Laterals

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Abstract

This chapter reviews acoustic and articulatory methods for studying the production of lateral consonants (i.e. 'L'-sounds), focusing on the alveolar lateral approximant /l/ in English. Laterals are generally characterized by an occlusion along the midline of the tongue and a formation of lateral channels for the airflow to escape on either one or both sides of the tongue. In this chapter, we first provide an overview of English /l/ and its relevance to the study of sociophonetics, including the regional/social variations in British Isles and beyond. We then review acoustic/articulatory data collection and analysis methods, including newer trends utilizing ultrasound tongue imaging and electromagnetic articulography (EMA) within and outwith the laboratory. While many sociophonetic analyses of laterals focus on representative features extracted at a single point in time, we show that dynamic properties are critical to understanding their nature and variation. We conclude with recommendations on how to implement dynamic approaches to lateral analysis with varying degrees of interpretability. In summary, the analysis of laterals captures a range of topics relevant to uncovering subtle and structural cross-dialect/linguistic variability that underpins sociophonetic theory and practice.
Keywords. Lateral allophony, English, formant, tongue shape, kinematics, ultrasound, EMA, dynamic data analysis, GAMMs, FPCA

1 Introduction

1.1 Laterals: an overview

The defining characteristic of the class of laterals is the passage of airflow around one or both sides of the tongue. Most laterals are approximants, although lateral obstruents are also attested, albeit more rarely (Ladefoged and Maddieson, 1996). Laterals occur at multiple lingual places of articulation, including alveolar, retroflex, palatal, and velar. By far the most common lateral, however, is the alveolar lateral approximant, which is also the lateral found in English. Given the extensive body of previous research, this chapter focuses on English /l/, while noting that the analytical methods discussed here are broadly applicable to the study of laterals cross-linguistically.

Central to (socio)phonetic research on English /l/ is its systematic allophonic variation between an "/i/-like", clear or light [l] and a "/u/-like", dark [ɫ] realization (Recasens, 2012, p. 368). Although clear and dark laterals have sometimes been treated as categorical variants (Chomsky and Halle, 1968; Giles and Moll, 1975), previous empirical work has demonstrated a high degree of gradience in the realization of lateral darkness (Turton, 2017; Sproat and Fujimura, 1993; Kirkham, Turton, et al., 2020). Turton (2017) argues that both categoricity and gradience must coexist within the grammar in order to account for the full range of lateral realizations observed across accents of British English. These realizations are shaped by multiple interacting factors, including syllabic position, vowel context, and morphosyntactic structure. In addition, word-final /l/ may undergo vocalization as a result of reduced apical contact with the alveolar ridge and a concomitant loss of tongue lateralization, yielding a percept similar to back vowels or /w/ (Wells, 1982; Strycharczuk, Derrick, et al., 2020). /l/-vocalization has been documented across varieties of English, including British English (Hardcastle and Barry, 1989; Scobbie and Pouplier, 2010), New Zealand English (Strycharczuk, Derrick, et al., 2020), American English (Ash, 1982), and Australian English (Szalay et al., 2022).

While clear and dark laterals are widely attested across languages and dialects, their phonetic realizations are language- and dialect-specific. Cross-linguistically, languages differ in their overall lateral quality; for example, laterals in German and French tend to be relatively clear, whereas Russian exhibits generally dark lateral realizations (Recasens, 2012). Substantial dialectal variation is also observed within languages. In British English, regional accents form a continuum of lateral darkness, ranging from predominantly dark realizations across syllabic positions in cities such as Leeds, Sheffield, and Manchester, to predominantly clear laterals in Newcastle, Norwich, and Peterborough (Carter and Local, 2007; Kirkham, Turton, et al., 2020; Turton and Baranowski, 2021). Among North American English dialects, where laterals are generally dark (Recasens, 2012), Newfoundland English stands out in exhibiting relatively clear realizations in both word-initial and word-final positions, reflecting the influence of early settlers from Ireland. Notably, the distinction between initial and final /l/ is less pronounced for older speakers than for younger speakers (De Decker and Mackenzie, 2017; Wells, 1982).

The complex interaction of multiple phonetic factors in the production of laterals makes them both a productive and a challenging object of sociophonetic research, particularly in the study of synchronic variation and diachronic change. Processes such as /l/-darkening illustrate how subtle phonetic variation can become conventionalized over time (Ohala, 2012; Turton, 2023; Strycharczuk, Derrick, et al., 2020). Instrumental investigation of synchronic variation in lateral acoustics and articulation therefore plays a crucial role in documenting changes in progress and in deepening our understanding of how sound systems evolve over time.

1.2 This chapter

The objective of this chapter is to provide an up-to-date guide for data analysis with respect to lateral acoustics and articulation. In the section below, we first provide a brief description of lateral acoustics, followed by a discussion of important considerations for reliable acoustic segmentation. We then describe lateral articulation, alongside methods for collecting and analyzing articulatory data, focusing mainly on ultrasound tongue imaging and electromagnetic articulography. Finally, we conclude by demonstrating that inherently complex structure in lateral production can be best studied by focusing on time-varying characteristics in a larger domain that includes both the lateral and the adjacent vowels Given the handbook's focus on research methods, we do not provide an extensive discussion of (socio-)linguistic factors of lateral allophony; interested readers are advised to refer to other existing sources (e.g., Turton, 2023). Data and codes to reproduce figures and analysis in this chapter can be accessed at `https://osf.io/2sk5t/`. All figures and analyses were produced in R version 4.4.3 via R Studio Desktop version 2024.12.1.563 (R Core Team, 2025; Posit team, 2025).

