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Gestural reduction, lexical frequency, and sound change: A study of post-vocalic /l/

Abstract: The magnitude of anterior and dorsal constrictions for laterals in /(C)(C)VlC/ words produced by eight American English speakers was measured using ultrasound imaging. The results replicate previous findings that laterals have weaker anterior constrictions when followed by labial or velar consonants than when followed by alveolar consonants. The main novel finding is that, in words with /VlC_{labial}/ or /VlC_{velar}/ sequences, this anterior constriction was weaker in high-frequency words (*help*, *milk*) than in low-frequency words (*whelp*, *ilk*). Although high-frequency words also showed slight reduction of the dorsal constriction, dorsal reduction was stable, small in magnitude, and not correlated with anterior reduction, consistent with alveolar reduction not being simply a consequence of overall weaker lingual constrictions in more frequent words. Acoustic measures for laterals showed that the degree of anterior constriction correlated with the frequency separation between F1 and F2: more reduced alveolar constrictions – especially likely in high-frequency words – were linked with greater formant proximity. These articulatory and acoustic patterns are interpreted as potentially contributing to the initiation and lexical diffusion of historical /l/ lenition. It is proposed that gestural reduction in high-frequency words in which the anterior gesture for laterals must be coordinated with another supralaryngeal constriction serves as a precipitating factor in /l/ vocalization and possibly (although to a lesser extent) /l/ loss.

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1 Introduction

This study investigates the effects of lexical frequency on the magnitude of the anterior and dorsal gestures for laterals produced by speakers of American English.

Previous research has shown that speakers often produce a reduced anterior constriction for /l/ in certain post-vocalic, pre-consonantal contexts. We test the hypothesis that the anterior gesture, but not the dorsal gesture, is especially likely to be reduced in high-frequency words in which /l/ occurs in those critical contexts. The broader aim of the investigation is to relate the articulatory patterns of reduction to the initiation and lexical diffusion of sound changes involving vocalization or loss of coda laterals.

In many languages, alveolar laterals, especially those in post-vocalic position, are produced with two lingual constrictions, one anterior and one dorsal (e.g., Gick et al. 2006). Articulatory data for some of these languages indicate that the anterior constriction is less extreme – achieving little or no apical contact, or being entirely absent – under conditions that depend on individual speakers, speaking rate, speech style, syllable structure, as well as on the phonetic characteristics of flanking vowels and consonants. The last of these – the influence of a following consonant on post-vocalic laterals – is of particular relevance to the current study, which investigates gestural reduction in high- and low-frequency English words containing /VlC/ sequences.

A clear pattern that emerges in the literature on production of English /l/ is that the anterior, alveolar gesture is especially likely to be reduced in /VlC/ sequences when C involves a non-alveolar constriction. Cinefluorographic images of lateral articulations in words with /VlC/ produced by American English speakers show that tongue tip contact in the alveolar region is less likely to occur for laterals in labial (e.g., *help*) and velar (*elk*) than in alveolar (*melt*) contexts (Giles and Moll 1975). Electropalatographic data from speakers of several English varieties indicate the same general pattern (Hardcastle and Barry 1989; Scobbie and Wrench 2003; Wrench and Scobbie 2003). (Similarly, for speakers of Majorcan Catalan, Recasens [2009] reported less frequent apical contact for /l/ before consonants that do not require tongue tip raising than before those that do.) One factor underlying these context effects may be homorganicity: the alveolar gesture for the lateral is either not reduced, or is less reduced, when the following consonant also requires an alveolar constriction gesture. However, other factors appear to be operable as well. For example, Scobbie and Pouplier's (2010) EPG measures of /Vl#C/ productions by speakers of two English varieties showed that some Southern British English speakers consistently produced alveolar contact for /l/ when C was /h/ but not when C was /b/. Moreover, Giles and Moll (1975) observed for American English speakers' /VlC/ productions that the greater the coarticulatory overlap between the alveolar constriction for /l/ and the constriction for a following labial or velar consonant, the greater the likelihood of reduced alveolar contact for /l/. These findings are consistent with articulatory coordination of the anterior gesture for the lateral with a distinct supralaryngeal gesture contributing to reduction of the anterior lateral gesture. An additional contributing factor may be that there is robust acoustic information for an alveolar gesture in /Vl$C_{alveolar}$/ sequences, whereas that information may be (partially) masked in certain non-alveolar contexts, especially in American English, whose speakers often do not achieve the alveolar constriction until after onset of the following consonant in /l$C_{non\text{-}alveolar}$/ sequences (see Section 2.4). Under that circumstance, context-specific reduction may be, at least in part, perceptually motivated. (See Jun [2004] for discussion of why, in CC clusters, non-coronal consonants are especially likely to obscure place information for a preceding consonant. See also Recasens [2012] for detailed discussion of positional effects on loss of alveolar contact for laterals.)

