall height. However, after the first 25%, the WYE trajectories are near-identical and the SSBE ones are also highly similar. Notably, the onset of pre-lateral GOOSE is comparable to the onset of its pre-coronal counterpart, but then *F*2 dips substantially due to the effect of the coda lateral. In summary, FOOT and GOOSE are distinct pre-coronally but remain only minimally distinct pre-laterally in *F*2.

TABLE II. Results of model comparisons for West Yorkshire data.

Comparison	χ^2	*df*	$p(\chi^2)$
*F*2			
Overall: vowel phoneme	60.51	5	<0.0001
Shape: vowel phoneme	9.78	4	<0.0001
Overall: following	96.74	5	<0.0001
Shape: following	25.70	4	<0.0001
Overall: vowel phoneme × following	86.62	11	<0.0001
Shape: vowel phoneme × following	18.26	8	<0.0001
TD advancement			
Overall: vowel phoneme	37.44	5	<0.0001
Shape: vowel phoneme	23.25	4	<0.0001
Overall: following	64.46	5	<0.0001
Shape: following	64.41	4	<0.0001
Overall: vowel phoneme × following	56.96	11	<0.0001
Shape: vowel phoneme × following	46.87	8	<0.0001
Lower lip protrusion			
Overall: vowel phoneme	91.39	5	<0.0001
Shape: vowel phoneme	77.04	4	<0.0001
Overall: following	47.08	5	<0.0001
Shape: following	43.66	4	<0.0001
Overall: vowel phoneme × following	15.81	11	<0.0001
Shape: vowel phoneme × following	7.46	8	0.061

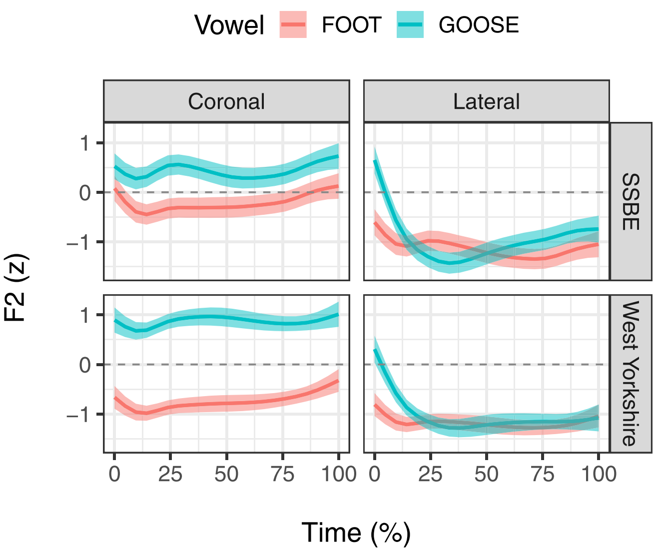

FIG. 2. (Color online) GAMM plot of time-varying *F*2 trajectories for FOOT and GOOSE vowels, faceted by following context and dialect. Higher *z*-scores correspond to higher *F*2 frequency.

B. TD advancement

Figure 3 shows the time-varying TD trajectories for FOOT and GOOSE vowels for each dialect. As with *F*2 trajectories, pre-coronal vowels are highly distinct, with the difference being slightly larger in WYE than in SSBE. This patterns with the *F*2 data, although we do see a different overall trajectory shape between the *F*2 and TD models. Our model comparison also found differences in height and shape for pre-lateral vowels. This is reflected in Fig. 3, where SSBE in particular shows a more U-shaped pattern for pre-lateral GOOSE and a positive slope for pre-lateral

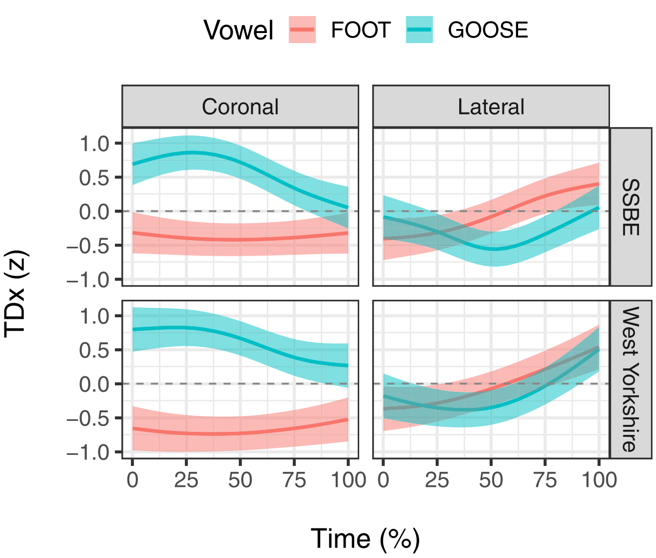

FIG. 3. (Color online) GAMM plot of time-varying TD advancement trajectories for FOOT and GOOSE vowels, faceted by following context and dialect. Higher *z*-scores correspond to a more advanced TD position.