2 Acoustic methods

2.1 Dimensions of acoustic analysis for laterals

The primary acoustic characteristic of clear-dark lateral allophony is the second formant frequency (F_2). Clear /l/ is characterized by a relatively higher F_2 at around 1,500-2,000 Hz whereas dark /l/ often exhibits lower F_2 frequencies about 800-1,200 Hz (Recasens, 2012). The F_2 frequency is associated with the back cavity resonance posterior to the primary oral constriction, and the retraction of tongue body decreases the F_2 values for dark /l/ (Narayanan et al., 1997).

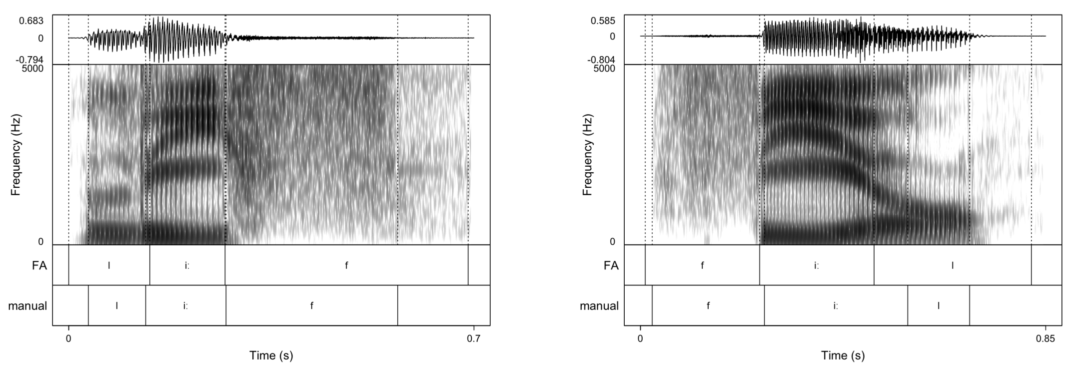
In addition to F_2, dark [ɫ] shows higher F_1 than clear [l] (Recasens, 2012), and this makes the distance between F_2 and F_1 (i.e., F_2-F_1) a good index of the degree of lateral darkness and tongue retraction (e.g., Kirkham, 2017; Nance, 2014; Sproat and Fujimura, 1993; Lehiste, 1965; De Decker and Mackenzie, 2017). Smaller F_2-F_1 values indicate a closer spacing between F_2 and F_1 that are associated with postvocalic /l/, similar to /w/ in spectral quality (Espy-Wilson, 1992). The F_2-F_1 measure summarises the relationships between the two formants into a single measure while achieving some degrees of vocal tract normalization that could better facilitate cross-speaker comparisons (Sproat and Fujimura, 1993; Kirkham, 2017; Syrdal and Gopal, 1986; Holmes-Elliott and Smith, 2018; Kirkham, Turton, et al., 2020).

2.2 Acoustic analysis considerations: segmentation

Lateral quality is commonly assessed at a single point in time in much sociophonetic research, most often at the acoustically-defined temporal midpoint that approximates the lateral acoustic target (Macdonald and Stuart-Smith, 2024; Kirkham, Nance, et al., 2019). Defining the temporal midpoint can be facilitated by identifying different events that are involved in lateral production: a transition from the preceding vowel, the steady state, and a transition into the following vowel. The F_2 steady-state is often used as an approximation of the lateral interval (Simonet et al., 2008; Lawson et al., 2011; Nance, 2014) although some studies do include the transition phase in the lateral interval (Mackenzie et al., 2018). Boundaries between the lateral and the adjacent vowels can be defined via a discontinuity in F_2, together with reduced amplitude profile, due to a greater degree of oral constriction around alveolar ridge compared to vowels (Lawson et al., 2011; Carter, 2002).

In practice, however, identifying the lateral-vowel boundary clearly in a reliable and principled manner can be difficult and often time-consuming, especially for postvocalic /l/ (Carter, 2002; Sproat and Fujimura, 1993; Kirkham, Nance, et al., 2019; Plug and Ogden, 2003; Mackenzie et al., 2018). Various phases in lateral production point towards an inherently dynamic structure in lateral acoustics, which can differ between clear and dark laterals (Kirkham, Nance, et al., 2019; Carter, 2002). The ease in identifying spectral F_2 discontinuity also differs depending on (1) the surrounding vocalic contexts, due to a strong lateral-vowel coarticulation (Sproat and Fujimura, 1993), and (2) the vocalization process (Lawson et al., 2011; Carter, 2002). These challenges in reliable segmentation between the lateral and the vowel may account for mixed findings regarding the duration effects on lateral darkness (Sproat and Fujimura, 1993; Yuan and Liberman, 2009; Mackenzie et al., 2018).

Examples of spectrograms are shown in Figure 1 for isolated word production of *leaf* (left) and *feel* (right) by a male American English speaker. While the F_2 steady-state and a change in waveform amplitude can be identified relatively easily for the initial /l/ in *leaf*, it is less clear for the final /l/ in *feel*. Figure 1 also compares segmentation based on a forced alignment (top tier) with manual segmentation (bottom tier). The lateral interval is defined as the F_2 steady-state for the manual segmentation, whereas the forced alignment, based on Montreal Forced Aligner version 2.0.6 (McAuliffe et al., 2017), includes the transition into and out of the adjacent vowel in the lateral interval.