It is quite possible that multiple factors underlie findings that the anterior lateral gesture tends to be more reduced in English words with /VlC_{labial}/ and /VlC_{velar}/ sequences than in those with /Vl$C_{alveolar}$/ sequences. The focus of this study, however, is not these factors. Rather, this study takes that place-dependent tendency as its starting point and asks whether reduction is especially likely to occur in high-frequency words. High-frequency words have been shown to exhibit certain variable phenomena, especially reduction phenomena, to a greater extent than do low-frequency words (Phillips 1984; Pierrehumbert 2001; Bybee 2002). A particularly well-studied example is deletion of English /t/ and /d/, especially in word-final clusters (e.g., *just, told*). Bybee's (2000) analysis of phonetically transcribed words ending in phonological /Ct/ or /Cd/ from Santa Ana's (1991) corpus of Chicano English showed more coronal stop deletion in high-frequency than low-frequency words. Subsequent studies of two other transcribed corpora, Switchboard telephone conversations (Jurafsky et al. 2001) and the Buckeye Corpus (Coetzee and Kawahara 2013), have demonstrated similar effects of word frequency on final /t/ and /d/ deletion rates. Reduction in more frequent words also emerges in acoustic measures for high- and low-frequency words. This reduction may occur in the temporal dimension, as in the finding that high-frequency words in English are shorter than their low-frequency homophones (Gahl 2008). Reduction linked to lexical frequency also occurs in the spectral dimension; for example, the acoustic vowel space of American English is less expanded in high- than in low-frequency words (Munson and Solomon 2004). Although these reduction processes are variable phonetic phenomena, they have the potential to spread to low-frequency words and, over time, to become systematic phonological processes (e.g., Phillips 1984, 2006).

Like the influences of phonetic context on reduction processes, the link between more frequent words and reduction processes may be rooted in multiple factors. One possibility is that speech intelligibility might be less in jeopardy for more frequent, more predictable words, and speakers might therefore be less prone to produce clear or more 'canonical' forms of these words (Lindblom 1990; Greenberg 1999; Wright 2004). However, we focus here on speaker rather than listener contributions to gestural reduction, including the very likely role of practiced, efficient articulatory routines for high-frequency words (Bybee 2002). These routines for frequent words might be expected to give rise to reduced gestural magnitude similar to articulatory findings for casual and fast speech (e.g., Giles and Moll 1975; Browman and Goldstein 1990). Moreover, lexical frequency may contribute to articulatory reduction by facilitating lexical retrieval. Under this view, high-frequency words are accessed in the lexicon more quickly than low-frequency words and – assuming a temporal link between planning and articulation – are consequently produced more quickly (Bell et al. 2009; Ernestus 2013).

This study investigates whether lexical frequency effects emerge in articulatory measures of the magnitude of the alveolar gesture in pre-consonantal lateral productions. We address this question for speakers of American English, who are expected to show non-categorical, gradient effects of the following consonant on tongue tip raising for laterals. Our primary hypothesis is that ultrasound images of the tongue tip and blade region will show weaker alveolar constrictions (i.e., greater apertures) in labial (*help*) and velar (*milk*) contexts than in alveolar (*built*) contexts, and that reduction will be greater in high-frequency (*help*, *milk*) than in low-frequency (*whelp, ilk*) words. We investigate as well two secondary hypotheses. First, if reduction of the alveolar gesture in high-frequency words is a possible precursor of sound changes involving vocalization to a /u/- or /w/-like articulation, the posterior constriction for these velarized laterals should not be substantially reduced. That is, anterior reduction in high-frequency words should not be accompanied by comparable reduction of the dorsal gesture. Second, especially weakened alveolar gestures should have systematic acoustic consequences. Specifically, loss of tongue tip contact would mean that the dorsal constriction – which in American English overlaps with the vowel and precedes onset of apical movement (Sproat and Fujimura 1993; Gick et al. 2006; Lin 2011: 31–32) – should dominate the resulting acoustic signal. Moreover, given that tongue tip and tongue dorsum positions are not independent, with tongue tip closure requiring a somewhat forward tongue body position (Stevens 1998: 355), a weakened alveolar gesture could be expected to exert less of a fronting influence on the tongue dorsum position, at least in certain vowel contexts. Both of these factors could be expected to give rise to greater proximity of the first two formants (i.e., smaller F2-F1 distance) for laterals with more reduced anterior gestures – by hypothesis, laterals in high-frequency words – relative to those with less reduced gestures.

Our interest in determining not only whether lexical frequency influences reduction of the anterior lateral gesture, but also whether loss of alveolar contact creates phonetic variants that may be detectable to listeners as being reduced, is motivated by our goal to relate the articulatory and acoustic patterns to the initiation and lexical diffusion of sound changes involving loss of the anterior constriction. As we have seen, the overall pattern in the speech production literature is that reduction of the alveolar gesture for post-vocalic laterals is especially likely in laterals followed by labial or velar consonants. In the context of an investigation of the phonetic bases for historical lateral weakening, the articulatory data naturally lead to the question of whether labial and velar contexts are strongly implicated in changes involving either lateral loss or vocalization of laterals into back (rounded) vowels or vowel-like approximants (usually /w/). Although vocalization and loss are distinct historical processes, both involve loss of alveolar contact at some stage of the change. In the case of vocalization, the change is consistent with the dorsal constriction being the primary lingual gesture.