FOOT. However, these differences are relatively small and remain in general agreement with the *F*2 model.

So far, we find correspondences between *F*2 frequency and TD horizontal advancement. There are some slight differences between measures, particularly in pre-lateral vowels, which appear to be more distinct in lingual fronting than in *F*2 and also show moderately different trajectory shapes between the two measures. In the following section, we investigate whether examining lower lip advancement (as a proxy for lip protrusion) helps to explain some of these small mismatches in greater detail.

C. Lower lip advancement

Figure 4 shows the model plot for lower lip horizontal advancement, which we use to model lip protrusion. For pre-coronal FOOT and GOOSE, there is almost complete overlap between the trajectories in both dialects. SSBE does, however, show slightly higher overall lower lip advancement relative to the *z*-scored mean than WYE.

The major finding here is the existence of pre-lateral vowel contrast in lower lip trajectories. Both dialects show more lip protrusion in GOOSE than FOOT, with this difference being largest in WYE around the 65% timepoint (remember that the interval for pre-lateral vowels includes both the vowel and the lateral portions). SSBE shows a notable difference between the beginning (vowel onset) and end (lateral offset) of the interval, suggesting lip protrusion in the vowel is greatest at vowel onset and smallest in the lateral. Notably, lip protrusion at vowel onset is similar pre-coronally and pre-laterally for SSBE, suggesting that the lateral has a prominent effect on reducing lip protrusion in this dialect. In contrast, WYE shows relatively constant lip protrusion across the entire interval, which is similar to the pre-coronal patterns in the same dialect. This suggests a greater degree of /l/ vocalisation in WYE compared to SSBE.

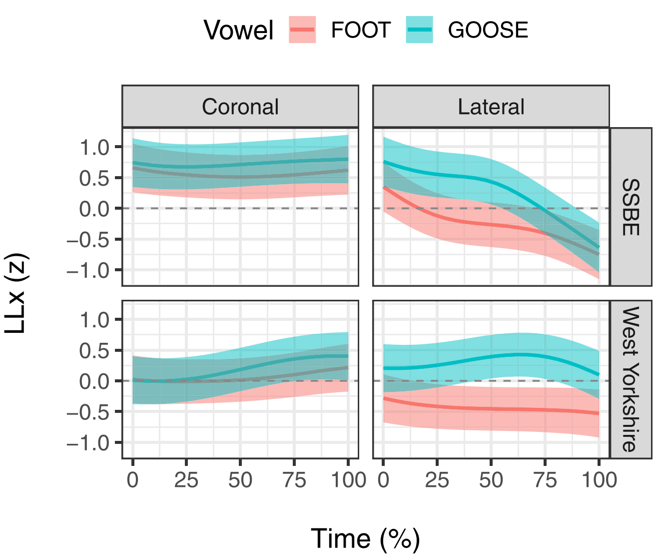

FIG. 4. (Color online) GAMM plot of time-varying lower lip protrusion trajectories for FOOT and GOOSE vowels, faceted by following context and dialect. Higher *z*-scores correspond to greater Lower Lip (LL) protrusion.

D. Interim summary

For pre-coronal vowels, we find a similar FOOT-GOOSE contrast in *F*2 and TD advancement, such that vowel trajectories are distinct in both domains, with GOOSE being the more advanced in lingual fronting and *F*2. There remain some differences in trajectory shape between the acoustic and articulatory data, in addition to very small differences in lip protrusion between pre-coronal vowels. In summary, the pre-coronal context appears to follow a relatively straightforward dynamic mapping between *F*2 and TD advancement.

In pre-lateral vowels, we also find some common patterns between acoustic and articulatory measures. For instance, we find only small evidence of vowel contrast in *F*2, alongside relatively small differences in TD advancement, albeit larger in magnitude than for *F*2. However, the overall trajectory shapes are not equivalent across measures. For example, we see an increase in TD advancement across time for FOOT in both dialects, whereas *F*2 dips slightly and then remains low. If we expected a linear relationship between *F*2 and TD fronting, then we would expect TD trajectories to remain relatively flat alongside the *F*2 trajectories. These mismatches go further when we consider the lower lip data. To re-cap, we would anticipate that TD advancement increases *F*2, while greater lip protrusion lowers *F*2 (Harrington *et al.*, 2011). However, we do not find a straightforward relationship between these articulatory variables. To take SSBE as an example, pre-lateral FOOT is relatively constant in *F*2 over time, whereas TD advancement increases (which should increase *F*2), and lip protrusion decreases (which should also increase *F*2). In order to examine this further, we now turn to speaker-specific variation in the pre-lateral vowel contrast.