(a) leaf (b) feel

Figure 1: Examples of acoustic segmentation of *leaf* and *feel* by a male American English speaker, based on forced alignment (FA: top) and manual segmentation (bottom). The lateral interval is defined as the F_2 steady state for the manual segmentation. Plots were created using the *praatpicture* package in R (Puggaard-Rode, 2024).

A key methodological consideration, therefore, is whether it is meaningful to define a vowel-lateral boundary (cf. Plug and Ogden, 2003). Even if aided by forced alignment tools, manual correction is often inevitable so that the segmentation is faithful to the researchers' definition of lateral acoustic intervals. However, determining a lateral-vowel boundary often involves an arbitrary decision due to a lack of clear acoustic landmarks between the vowel and the lateral (Mackenzie et al., 2018). Due to a strong vocalic coarticulation, it is therefore often fruitful to analyze the lateral quality together with the adjacent vowels (e.g., syllable rime: syllable-final vowel-lateral sequence) as a single unit of analysis. This underpins the assumption that lateral quality is inherently dynamic and thus is impossible to be characterized with a single point measurement (Turton, 2023). For this, dynamic analysis methods allow for a systematic, quantitative analysis of time-varying trajectories (Sonderegger and Sóskuthy, 2025), which we will introduce in Section 4.

3 Articulatory methods

3.1 Dimensions of articulatory analysis for laterals

The clear–dark allophony of laterals arises from position-dependent tongue shape and the spatiotemporal coordination of articulatory gestures. Among articulatory methods, ultrasound tongue imaging and electromagnetic articulography (EMA) are arguably the most useful for studying lateral articulation in sociophonetic contexts, for their increased portability (especially ultrasound), high temporal resolution (especially EMA), and their ability to image or track tongue movement even in the absence of linguopalatal contact (Heyne et al., 2020; Nance, Dewhurst, et al., 2024; Strycharczuk, Lloyd, et al., 2023; Wieling et al., 2016). This section reviews articulatory dimensions that characterize lateral darkness and that are accessible using ultrasound and EMA. For specific methodological details of these techniques, readers are referred to Chapter 17 of this volume. (See also Pucher et al. (2020) for the influence of ultrasound headset on speech production.)

3.1.1 Midsagittal tongue shape

One articulatory dimension that is particularly relevant to English /l/ is midsagittal tongue shape. Midsagittal tongue shape profiles are often extracted at a single point in time, analogous to midpoint-based acoustic analyses, such as at the lateral midpoint or at the point of maximal displacement of the tongue tip and/or tongue dorsum (Lee-Kim et al., 2013; Turton, 2017). Lateral darkness correlates with the overall height and backness of the midsagittal tongue shape: dark [ɫ] typically exhibits a lower and more retracted tongue configuration, reflecting tongue root retraction and velarization (Turton, 2017; Strycharczuk, Derrick, et al., 2020; De Decker and Mackenzie, 2017). However, Turton (2017) and Turton and Baranowski (2021) demonstrate that the degree of clear–dark contrast in tongue shape varies across accents of British English, with Newcastle and Manchester showing smaller differences than Received Pronunciation, London English, and Belfast English across phonological contexts. Figure 2 illustrates clear–dark tongue shape contrasts from ultrasound recording of 265 tokens of word-initial (n = 133) and word-final (n = 132) laterals in an /i/ context, elicited via word-list reading (e.g., ***l**eaf* and *fee**l***) from nine North American English speakers.

Articulatory manifestations of lateral darkness are mediated by several factors, including vowel context, morphosyntactic structure, and accent variation. For instance, in New Zealand English, the clear–dark contrast is particularly large when laterals are preceded by the FLEECE vowel (e.g., he***l***ix), where darkness is manifested through both tongue root retraction and tongue mid lowering. In contrast, only tongue root retraction is observed in KIT and THOUGHT contexts (Strycharczuk, Derrick, et al., 2020). These vowel effects likely reflect strong lateral–vowel coarticulatory interactions. In many cases, the interaction arises from differences between onset and coda laterals (a coarticulatory effect), while in others it may reflect acquired allophonic patterns that go beyond simple coarticulation.

More generally, adjacent vowels influence lateral quality such that laterals are typically clearer when flanked by front vowels than by back vowels (Recasens, 2012; Bladon and Al-Bamerni, 1976; Lehiste, 1965; Giles and Moll, 1975). The FLEECE vowel involves tongue body raising and fronting, which increases the degrees of freedom available for tongue dorsum movement during the lateral, allowing for greater gradient variability in intermediate lateral realizations compared to contexts such as THOUGHT, LOT, or STRUT (Strycharczuk, Derrick, et al., 2020; Lee-Kim et al., 2013). Finally, even within the same vowel context, varying degrees of darkness have been reported across different morphological environments, including contrasts between word-initial and word-final pre-consonantal laterals in New Zealand English, as well as between stem-final, pre-boundary intervocalic, and post-boundary stem-initial laterals in Canadian English (Strycharczuk, Derrick, et al., 2020; Lee-Kim et al., 2013).