Studies of varieties of English that have undergone or are undergoing loss or vocalization of post-vocalic /l/ generally show that these phenomena are more advanced in pre-labial and pre-velar than in pre-coronal contexts, as might be expected from the production data. For example, Horvath and Horvath (2002) surveyed ongoing vocalization in nine Australian and New Zealand localities and found (based on auditory coding) that nearly one-third of laterals in preconsonantal contexts were realized as /u/-like vowels, with vocalization rates decreasing from velar (59%) to labial (32%) to coronal (24%) contexts. Dodsworth's (2005) much more localized study of the variety of American English spoken near Columbus, Ohio, identified a strikingly similar pattern, with vocalization again decreasing from velar (31%) to labial (24%) to coronal (12%) contexts. Descriptive studies show similar influences of velars and labials on vocalization in Southern American English (Caffee 1940; Allen 1976: 315) and of labials on /l/ loss in Appalachian English (Wolfram and Christian 1976: 48). Additionally, Johnson and Britain (2007) investigated, for the Fenland dialect in southeastern England, the influence of the place of articulation of *preceding* consonants on syllabic /l/ (e.g., *apple, tickle, little*) and found that vocalization was most likely in labial and glottal contexts and least likely in coronal. These relatively recent developments mirror patterns of vocalization and loss in the much earlier history of English (see Caffee [1940] and Johnson and Britain [2007] for Middle English and Stuart-Smith et al. [2006] for Older Scots). (That the same consonantal influences on /l/ weakening do not emerge in the history of the Romance languages, as documented in detail by Recasens [1996, 2009, 2012] and Müller [2011], is also of interest, and is considered in Section 4.)

Thus, although not all English varieties with variable /l/ realization show strong effects of the place of the post-lateral consonant (cf. Ash [1982] for Philadelphian English), in the varieties that do exhibit such effects, /l/ loss or vocalization tends to be promoted before labials or velars and suppressed before coronals. We take these parallel contexts for articulatory reduction of the alveolar gesture for /l/ and variable lateral weakening in English dialects to be strongly suggestive that the former may be implicated in the latter. Building on this parallel, this study asks whether the frequency of words with laterals in non-coronal contexts further contributes to reduction phenomena that may give rise to sound change.

2 Methodology

We used ultrasound imaging and acoustic analysis to test the three hypotheses stated in the Introduction: (i) the anterior constriction for American English /l/ should be especially reduced in high-frequency words with /VlC_{labial}/ and /VlC_{velar}/ sequences, (ii) the posterior constriction for laterals in these words will not be substantially reduced, and (iii) F2-F1 proximity should be greater for laterals with reduced anterior gestures (and consequently, we claim, for laterals in high-frequency /VlC_{labial}/ and /VlC_{velar}/ words).

2.1 Stimuli

In constructing the list of high- and low-frequency words for this study, CELEX (Baayen et al. 1995) was used to determine lemma frequencies for all English words of the form /(C)(C)VlC_{labial}/ or /(C)(C)VlC_{velar}/. From each of the labial- and velar-final subsets, near-minimal word pairs or triplets were constructed with at least one high-frequency item from the most frequent third of the /(C)(C)VlC/ word list and at least one low-frequency item from the least frequent third. In each high-low frequency group, all words ended with the same consonant. Ideally, members of a given high-low frequency group also had the same vowel, but this was not always possible, as in the pair *film*/*helm*, for example. Although the onsets of the words in each high-low frequency group differed by necessity, onsets in a group were either all apical or not, in order to reduce potential coarticulatory effects of the onset on the anterior constriction for the lateral.

Anterior constrictions for laterals followed by labial or velar consonants are expected to be weaker compared with those for laterals followed by an alveolar consonant. In testing this expectation, each high-low frequency word group was

Table 1: Target (high- and low-frequency) and reference (alveolar) stimuli.

C2 place	Frequency group		Alveolar reference
	High	Low	
Labial	help	whelp	pelt
	film	helm	filled, held
	self, shelf	sylph	stealth, silt
	twelve	delve	weld
Velar	milk	ilk	built
	bulk	hulk	mulled

paired with one or two alveolar reference words having similar phonetic structure as the high-low frequency word group but ending in an alveolar consonant. Frequency pairings that included two different vowels (*film/helm* and *self/shelf/sylph*) were grouped with one alveolar reference item for each vowel. Under the above criteria, six word groups were constructed and are listed in Table 1, one group per row. Additional filler CVC and CVCC words were included to make up a total of 40 unique items.

2.2 Participants

Thirteen undergraduate and graduate students were recruited to participate in this study. All participants were native speakers of American English and reported no known hearing or speaking difficulties. Participants received $20 for their participation. Of the 13 participants, data from 4 were excluded due to poor ultrasound image quality, and data from 1 were excluded due to an upper respiratory infection on the day of recording. Data from the remaining 8 speakers (ages 18–23 years) were analyzed.