E. Speaker-specific variation in pre-lateral vowels

Figure 5 shows by-speaker average trajectories for the pre-lateral FOOT-GOOSE contrast across the three measures. The *F*2 data for GOOSE shows that the majority of SSBE speakers have a high onset followed by a steep dip; in some cases, *F*2 then rises after the midpoint into the lateral phase, which is particularly evident for speakers such as SF2 and SM3. Only one SSBE speaker (SM4) shows a completely different pattern, with a linear downwards slope for both vowels. The WYE speakers are more consistent with one another, generally showing a smaller difference between vowels, except for YF5, who shows a bigger difference in the height of the GOOSE trajectory.

The TD data show greater variation in lingual fronting, with some speakers clearly showing a fronter GOOSE vowel compared to FOOT (SM4, YF2, YF4), whereas others clearly show a fronter FOOT vowel compared to GOOSE (SF3, SM1, SM5, YF3, YM1, YM2). The remaining speakers show greater similarities between vowels in TD advancement. On an individual level, there are bigger distinctions between vowel pairs in lingual fronting than in *F*2 but greater between-speaker variability in lingual fronting. Notably, the above patterns do not appear to be entirely resolved by the

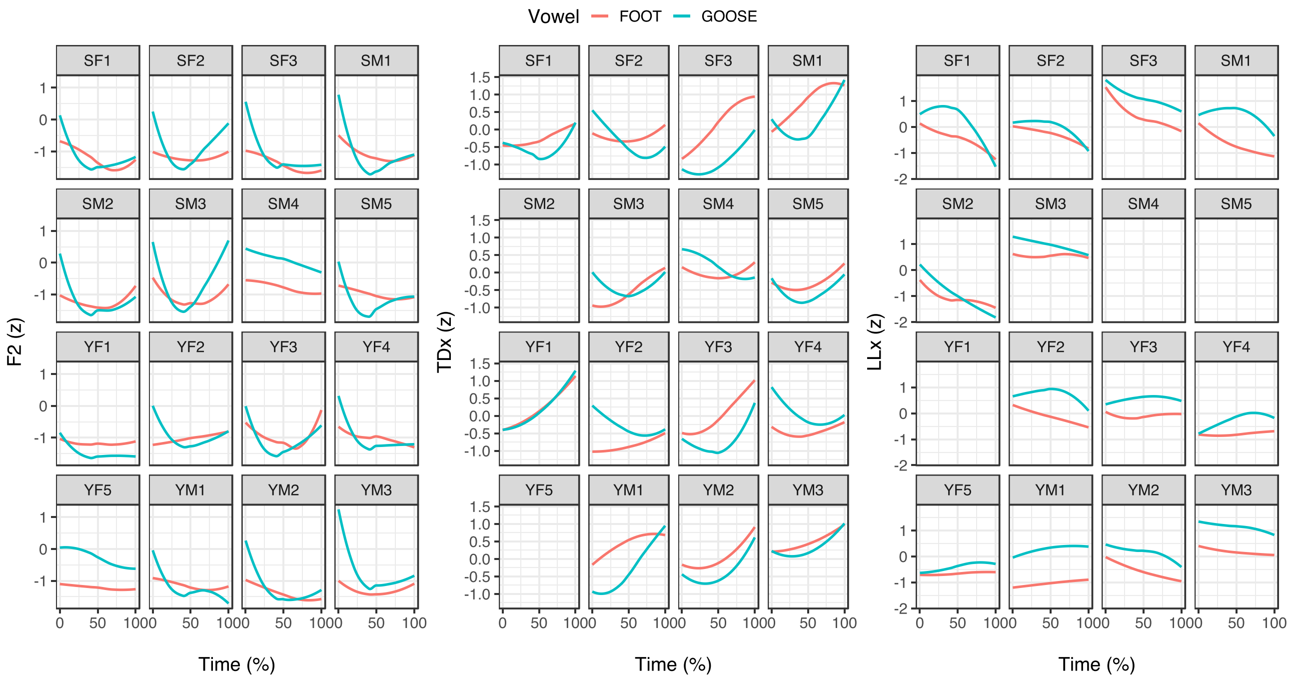

FIG. 5. (Color online) Smoothed by-speaker average $F2$ (left), TDx (middle), and LLx (right) trajectories in pre-lateral FOOT and GOOSE vowels. Higher z-scores correspond to higher $F2$, more advanced TD, and greater LL protrusion. Empty facets represent missing data for that speaker due to unreliable data from that particular sensor.

lower lip data, with every speaker producing greater lip protrusion during GOOSE than FOOT, albeit with variation in the magnitude of this difference.