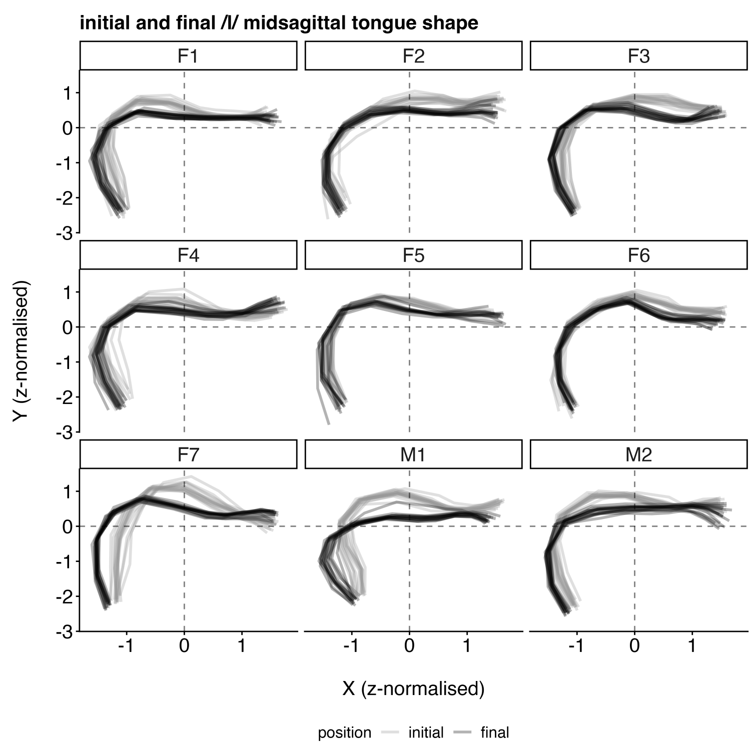


Figure 2: Tongue shape extracted at the lateral midpoint for word-initial (light gray) and word-final (black) laterals produced by North American English speakers in the /i/ context. F = female, M = male speakers.

3.1.2 Midsagittal kinematics

Another important articulatory dimension is tongue kinematics. Laterals primarily involve two midsagittal articulatory gestures: a tongue tip (consonantal) gesture and a tongue dorsum (vocalic) gesture (Sproat and Fujimura, 1993; Browman and Goldstein, 1995; Gick, 1999). Articulatory gestures are abstract phonological events that drive the vocal tract to achieve linguistic tasks (Browman and Goldstein, 1995). Active spatiotemporal coordination between coronal and dorsal gestures indicates that lateral articulation is inherently dynamic. Accordingly, many studies examine laterals using kinematic analyses that identify maximal displacements of the tongue tip and dorsum and/or track time-varying changes in articulatory position (Strycharczuk, Derrick, et al., 2020; Ying et al., 2021).

Flesh-point tracking methods have traditionally been used to study lateral kinematics (Sproat and Fujimura, 1993; Browman and Goldstein, 1995; Strycharczuk, Derrick, et al., 2020). However, recent methodological advances have made ultrasound-based kinematic analysis increasingly feasible. In particular, deep-learning-based tongue surface estimation enables fast, automatic processing with measurement accuracy comparable to EMA (Wrench and Balch-Tomes, 2022; Balch-Tomes et al., 2024; Kirkham and Strycharczuk, 2025; Kirkham, Strycharczuk, et al., 2023).

Syllabic position strongly influences gestural coordination. Generally, it has been proposed that syllable-initial consonants tend to involve a greater degree of consonantal (i.e. peripheral) gesture that is timed earlier than the vocalic (i.e. central) gesture (Krakow, 1999; Browman and Goldstein, 1995). This pattern extends to the clear–dark allophony of laterals. Prevocalic clear [l] is characterized by a stronger coronal constriction that occurs earlier than, or synchronously with, tongue body retraction or lowering; postvocalic darker laterals, on the other hand, typically exhibit tongue body retraction or lowering that precedes coronal constriction (Sproat and Fujimura, 1993; Browman and Goldstein, 1995; Narayanan et al., 1997; Recasens, 2012; Recasens and Espinosa, 2005; Ying et al., 2021).

This coordination pattern can be quantified using Tip Delay, defined as the temporal lag between the time points associated with maximal tongue tip raising or fronting and maximal tongue dorsum retraction or lowering (Sproat and Fujimura, 1993; Ying et al., 2021). Tip Delay values are negative when the tongue tip gesture precedes the tongue dorsum gesture and positive when the order is reversed.

Figure 3 illustrates a kinematic analysis based on word-list recordings from a female North American English speaker, containing word-initial and word-final laterals in an /i/ context. Tongue tip and dorsum movements are estimated from ultrasound data by tracking the positions of 'knots', which represent functional points identified using a pre-trained deep learning model for markerless pose estimation (Wrench and Balch-Tomes, 2022; Mathis et al., 2018). In this figure, tongue tip movement is represented by knot 10 (Tip 1) and tongue dorsum movement by knot 5 (Body 2) (cf. Strycharczuk, Kirkham, et al., 2025). Word-initial tokens show the tongue tip maximum occurring slightly before the tongue dorsum minimum, with near-synchronous timing overall. In contrast, word-final tokens show the tongue tip maximum occurring after the tongue dorsum minimum, with a substantially larger temporal lag.