2.3 Apparatus and experimental methodology

Midsagittal images of participants' tongues were recorded using a Zonare z.one mini system with a P4-1c transducer operating at a scan rate of 70 Hz, and set to a depth of 8 cm in b-mode operation. The transducer was stabilized in relation to the head using an ultrasound stabilization helmet from Articulate Instruments Ltd. Participants were seated inside a sound-attenuated recording booth in the

Phonetics Lab at the University of Michigan. To capture the clearest audio recordings possible, the ultrasound engine and recording devices were located outside the booth; the transducer cable was passed through an insulated portal in the booth's wall. Participants' speech was recorded using an AKG microphone connected to a MacBook laptop via an Edirol USB sound mixer. The video feed from the ultrasound engine was recorded digitally at 60 fps on an NAI Medical Recording Device.

At the start of each session, participants were given a bottle of water and shown how to produce a water bolus. Before the sentence-reading task began, a bolus swallowing video was taken, in order to create a palate trace for analysis. Participants were then seated in front of a monitor displaying the text prompts. Each screen displayed a set of five stimulus items in the carrier phrase "Say ____ for me." Stimuli were blocked by repetition and randomized within the block, except that each set was structured such that no two target /(C)(C)VlC/ stimuli were adjacent to one another. Following each set of five utterances, participants were given a short 3–5 second pause, after which a new set of five utterances appeared on the monitor. Participants were also allowed a short 2–3 minute break after every 28 sets, approximately every 7 minutes. Each participant produced 14 repetitions of each stimulus utterance, for a total of 560 utterances per participant. Each session lasted approximately 45 minutes: 5 minutes for stabilization helmet fitting, 10 minutes for bolus production instruction and imaging, and 30 minutes for utterance production.

2.4 Analysis

For each target word, waveform and spectrographic representations in Praat (Boersma and Weenink 2008) were used to mark the acoustic onset of the vowel, and the acoustic offset of both the /l/ and following consonant. The corresponding frames from the ultrasound videos were extracted, and EdgeTrak (Li et al. 2005) was used to trace the tongue contour in each frame. Figure 1 shows an example frame from the word *mulled* as produced by speaker S009, with the tongue trace superimposed. Altogether, six members of the Phonetics Lab performed edge detection, including the three authors. The first author trained each of the remaining five analysts. A single person handled all utterances from a given participant. Reliability and consistency of the measures taken by different analysts were checked in two ways. First, 25 utterances randomly sampled from each speaker were checked by the first author for consistency across analysts. Second, one additional analyst was trained and performed edge-detection on contours from three speakers (S003, S004, and S006) whose contours had previously been

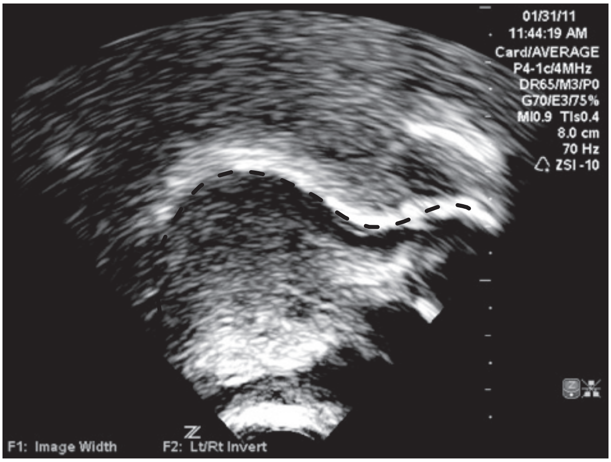

Fig. 1: Example ultrasound still image, during /l/ production from speaker S009, showing tongue tip raising (right) and tongue dorsum retraction (left), with superimposed EdgeTrak tongue trace (dashed line).

traced by other analysts. Over 90% of the derived aperture values (described below) from the contours from the additional analyst were within 0.5 mm of those from contours provided by the original analysts. Furthermore, linear regression comparing derived aperture values from the additional analyst against those from the original analysts demonstrated high r^2 values (0.88, 0.99, and 0.89 for speakers S003, S004, and S006, respectively), indicating that the values derived from contours defined for these participants were robust.

Similarly, edge detection was also used to trace the tongue during swallowing of the water bolus. Traces from ultrasound images towards the end of water bolus swallowing from a given speaker were averaged together to form a palate trace for that speaker. Contours from the end of swallowing were used because the malleability of the soft palate is such that, if the palate trace were created from contours where the water bolus was not deforming the soft palate, maximal excursion of the tongue dorsum could result in a contour that crossed the palate trace. Contours from the end of swallowing were also sufficient for tracing the hard palate: towards the end of swallowing, participants' tongue blades and tips were raised, with minimal air between the tongue and the hard palate, allowing for clear imaging of the hard palate.