To explore this in greater detail, Fig. 6 shows by-speaker $F2$ and TDx trajectories for each pre-lateral vowel in the same facet, which facilitates more direct comparison of acoustic-articulatory trajectories on the individual speaker level. This plot shows speaker variability in pre-lateral FOOT: $F2$ and TD trajectories are similar to each other for some speakers (SF2, SM4, YF2, to some extent also SM5, YF4, YM3), but in the majority of cases lingual fronting increases over time, whereas $F2$ remains more constant,

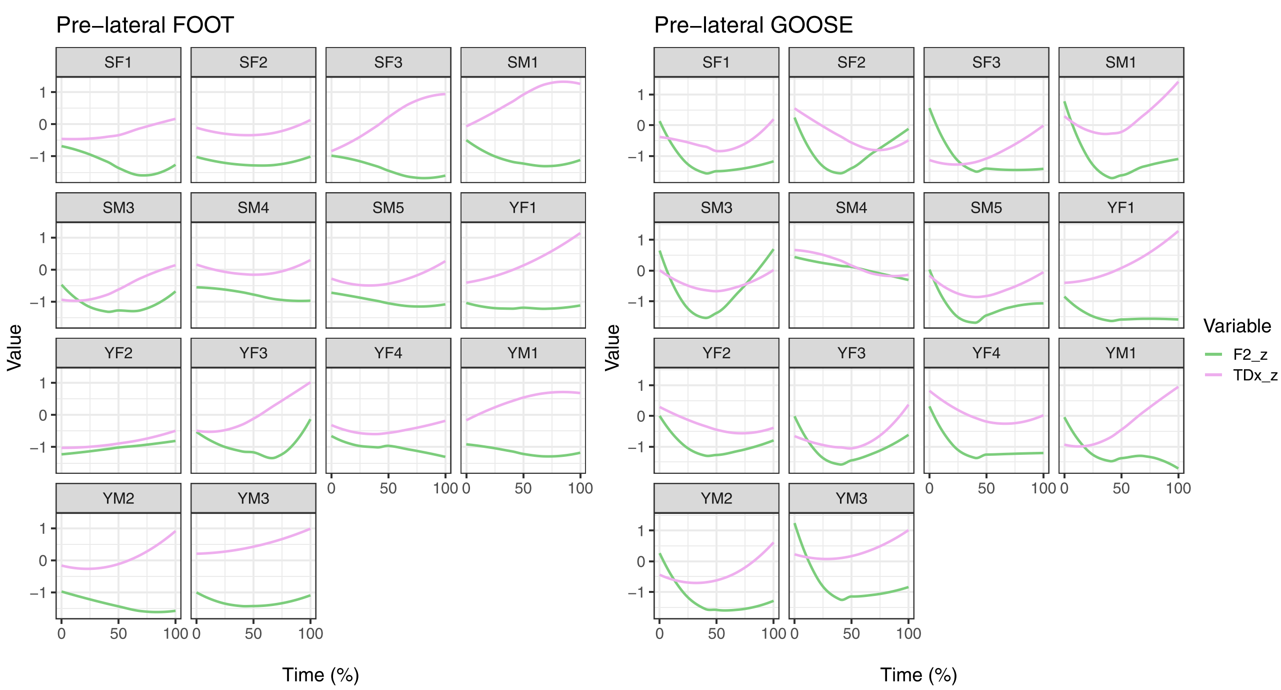

FIG. 6. (Color online) Smoothed by-speaker average $F2$ and TDx trajectories in pre-lateral FOOT (left) and GOOSE (right) vowels. Higher z-scores correspond to a greater $F2$ and TD advancement. Two speakers are excluded from this plot due to an unreliable TD sensor.

or dips and then rises. For pre-lateral GOOSE, the majority pattern is a high $F2$ onset followed by a big dip and, in some cases, followed by a rise. Only one speaker shows near-identical acoustic and articulatory trajectories in this context (SM4).

Overall, there are some common patterns and clear relationships in the individual speaker data, especially for pre-lateral FOOT, with the prominent patterns being (1) tight patterning between acoustic-articulatory trajectories; and (2) increase in lingual advancement, with a steady $F2$ or a small increase in $F2$. However, there is also clear evidence of speaker-specificity in the relationship between $F2$ and TD advancement. Our analysis shows that this is primarily due to variation in lingual fronting, despite relatively consistent patterns in $F2$. This suggests greater between-speaker variability in articulation than in acoustics. We now unpack these results with respect to previous research on acoustic-articulatory relations in vowels and gestural configuration in vowel-lateral sequences.