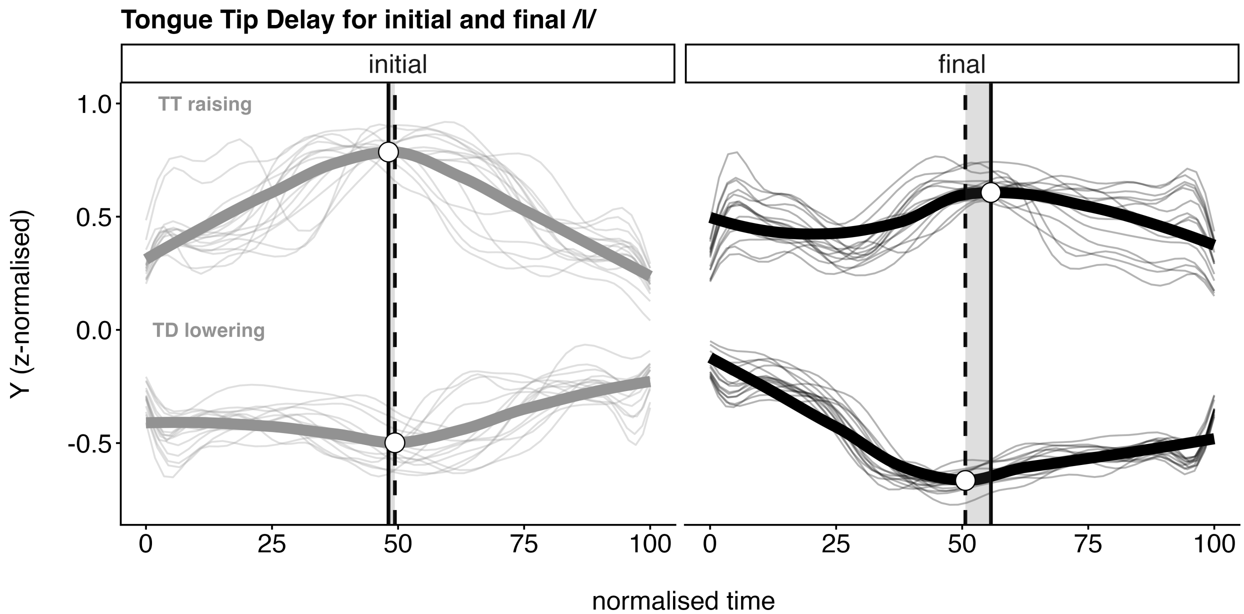


Figure 3: Time-varying changes in vertical tongue tip (TT: top) and horizontal tongue dorsum (TD: bottom) positions for a female North American English speaker in word-initial lateral–vowel (left) and word-final vowel–lateral intervals (right) in the /i/ context. Individual tokens are shown as fine lines with a superimposed smooth indicating the overall trend. A 350-ms interval is padded before and after the target intervals to capture movement to and from the speech rest position.

3.1.3 Lateralization

A major advantage of modern EMA systems is their ability to track sensor positions in three-dimensional space with high temporal resolution, enabling the simultaneous measurement of tongue lateral movement alongside midsagittal motion (Katz et al., 2018; Howson and Kochetov, 2015; Ying et al., 2021). Studies have shown that speakers employ different lateralization strategies, such as lowering one or both sides of the tongue, as observed in Czech laterals (Howson and Kochetov, 2015). In Australian English, Ying et al. (2021) report stable timing relationships between lateral and dorsal gestures across onset and coda laterals, suggesting active coordination of tongue lateralization. Tongue lateral movement may therefore form part of the broader gestural coordination underlying lateral production (Strycharczuk, Derrick, et al., 2020; Ying et al., 2021). Moreover, Strycharczuk, Derrick, et al. (2020) find that tongue lateralization is substantially reduced in /l/-vocalization contexts, which may be mechanically associated with tongue mid lowering.

Direct measurement of tongue lateralization has the potential to uncover new insights into lateral articulation beyond the midsagittal plane. Although lateralization is the defining characteristic of laterals, it remains one of the least well-understood aspects of their production, particularly in sociophonetic contexts (De Decker and Mackenzie, 2017). Previous research has focused primarily on idiosyncratic and contextual variation; future work could instead examine how lateral channels are formed, how lateralization is coordinated as part of the lateral gestural complex, and how these patterns vary across regional and social variations.

4 Addressing dynamics in the production of laterals

The dynamic nature of lateral production underscores the importance of preserving the time-varying changes in acoustic and articulatory signals in the data. Conventional analysis methods based on a single measurement point is known to be a drastic simplification, so alternative approaches are needed to capture how rich acoustic and articulatory variation unfolds over time. The key consideration here is the quantification of the non-linearity in time and space, including time-varying changes in formant frequency in acoustics and dynamic changes in tongue shape.

Here, we introduce two dynamic analysis methods that are commonly used in phonetics research: Generalized Additive Mixed-effect Models (GAMMs) and Functional Principal Component Analysis (FPCA). We illustrate these methods with an example dynamic acoustic analysis, focusing on the time-varying changes in F2 contours. We use a subset of data publicly available in Nagamine (2024b). The data include 1,218 tokens of word-initial lateral-vowel sequences in three vowel contexts, elicited with isolated word-list reading (/æ/: ***la***mb, ***la***mp, ***la***p, /i/: ***lea***f, ***lea***p, ***lea***ve, /u/: ***loo***m, ***lu***be) from 14 L1 English speakers (11 famale, 3 male) and 31 L1 Japanese speakers (17 female, 14 male). F2 frequencies were sampled every 2 ms throughout the lateral-vowel interval and binned into 11 equidistant points using FastTrack (Barreda, 2021), allowing us to track time-varying changes in F2 at 10% increments from lateral onset (0%) to vowel offset (100%). While the data set comes from a second language speech production study, the methods demonstrated here are widely applicable to sociophonetic research. Raw F2 trajectories are visualized in the top left panel in Figure 4, and here we illustrate how they could be analyzed using GAMMs (Section 4.1) and FPCA (Section 4.2).