Each speaker's first 10 repetitions of each of the 21 target stimuli were analyzed. Stimuli from later repetitions were analyzed when speakers made mistakes during production, or when ultrasound images from earlier productions were not clear enough for analysis. For each stimulus, three values were determined: minimum tongue tip aperture (mm), minimum tongue dorsum aperture (mm), and the acoustic difference between F2 and F1 (Hz).

Tongue tip and dorsum apertures were calculated relative to two regions of interest along a speaker's palate trace. To determine these regions, each speaker's palate trace was plotted against tongue traces taken at the end of acoustic /l/ from 10 utterances from that speaker. One repetition was randomly selected from each of the following 10 words: *pelt, filled, silt, weld, built, mulled, milk, hulk, ilk,* and *bulk*. (The bias towards words with a final alveolar consonant ensured adequate coverage of the anterior constriction region, while inclusion of all four velar-final words gave coverage of the dorsal constriction region.) The two regions of interest represented areas of maximum constriction of the tongue tip and tongue dorsum, or minimum distance between the palate trace and the tongue tip and dorsum. Regions of interest defined for the tongue dorsum were consistently larger than those for the tongue tip, due to greater variability in tongue dorsum constriction locations. An example of a palate trace and tongue contour plot is shown in Figure 2. In each utterance, minimum tongue tip and tongue dorsum aperture values were determined by finding the minimum distance between the tongue trace and the palate trace within the region of interest across all frames after vowel onset for a given stimulus. Because in most cases the actual tongue tip is obscured in ultrasound images by the shadow of the jaw, 'tongue tip aperture' values more accurately represent the distance from the most anterior portion of the tongue blade visible in the ultrasound images.

The acoustic measures, F1 and F2 frequencies, were generated using Praat's (Boersma and Weenink 2008) automatic formant tracker. The automatic formant tracker utilizes LPC analysis and was set to a window length of 25 ms. In 86% of the productions collected, peak anterior constriction followed acoustic onset of

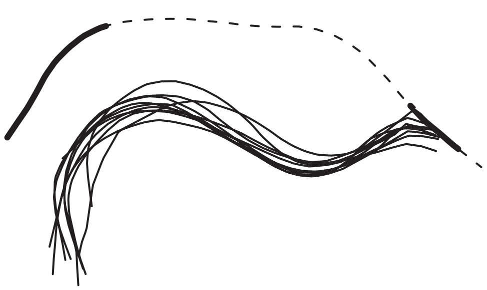

Fig. 2: Example of a palate trace (dashed line) and tongue contours for 10 /l/ productions (thin solid lines) from different words produced by speaker S009, demonstrating anterior and posterior regions of interest (thick solid lines).

the following consonant. In these cases, F1 and F2 frequencies were measured with the right boundary of the 25 ms window set at the acoustic offset of the lateral. In the remaining 14% of items where peak anterior constriction preceded the acoustic onset of the following consonant by more than 12.5 ms, F1 and F2 frequencies were measured with the center of the 25 ms window at the timestamp of the peak anterior constriction. F1 and F2 frequencies were recorded in Hz and converted to Bark using the conversion $B = (26.81/(1 + (1960/f)) - 0.53$, where f is frequency in Hz (Traunmüller 1990).

3 Results

The statistical results discussed in this section resulted from linear mixed effects models, computed using the lmer() function from the lme4 package in R (Bates et al. 2012). In all models computed, random factors included were Subject, Repetition, and Word Group. Word Group – where each group has both high- and low-frequency words (e.g., *help/whelp/pelt*; *milk/ilk/built*; see Table 1) – was included as a random factor rather than individual words because each word has a unique frequency. Whereas factoring out the contribution of Word would obscure potential frequency effects, including Word Group should not. (Frequency is a fixed factor in the majority of the analyses in this study.) Also, because Vowel Quality and Word Group are nearly perfectly correlated, Vowel Quality was not included as a factor, fixed or random, in any model except those investigating the spectral properties of the laterals (see Section 3.3). Because we expect that individuals differ with respect to the extent that frequency affects articulation, wherever Frequency was included as a fixed factor and Speaker as a random factor, both random intercept and random slopes for the relationship between Frequency and Speaker were included. As inclusion of random slopes in addition to random intercepts prevents use of Markov Chain Monte Carlo simulations for estimating p-values, we consider $|t| > 2$ to approximate $p < 0.05$ (Baayen 2008: 248).