IV. DISCUSSION

A. Acoustics and articulation of vowel fronting in SSBE

Recall from Sec. I B that Strycharczuk and Scobbie (2017) analysed the same vowel contrast in SSBE using the same stimuli, but using midsagittal ultrasound instead of EMA for quantifying tongue advancement. They found that pre-lateral FOOT and GOOSE were merged in acoustics, but distinct in articulation. We found evidence for pre-lateral vowel contrast in acoustics and articulation, but note that the articulatory contrast was bigger than the acoustic contrast, which points in the same direction as Strycharczuk and Scobbie (2017). In summary, our results broadly agree with the previous findings in this area.

Strycharczuk and Scobbie (2017) explain their results by hypothesising a potential contribution of lip movement to $F2$, which may counteract the differences in tongue position evidenced in the articulatory data. Our lip protrusion data does not help to straightforwardly resolve this issue. In fact, we found that the lip data patterns in an opposite way to our predictions. For instance, SSBE pre-lateral FOOT shows an increase in TD advancement over time, whereas lip protrusion decreases over time. Both of these articulatory gestures should result in $F2$ raising, yet $F2$ remains relatively constant over its post-onset duration. This complicates the picture further, as there is no clear trading relation between the tongue and lips in modifying $F2$. We note, however, that these mismatches largely remain restricted to the pre-lateral context.

One explanation for this result could be aspects of vocal tract shaping that are not directly captured by EMA sensors. For example, in the production of both laterals and /u/ vowels, there is likely to be a small sublingual cavity, which is often modelled as a side branch that introduces additional poles and zeros into the transfer function (Stevens, 1998, p. 194). While the comparably small sublingual cavity in laterals is not predicted to have significant influences on the lower formants (Charles and Lulich, 2019), in principle it can lower the front cavity resonance and push it closer to $F2$, particularly for more retroflex-like articulations (Stevens, 1998, p. 535). Our EMA point tracking technique cannot adequately model such phenomena directly, meaning that there are various unmeasured aspects of vocal tract shaping that could be influencing the acoustic output and, therefore, could account for some of the apparent acoustic-articulatory mismatches that we report.

B. Effects of a coda lateral on vowel fronting

Previous studies show that a coda lateral exerts substantially different phonetic pressures on preceding back vowels compared with coronals, including greater lingual retraction and lower $F2$ (e.g., Carter and Local, 2007; Kleber *et al.*, 2011; Ladefoged and Maddieson, 1996). As a result, pre-lateral fronting of back vowels is considered to be a later stage of the sound change (e.g., see Fridland and Bartlett, 2006). This is supported by previous acoustic studies of British English, showing that pre-lateral GOOSE-fronting can occur, but that its progression through a speech community is likely to be gradual, evidenced in factors such as social class stratification (Baranowski, 2017).

Our results show the predictable lack of GOOSE fronting in pre-lateral contexts, evidenced in lower $F2$, a more retracted TD, and a more U-shaped TD trajectory compared with the rise-fall trajectory in the pre-coronal context. The FOOT vowel, however, is more complex. Predictably, pre-lateral FOOT shows lower $F2$ than pre-coronal FOOT in both dialects, with the contrast between pre-coronal and pre-lateral FOOT being much smaller than for GOOSE, particularly in WYE. From an articulatory perspective, however, the pre-lateral context does not condition lesser degrees of TD fronting than the pre-coronal context in either dialect. TD trajectories for FOOT show similar values at vowel onset in pre-lateral and pre-coronal contexts. However, we see lingual advancement in both dialects for this vowel over the timecourse of the vowel-lateral interval, despite no obvious effects of this on $F2$, and no straightforward evidence that this is counteracted by lip protrusion. In fact, in SSBE, we see that pre-lateral FOOT involves more lingual fronting than GOOSE after the first 25% of the interval. This could be suggestive of FOOT-fronting being at a more advanced stage in SSBE than WYE, which is predictable from the literature (e.g., Ferragne and Pellegrino, 2010; Watt and Tillotson, 2001). The overall model does not explain, however, why WYE FOOT shows more lingual fronting pre-laterally than pre-coronally.