4.1 Generalized Additive Mixed-effect Models: GAMMs

Generalized Additive Mixed-effect Models (GAMMs) are one of the most prevalent dynamic statistical approaches for both acoustics (Sóskuthy, 2017; Sóskuthy, 2021; Kirkham, Nance, et al., 2019; Nagamine, 2024b) and articulation (Strycharczuk, Derrick, et al., 2020; Wieling et al., 2016; Wieling, 2018). In the study of time-varying lateral acoustics, GAMMs allow for a holistic modelling of formant trajectories over the transition and steady-state phases during the lateral production, demonstrating that regional and social differences in the lateral acoustics could be observed in the transition phase (Kirkham, Nance, et al., 2019; Macdonald and Stuart-Smith, 2024). GAMMs can also characterize the dynamics in time-varying changes in articulator positions in EMA data (Strycharczuk, Derrick, et al., 2020).

Similarly to Smooth-Spline Analysis of Variance (SS-ANOVA), GAMMs afford modelling of non-linear trajectories by combining multiple underlying basis functions, in which a larger number of basis function leads to a smoother GA(M)Ms trajectory (Sonderegger and Sóskuthy, 2025; Davidson, 2006). In a GAMMs model, a dependent variable can be modelled by a parametric term (equivalent to fixed effects in the linear mixed-effect model terminology), and a smooth term, which allow GAMMs to model a non-linear effect of a predictor variable as a function of a continuous scale (e.g., time). GAMMs also offers various ways to incorporate random effects; a common practice is to use factor smooths that account for by-subject and by-item variability in trajectory shape, extending flexibility compared to the random slope and intercept in the linear models (Sóskuthy, 2021).

F2 trajectories predicted by a GAMMs model is visualized in the top right panel in Figure 4, in which L1 English and L1 Japanese speakers exhibit different trajectory shape in the /æ/ and /u/ context. In the /i/ context, despite a broad similarity in shape, L1 Japanese speakers show an earlier onset of the vowel steady-state than L1 English speakers. In the GAMMs model, F2 frequencies are predicted by a parametric and smooth terms using a factor interaction between *language* and *context*, following Coretta and Casillas (2025). Also included in the model are factor smooths to model by-subject and by-item random effects, and an autoregressive (AR1) error model to accounts for the residual autocorrelation (Wieling, 2018; Sóskuthy, 2017). Finally, it is recommended to triangulate multiple checks to carefully assess statistical significance of a given effect (Sóskuthy, 2021).

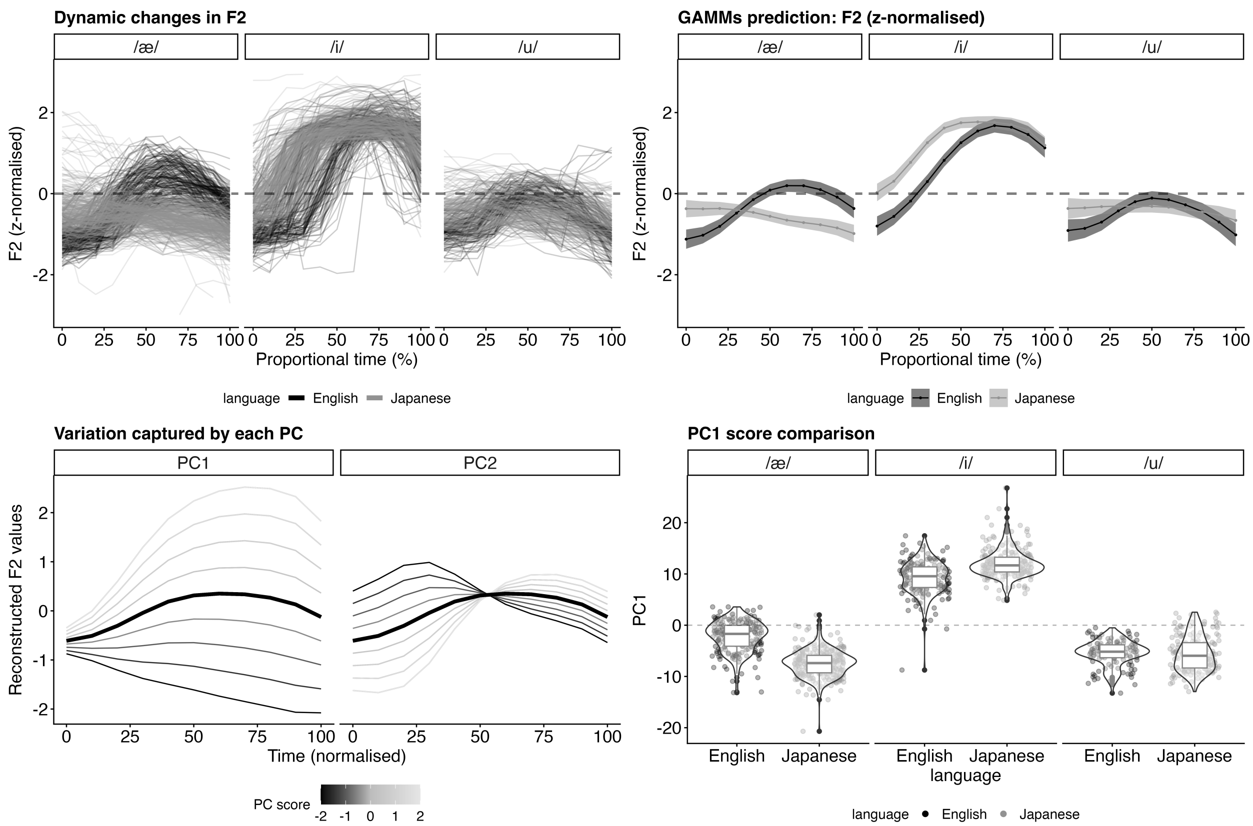


Figure 4: Examples of dynamic analysis of F2 contours. Top left: Raw within-speaker z-normalised F2 contours for word-initial lateral–vowel sequences in three vowel contexts produced by L1 English (dark gray) and L1 Japanese speakers (light gray). Top right: GAMM-predicted F2 trajectories with 95% confidence intervals. Bottom left: Principal components identified by FPCA. Bottom right: Comparisons of PC1 scores.