3.1 Place of articulation of the post-lateral consonant

The first analysis seeks to corroborate previous findings for English laterals, and addresses the hypothesis that laterals in a /VlC/ context should show weaker alveolar constrictions in labial and velar contexts than in alveolar contexts. A linear mixed-effect comparison was performed on minimum tongue tip aperture, with Place of Articulation of the following consonant as the fixed factor. Frequency is not investigated in this initial model testing for an effect of Place because the

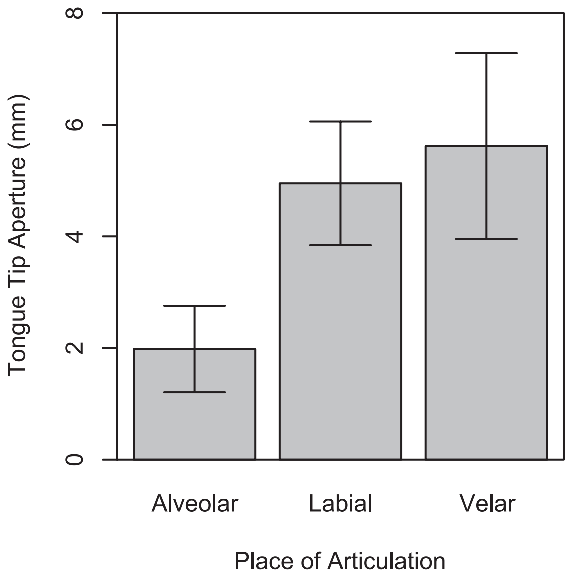

Fig. 3: Lateral tongue tip aperture (mm) by place of articulation of the following consonant. Larger tongue tip aperture in labial and velar contexts indicates weaker tongue tip constriction, and thus more anterior reduction.

stimuli were designed to manipulate frequency in the labial and velar, but not the alveolar, contexts.

Figure 3 illustrates the relation between the degree of alveolar constriction, represented by tongue tip aperture, and the place of articulation of the following consonant, averaged across all speakers. (Here and throughout the paper error bars represent one standard error above and below the estimated group mean.)

The analyses indicate that tongue tip aperture in laterals was significantly smaller (i.e., laterals had tighter anterior constrictions) in an alveolar context than in either a labial ($\beta = -2.97$, $t = -4.68$) or velar ($\beta = -3.64$, $t = -2.84$) context. The alveolar context aperture values indicate that tongue tip constriction is complete or nearly complete for post-vocalic laterals in this context, which is consistent with previous studies of American English (e.g., Giles and Moll 1975). (These tongue tip aperture values are not zero, which might seem to suggest incomplete closure. However, because tongue 'tip' aperture values often more accurately represent tongue blade apertures, it is not surprising that aperture is low but not zero even in the alveolar context.) The fixed factor Place was re-leveled to test the difference in tongue tip aperture values between labial and velar contexts, which was not found to be significant ($\beta = 0.69$, $t = 0.81$).

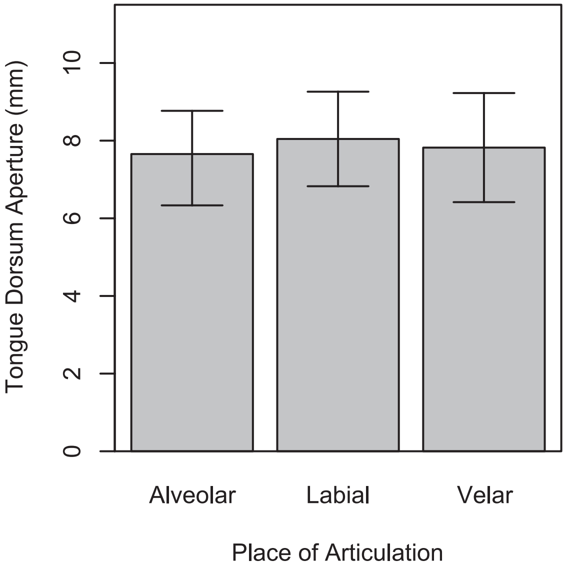

Fig. 4: Lateral tongue dorsum aperture (mm) by place of articulation of the following consonant.

By way of comparison, Figure 4 illustrates the relation between tongue dorsum aperture and place of the following consonant. A linear mixed model, identical to the previous one except that it was performed on minimum tongue dorsum aperture, indicated that tongue dorsum aperture was significantly smaller in laterals in an alveolar context compared to a labial context ($\beta = -2.09$, $t = -3.42$), but not compared to a velar context ($\beta = -0.72$, $t = -0.74$). Again, Place was re-leveled, and the model rerun, showing no significant difference between tongue dorsum aperture in labial compared to velar contexts ($\beta = 1.37$, $t = 1.20$). The relationship between alveolar and labial contexts is the same as that found for tongue tip aperture, although the size of the effect is markedly smaller for tongue dorsum aperture. This outcome generally conforms to the finding of Giles and Moll (1975) that, across /VlC/ sequence types, tongue tip contact differed considerably but tongue dorsum position did not.