Our speaker-specific analysis sheds some more light on these issues. Different speakers appear to use different patterns of lingual advancement between pre-lateral vowel pairs in order to achieve similar outcomes in $F2$. We do not find these differences to such an extent in the lip protrusion data. It is possible that the larger speaker differences in articulation may represent motor equivalent strategies for achieving similar acoustic outcomes (Carignan, 2014; Hogden *et al*., 1996; Perrier and Fuchs, 2015). However, it is clear that a more thorough account of multi-dimensional articulatory-acoustic relations is required in order to understand these patterns in more detail, especially as our analysis has only focused on a very minimal set of parameters, rather than a dynamic area function (see Carignan *et al*., 2020 for a very promising approach to analysing dynamic change in area functions from Magnetic Resonance Imaging data).

C. Acoustic-articulatory relations and vowel-lateral dynamics

Before unpacking the nature of acoustic-articulatory relations in more theoretical terms, we note one obvious methodological reason why pre-lateral vowels behave differently from pre-coronal vowels in our study. That is, the pre-coronal analysis examines only the vowel interval, whereas the pre-lateral analysis includes both the vowel and following lateral. This difference is inevitable, given the difficulties of reliable segmentation between vowels and laterals, which is particularly evident in the case of coda laterals. Indeed, much previous research has taken a similar approach, analysing the dynamics of the vowel-lateral interval as an entire syllable unit (Carter and Local, 2007; Kirkham, 2017; Kirkham *et al*., 2019; Nance, 2014).

That said, we believe that this alone does not account for the patterns that we see here. There are a number of potential explanations for why pre-lateral vowels may show less straightforward acoustic-articulatory relations. Previous research shows that the lateral context is the last stage to show fronting (Baranowski, 2017). Notably, this mismatch is more pronounced for FOOT, which we also expect to be at a later stage of sound change (Jansen, 2019). It could be the case that pre-lateral fronting of both vowels is in-progress in the communities under study in this paper, with FOOT being a much newer change. This may explain the higher degree of between-speaker variability in this context, as speakers could be at different stages of the sound change for this vowel.

An explanation that is also compatible with the above comes from quantal theories of speech production (Stevens, 1989, 1997). The specific dynamics of the lingual transition between FOOT and the following lateral may operate in a part of the vocal tract that exhibits a higher degree of acoustic-articulatory instability, such that articulatory change is not proportional to acoustic change in the way it might be in other areas of the vocal tract. While it would seem unusual for this to be the case for one vowel, a combination of the quantal nature of speech along with the high inter-speaker variability associated with early stages of sound change could account for the nature of our data. For instance, it is likely that sound changes-in-progress involve speakers subtly modifying vocal tract articulations, which may take time to stabilise into a quantal part of the vocal tract that yields a high degree of acoustic-articulatory stability. Previous work supports this, with evidence that articulatory change may sometimes precede acoustic change (Lawson *et al*., 2011). At present, however, this explanation is purely speculative and would need to be investigated with a much larger set of sounds that are at different stages of change.

Another important factor in explaining these results is the complex gestural configuration of laterals and how they interact with vowels. Proctor *et al*. (2019) compare laterals with rhotics and show that laterals may exhibit greater gestural independence from an adjacent vowel than rhotics. This is not to say, however, that the lateral does not exert significant influence on the vowel. Previous research shows surprisingly long-range coarticulation from liquids, sometimes multiple syllables prior to the vowel (Heid and Hawkins, 2000). This makes it highly likely that entire vowel-lateral trajectories will substantially differ from vowels followed by a non-liquid consonant. This does not explain, however, why we see markedly different patterns between pre-lateral FOOT and GOOSE. It is likely, then, that there is a complex dynamic involved in the acoustic-articulatory relations of pre-lateral vowels undergoing sound change.

Finally, we must stress that our focus on single points on the tongue and lower lip does not adequately capture the complex vocal tract shaping involved in vowel or lateral production. Vocal tract resonances arise from a three-dimensional airspace, which is of course modulated by the tongue, but a point on the tongue does not adequately capture the oral tract area function in its rich detail. It is, therefore, very likely that there are many unmeasured articulatory dimensions that are contributing to the $F2$ of pre-lateral vowels in these data. Future research should seek to better handle such issues by developing interpretable ways of tracking the relationship between multi-dimensional acoustic and articulatory variables over time.

V. CONCLUSION

This study has taken a dynamic approach to investigating the effect of a coda consonant on acoustic-articulatory relations in British English back vowel fronting. While both SSBE and WYE dialects display similar trajectories across $F2$ and tongue advancement for pre-coronal vowels, we observe significant mismatches between $F2$ and tongue advancement in the pre-lateral context, which lip protrusion is also unable to explain. We find a substantial amount of speaker-specific variation in lingual fronting for pre-lateral vowels, which points towards relatively consistent acoustic targets despite a high degree of articulatory variability (at least in pre-lateral vowels).