4.2 Functional Principal Component Analysis: FPCA

Another potentially useful approach to dynamic analysis is Functional Principal Component Analysis (FPCA). FPCA is the functional analogue of ordinary principal component analysis, in which functions, such as trajectories defined over time or space, are taken as input. It extracts dominant patterns of variation from trajectories composed of temporally or spatially dependent observations, and summarises each curve as a weighted sum of functional principal components (Gubian et al., 2015; Coretta and Sakr, 2025). Each individual trajectory is represented by a set of PC scores, which quantify the extent to which it conforms to each mode of variation (Gubian et al., 2015; Ramsay et al., 2009). As a data-driven technique, FPCA makes no *a priori* assumptions about trajectory shape; instead, these patterns are estimated directly from the data (Sonderegger and Sóskuthy, 2025). Although FPCA has not yet been widely applied to the study of laterals, it has proven useful for modelling time-varying changes in acoustic and articulatory signals, including fundamental frequency (*F0*) trajectories (Asano and Gubian, 2018; Cronenberg, Gubian, et al., 2020), formant trajectories (Cronenberg, Chitoran, et al., 2024), and velocity profiles derived from EMA data (Strycharczuk, Kirkham, et al., 2024). Its strongly data-driven nature and flexibility in subsequent statistical modelling makes FPCA particularly well suited for exploratory analyses of dynamic data (Gubian et al., 2015; Nagamine, 2024a).

The FPCA-based dynamic analysis is illustrated in the bottom half of Figure 4. The first principal component (PC1) accounts for 78.70% of the total variance, while PC2 explains a further 14.48%, indicating that PC1 captures the majority of trajectory shape variability. In the bottom left panel, the thick black curve represents the overall mean trajectory, and variation along each PC dimension is visualized using gray-scale gradient curves obtained by adding and subtracting one standard deviation of the PC scores from the mean. PC1 primarily reflects gradient changes in F2 trajectory convexity, such that larger PC1 scores correspond to more convex trajectories, likely driven by differences in F2 values in the following vowel. By contrast, PC2 captures variation in F2 within the lateral itself, with larger PC2 scores corresponding to higher F2 values.

Trajectory shape variability can be further quantified by examining the PC scores within each principal component dimension. The bottom right panel of Figure 4 compares PC1 scores across speaker groups and vowel contexts. In the /æ/ condition, L1 English speakers exhibit higher PC1 scores than L1 Japanese speakers, indicating a more convex overall trajectory shape. Conversely, in the /i/ context, L1 Japanese speakers show higher PC1 scores than L1 English speakers. Although the timing differences discussed earlier are not directly captured by PC1, the PC1 score distributions nonetheless suggest systematic group-level differences in overall trajectory height, with the majority of L1 Japanese speakers' trajectories exceeding those of L1 English speakers in the /i/ context. In this way, FPCA enables complex non-linear trajectory patterns to be decomposed into a small number of interpretable dimensions, within which variability can be modelled statistically.

4.3 Quantifying tongue shape variation

Finally, we turn to a methodological challenge in tongue shape analysis. While tongue shape differences are often relatively easy to visualize and assess qualitatively, their rich dimensionality and inherent non-linearity complicate the task of quantifying variation in a principled and interpretable manner. Dynamic analysis methods offer a way to address this challenge by enabling holistic, quantitative, and objective analyses of tongue shape. Figure 5 illustrates tongue shape visualization using Multivariate GAM (MGAM) and Multivariate Functional PCA (MFPCA), based on the same corpus as Figure 2 (Coretta and Sakr, 2025). MGAM and MFPCA are extensions of conventional GAM(M)s and PCA that have been widely applied in quantitative tongue shape analysis (e.g., Strycharczuk, Derrick, et al., 2020; Turton, 2017; Nance and Kirkham, 2023).