3.2 Word frequency

In the remaining analyses, all of which examine the effect of word frequency, the data were restricted to laterals preceding velar and labial consonants. Figure 5

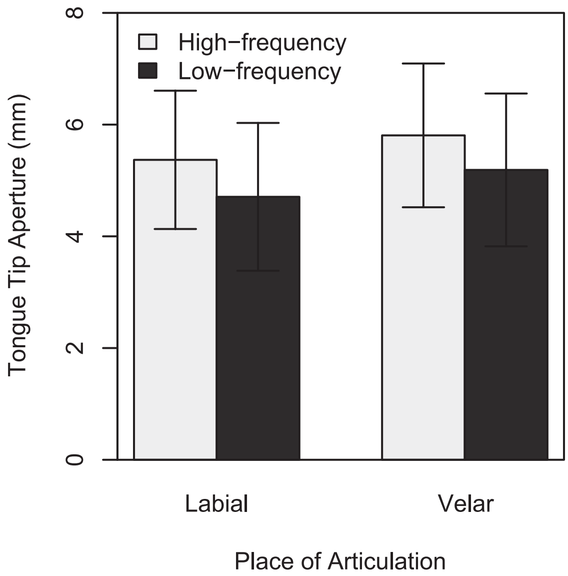

Fig. 5: Lateral tongue tip aperture according to word frequency and place of the following consonant.

gives the averaged tongue tip aperture values for laterals in pre-velar and pre-labial contexts in high- and low-frequency words. To test the hypothesis that reduction of the anterior gesture should be greater in high-frequency than in low-frequency words, a linear mixed model was computed on tongue tip aperture measures, with both Place and Frequency as fixed factors, including their interaction. Overall, Frequency had a small but significant effect, such that tongue tip aperture was greater in high-frequency compared to low-frequency words ($\beta = 0.66$, $t = 2.11$). Tongue tip aperture differences for laterals in labial compared to velar contexts were not significant ($\beta = 0.44$, $t = 0.74$), nor was the interaction between Frequency and Place ($\beta = 0.04$, $t = 0.12$).

The random coefficients for the relationship between tongue tip aperture and frequency are listed in Table 2 and show that an effect of frequency on aperture size was found in the predicted direction for all speakers, although the strength of the effect varied considerably across speakers. For instance, tongue tip aperture was on average 1.73 mm smaller in low-frequency words than in high-frequency words for speaker S006, but only 0.17 mm smaller for speaker S013.

Having established a link between word frequency and reduction of the tongue tip constriction in laterals, we turn to whether word frequency also affects

Table 2: Random coefficients for the relationship between Speaker and Frequency on tongue tip aperture (mm) for each speaker.

Speaker	Coefficient
S003	−1.05
S004	−0.52
S005	−0.20
S006	−1.73
S007	−0.21
S009	−0.75
S012	−0.66
S013	−0.17

the tongue dorsum constriction. The hypothesis offered in the Introduction was that this might not be the case. That is, if the reduced alveolar gesture were a possible precursor of vocalization involving a dorsal constriction, such as /u/ or /w/, then tongue tip and tongue dorsum reduction should not be tightly yoked, and the dorsum constriction should not be substantially reduced in high-frequency words. Alternatively, if increased tongue tip aperture in high-frequency words is more generally a manifestation of failure to reach the articulatory 'target', then perhaps both lingual gestures for the lateral will be reduced in high-frequency words.

The tongue dorsum aperture measures in Figure 6 show that, like tongue tip aperture, tongue dorsum aperture was affected by word frequency, with laterals in high-frequency words (in pre-velar and pre-labial contexts) being produced with slightly greater dorsum apertures, and thus weaker constrictions, than those in low-frequency words. A linear mixed model was computed on dorsum aperture measures, with Place and Frequency as fixed effects, including their interaction. The model results showed a small but significant effect of Frequency, such that tongue dorsum aperture was greater in high-frequency than in low-frequency words ($\beta = -0.32$, $t = -2.27$). As stated in Section 3.1, there was no significant difference in tongue dorsum aperture between laterals followed by labial compared to velar consonants, and the interaction between Frequency and Place was likewise not significant ($\beta = -0.34$, $t = -1.39$).

Table 3 gives the random coefficient for the relationship between tongue dorsum aperture and word frequency for each speaker. These coefficients are nearly uniform: for all of the speakers participating in this study, tongue dorsum constriction was approximately 0.4 mm tighter in low-frequency words compared to high-frequency words. This lack of inter-speaker variability with respect to the

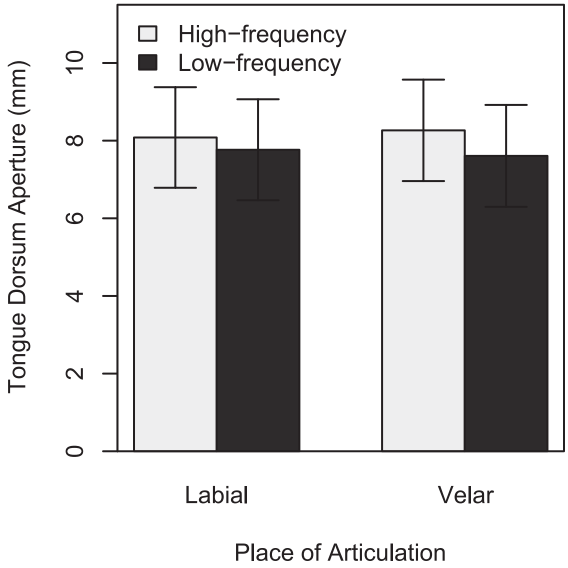

Fig. 6: Lateral tongue dorsum aperture according to word frequency and place of following consonant.