Overall, we hypothesise that the acoustic-articulatory patterns observed in pre-lateral vowels may be due to the complex gestural configuration that accompanies laterals and how this interacts with vowel gestures in such contexts. Future research will aim to more comprehensively understand coarticulatory dynamics and acoustic-articulatory relations in vowel-lateral sequences. This will necessarily involve developing ways of better quantifying time-varying acoustic-articulatory relations and being able to compare

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how these vary between speakers. We also believe that an apparent-time comparison of younger and older speakers would help to explain whether the acoustic-articulatory relations reported here are due to the pre-lateral vowels being at different stages of sound change for different speakers.

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Atal, B. S., Chang, J. J., Mathews, M. V., and Tukey, J. W. (**1978**). "Inversion of articulatory-to-acoustic transformation in the vocal tract by a computer-sorting technique," J. Acoust. Soc. Am. **63**(5), 1535–1555.

Baranowski, M. (**2017**). "Class matters: The sociolinguistics of GOOSE and GOAT in Manchester English," Lang. Var. Change **29**(3), 301–339.

Blackwood Ximenes, A., Shaw, J. A., and Carignan, C. (**2017**). "A comparison of acoustic and articulatory methods for analyzing vowel differences across dialects: Data from American and Australian English," J. Acoust. Soc. Am. **142**(1), 363–377.

Carignan, C. (**2014**). "An acoustic and articulatory examination of the 'oral' in 'nasal': The oral articulations of French nasal vowels are not arbitrary," J. Phon. **46**, 23–33.

Carignan, C. (**2019**). "A network-modeling approach to investigating individual differences in articulatory-to-acoustic relationship strategies," Speech Commun. **108**, 1–14.

Carignan, C., Hoole, P., Kunay, E., Pouplier, M., Jospeh, A., Voit, D., Frahm, J., and Harrington, J. (**2020**). "Analyzing speech in both time and space: Generalized additive mixed models can uncover systematic patterns of variation in vocal tract shape in real-time MRI," Lab. Phonol. **11**(1), 1–26.

Carter, P., and Local, J. (**2007**). "F2 variation in Newcastle and Leeds English liquid systems," J. Int. Phon. Assoc. **37**(2), 183–199.

Charles, S., and Lulich, S. M. (**2019**). "Articulatory-acoustic relations in the production of alveolar and palatal lateral sounds in Brazilian Portuguese," J. Acoust. Soc. Am. **145**(6), 3269–3288.

Fant, G. (**1960**). *Acoustic Theory of Speech Production: With Calculations Based on X-Ray Studies of Russian Articulations* (Mouton, The Hague).

Ferragne, E., and Pellegrino, F. (**2010**). "Vowel systems and accent similarity in the British Isles: Exploiting multidimensional acoustic distances in phonetics," J. Phon. **38**(4), 526–539.

Fridland, V., and Bartlett, K. (**2006**). "The social and linguistic conditioning of back vowel fronting across ethnic groups in Memphis, Tennessee," Eng. Lang. Ling. **10**(1), 1–22.

Goldstein, L., and Fowler, C. A. (**2003**). "Articulatory phonology: A phonology for public language use," in *Phonetics and Phonology in Language Comprehension and Production: Differences and Similarities*, edited by N. O. Schiller and A. S. Meyer (Mouton de Gruyter, Berlin), pp. 159–207.

Guenther, F. H. (**2016**). *Neural Control of Speech* (The MIT Press, Cambridge, MA).

Harrington, J., Kleber, F., and Reubold, U. (**2011**). "The contributions of the lips and the tongue to the diachronic fronting of high back vowels in Standard Southern British English," J. Int. Phon. Assoc. **41**(1), 137–156.

Heid, S., and Hawkins, S. (**2000**). "An acoustic study of long-domain /r/ and /l/ coarticulation," in *Proceedings of the 5th Seminar on Speech Production: Models and Data*, May 1–4, Kloster Seeon, Germany, pp. 77–80.

Hogden, J., Lofqvist, A., Gracco, V. L., Zlokarnik, I., Rubin, P., and Saltzman, E. (**1996**). "Accurate recovery of articulator positions from acoustics: New conclusions based on human data," J. Acoust. Soc. Am. **100**(3), 1819–1834.

Honda, M., Fujino, A., and Kaburagi, T. (**2002**). "Compensatory responses of articulators to unexpected perturbation of the palate shape," J. Phon. **30**(3), 281–302.

Hughes, A., Trudgill, P., and Watt, D. (**2005**). *English Accents and Dialects: An Introduction to Social and Regional Varieties of English in the British Isles* (Hodder, London).