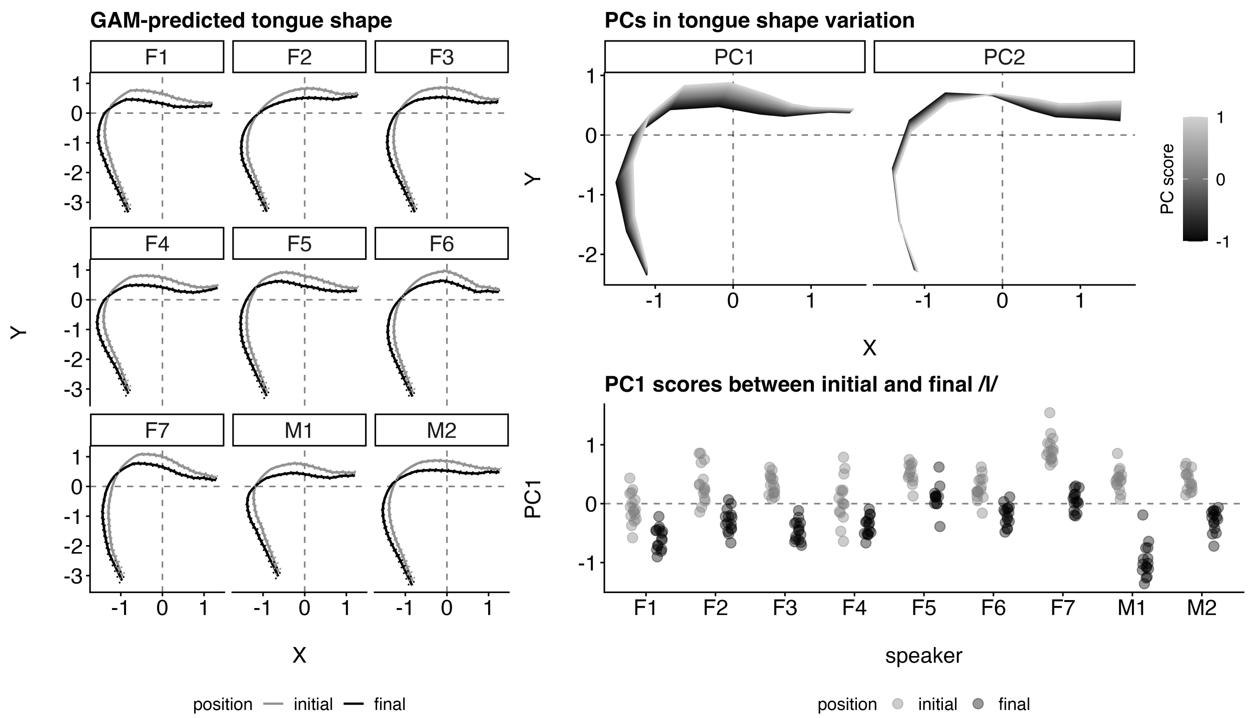


Figure 5: Left: Tongue shape comparison based on a bivariate GAM with 95% confidence intervals. Top right: Principal components from multivariate FPCA. Bottom right: Comparisons of PC1 scores across speakers. Both MGAM and MFPCA analyses are based on Coretta and Sakr (2025).

The left panel of Figure 5 shows MGAM predictions of tongue shape for word-initial and word-final laterals (using the same data set as in Figure 2), plotted as solid curves, with the upper and lower bounds of the 95% confidence interval shown as dotted curves. The GAM predictions broadly mirror the observations shown in Figure 2, revealing a lower and more retracted tongue shape for initial /l/ compared to final /l/. The right panel of Figure 5 presents the results of the MFPCA analysis. The upper subpanel shows the principal modes of variation captured by the first two principal components (PC1 and PC2) in the original two-dimensional tongue coordinate space, while the lower subpanel compares PC scores along the PC1 dimension across speakers. In this analysis, two PCs are extracted from a total of ten PCs identified by MFPCA, accounting for 50.50% and 18.63% of the total variance, respectively. Reconstruction of tongue shapes along PC1 suggests that this component primarily captures a combined front-back and high–low movement, with lower

PC1 scores corresponding to a lower and more retracted tongue configuration, consistent with a darker lateral. This clear-dark distinction is reflected in the PC1 score distributions, with word-final /l/ consistently exhibiting lower PC1 scores across speakers.

While GAM(M)s allow for direct multidimensional statistical modelling of both within- and between-speaker variation, they are often computationally demanding and can require substantial processing time (Al-Tamimi and Palo, 2024). PCA-based approaches, by contrast, are computationally efficient, but typically yield multiple dimensions that must be analyzed and interpreted when more than one principal component is retained (Coretta and Sakr, 2025; Al-Tamimi and Palo, 2024; Sonderegger and Sóskuthy, 2025). Despite these trade-offs, recent analytic practices in phonetics have moved beyond conventional single-point measurements and purely qualitative visual inspections of tongue shape differences, with dynamic analysis tools playing an increasingly important role. Please see existing tutorials and empirical studies employing these approaches for further methodological details (for GAMMs: e.g., Wieling 2018; Sóskuthy 2017; Sóskuthy 2021; Wood 2017, for FPCA: Gubian et al. 2015; Ramsay et al. 2009; Strycharczuk, Kirkham, et al. 2024; Cronenberg, Gubian, et al. 2020; Cronenberg, Chitoran, et al. 2024, and for quantitative tongue shape analysis more broadly: Johnson 2008; Turton 2017; Nagamine 2025; Al-Tamimi and Palo 2024). See also Sonderegger and Sóskuthy (2025) for a comprehensive review of quantitative data analysis methods in phonetic research.

5 Conclusion

This chapter has reviewed recent trends in data collection and analysis for investigating the acoustics and articulation of laterals, with a particular focus on English /l/. A central consideration in lateral analysis is how to account for the inherently dynamic nature of laterals, which arises from complex articulatory coordination and strong coarticulatory interactions with adjacent vowels. While dynamic approaches provide a more complete representation of lateral production than single-point measurements, they also introduce challenges for interpretation due to the richness and complexity of time-varying data. In particular, treating the lateral–vowel rime as a single analytical unit can make it difficult to disentangle whether observed non-linear patterns are driven primarily by the lateral, the vowel, or their interaction.

However, this analytical challenge reflects the fundamental nature of lateral production itself. Given the strong lateral–vowel coarticulation, attempts to isolate the lateral from its vocalic context may obscure rather than clarify the mechanisms underlying lateral quality. Analyzing the time-varying properties of lateral acoustics and articulation therefore offers a more principled and holistic approach than conventional single-point, parametric methods. Although dynamic data introduce additional layers of analytical and interpretive complexity, when used appropriately, modern data collection techniques and analytical tools can support transparent and theoretically informed analyses of laterals. Ultimately, embracing the dynamic nature of lateral production will facilitate a deeper understanding of the phonetic factors shaping both synchronic and diachronic variation in laterals.

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