Iskarous, K. (**2016**). "Compatible dynamical models of environmental, sensory, and perceptual systems," Ecol. Psychol. **28**(4), 295–311.

Jansen, S. (**2019**). "Change and stability in GOOSE, GOAT and FOOT: Back vowel dynamics in Carlisle English," Eng. Lang. Ling. **23**(1), 1–29.

Kirkham, S. (**2017**). "Ethnicity and phonetic variation in Sheffield English liquids," J. Int. Phon. Assoc. **47**(1), 17–35.

Kirkham, S., and Nance, C. (**2017**). "An acoustic-articulatory study of bilingual vowel production: Advanced tongue root vowels in Twi and tense/lax vowels in Ghanaian English," J. Phon. **62**, 65–81.

Kirkham, S., Nance, C., Littlewood, B., Lightfoot, K., and Groarke, E. (**2019**). "Dialect variation in formant dynamics: The acoustics of lateral and vowel sequences in Manchester and Liverpool English," J. Acoust. Soc. Am. **145**(2), 784–794.

Kleber, F., Harrington, J., and Reubold, U. (**2011**). "The relationship between perception and production of coarticulation during a sound change in progress," Lang. Speech **55**(3), 383–405.

Ladefoged, P., and Maddieson, I. (**1996**). *The Sounds of the World's Languages* (Blackwell, Oxford, UK).

Lawson, E., Stuart-Smith, J., and Rodger, L. (**2019**). "A comparison of acoustic and articulatory parameters for the GOOSE vowel across British Isles Englishes," J. Acoust. Soc. Am. **146**(6), 4363–4381.

Lawson, E., Stuart-Smith, J., Scobbie, J. M., Yaeger-Dror, M., and Maclagan, M. (**2011**). "Liquids," in *Sociophonetics: A Student's Guide*, edited by M. Di Paolo and M. Yaeger-Dror (Routledge, London), pp. 72–86.

Mermelstein, P. (**1967**). "Determination of the vocal-tract shape from measured formant frequencies," J. Acoust. Soc. Am. **41**(5), 1283–1294.

Nance, C. (**2014**). "Phonetic variation in Scottish Gaelic laterals," J. Phon. **47**(1), 1–17.

Perkell, J. S., Matthies, M. L., Svirsky, M. A., and Jordan, M. I. (**1993**). "Trading relations between tongue-body raising and lip rounding in production of the vowel /u/: A pilot 'motor equivalence' study," J. Acoust. Soc. Am. **93**(5), 2948–2961.

Perrier, P., and Fuchs, S. (**2015**). "Motor equivalence in speech production," in *The Handbook of Speech Production*, edited by M. A. Redford (Wiley, New York), pp. 225–247.

Proctor, M., Walker, R., Smith, C., Szalay, T., Goldstein, L., and Narayanan, S. (**2019**). "Articulatory characterization of English liquid-final rimes," J. Phon. **77**, 100921.

Sóskuthy, M. (**2017**). "Generalised additive mixed models for dynamic analysis in linguistics: A practical introduction," arXiv:1703.05339.

Sóskuthy, M., Foulkes, P., Hughes, V., and Haddican, B. (**2018**). "Changing words and sounds: The roles of different cognitive units in sound change," Topics Cogn. Sci. **10**(4), 787–802.

Stevens, K. N. (**1989**). "On the quantal nature of speech," J. Phon. **17**(1), 3–45.

Stevens, K. N. (**1997**). "Articulatory-acoustic-auditory relationships," in *The Handbook of Phonetic Sciences*, edited by W. J. Hardcastle and J. Laver (Blackwell, Oxford, UK), pp. 462–506.

Stevens, K. N. (**1998**). *Acoustic Phonetics* (MIT Press, Cambridge, MA).

Strycharczuk, P., and Scobbie, J. M. (**2017**). "Fronting of Southern British English high-back vowels in articulation and acoustics," J. Acoust. Soc. Am. **142**(1), 322–331.

Tremblay, S., Shiller, D. M., and Ostry, D. J. (**2003**). "Somatosensory basis of speech production," Nature **423**, 866–869.

Watt, D., and Tillotson, J. (**2001**). "A spectrographic analysis of vowel fronting in Bradford English," English World-Wide **22**(2), 269–303.

Wieling, M. (**2018**). "Generalized additive modeling to analyze dynamic phonetic data: A tutorial focusing on articulatory differences between L1 and L2 speakers of English," J. Phon. **70**, 86–116.

Wood, S. N. (**2017**). *Generalized Additive Models: An Introduction with R*, Second Edition (CRC Press, Boca Raton, FL).