Table 3: Random coefficients for the relationship between Speaker and Frequency on tongue dorsum aperture (mm) for each speaker.

Speaker	Coefficient
S003	−0.41
S004	−0.43
S005	−0.41
S006	−0.47
S007	−0.43
S009	−0.41
S012	−0.41
S013	−0.42

effect of frequency on tongue dorsum aperture contrasts with the highly variable effect of frequency on tongue tip aperture and, in combination with the very small effect of place of the following consonant on tongue dorsum aperture, is suggestive of a relatively stable posterior – but not anterior – constriction in post-vocalic laterals.

3.3 Relation between anterior and posterior constrictions

Inasmuch as both tongue tip and tongue dorsum constrictions were reduced in high-frequency relative to low-frequency words, there is a possibility that the relationship between word frequency and tip and dorsum aperture size is the consequence of overall reduction of lingual gestures. That is, it may be the case that, in a given high-frequency word, both tongue tip and tongue dorsum gestures were reduced compared to their low-frequency counterparts. To test this possibility, Tongue Tip Aperture was added to the previous model as a continuous fixed factor, to determine whether there was a significant correlation between Tongue Tip and Tongue Dorsum Apertures. A log-likelihood ratio test performed on a version of this model with full interactions against one with no interactions demonstrated that the interactions were not significant ($\chi^2[2, 13] = 3.60$, $p = 0.1655$). We therefore report the results of the simpler model with no interactions. The main effect of Frequency from the previous model held constant, but the additional correlation between tongue tip and tongue dorsum apertures was not found to be significant ($\beta = -0.01$, $t = -0.28$). These results suggest that, even though tongue tip and tongue dorsum reduction both occur in high-frequency words, they do not necessarily always occur together.

Finally, not only is the extent of the effect of frequency on tongue dorsum apertures substantially less variable across speakers than that on tongue tip apertures (as shown in Tables 3 and 2, respectively), it is on the whole smaller in magnitude (compare Figures 6 and 5). To determine whether this difference in magnitude of reduction is significant across speakers and contexts, a linear mixed model was run on tongue tip and dorsum aperture values combined, with fixed factors aperture Type (tongue tip vs. tongue dorsum) and Frequency and their interaction, and random factors Speaker, Repetition, Vowel, and Word Group. There was a significant interaction between Frequency and aperture Type ($\beta = -0.50$, $t = -2.21$), such that the magnitude of gestural reduction found in high-frequency words is greater for tongue tip than for tongue dorsum gestures. (Of course, differences in anterior and posterior aperture values must be interpreted with caution, in part because dorsum apertures for /l/ for these speakers are substantially larger than tip apertures, irrespective of word frequency.)

3.4 Acoustic consequences of reduction of the anterior constriction

The final analysis addresses the hypothesis that reduction of the alveolar constriction of laterals might have systematic effects on the resulting acoustic signal.

Specifically, all else being equal, alveolar reduction might be expected to result in a less forward tongue body position and/or greater influence of the dorsal constriction on the acoustic spectrum, either of which could contribute to a lower F2 frequency and increased proximity between F2 and F1. Thus, regardless of word frequency or place of the following consonant (alveolar, labial, or velar), postvocalic /l/ productions in which the lateral has a weaker tongue tip constriction should have a smaller F2-F1 difference than do productions with a stronger tongue tip constriction. Moreover, because tongue tip constrictions are especially reduced in high-frequency words, laterals should have a smaller F2-F1 difference in high- than in low-frequency words.

To test this hypothesis, a linear mixed model on F2-F1 frequencies was performed, with Frequency, Tongue Tip Aperture, and Tongue Dorsum Aperture as fixed effects. Because formant frequencies are also expected to be influenced by the quality of the preceding vowel ([ɪ], [ɛ], or [ʌ]), and predictably so – that is, we expect that F2-F1 differences in laterals following [ɪ] to be significantly greater than those from laterals following [ɛ] or [ʌ] – the model also includes Vowel as a fixed rather than a random factor. The model did not include Word Group as a random factor, as Vowel quality and Word Group are nearly entirely confounded.

The minimal converging model that is not significantly different from the full model included a three-way interaction between Tongue Tip and Tongue Dorsum Apertures and Vowel quality. That Frequency did not interact with any of the other three factors indicates that any effects of Aperture values or Vowel quality on F2-F1 are consistent regardless of frequency category. This model demonstrated a significant effect of Tongue Tip Aperture on F2-F1 ($\beta = -6.24$, $t = -2.44$), such that larger tongue tip aperture values, and therefore weaker alveolar constrictions, are linked with smaller F2-F1 differences. Generally, every millimeter increase in tongue tip aperture results in a 6.2 Hz decrease in F2-F1. In contrast, Tongue Dorsum Aperture was not found to have a significant effect on F2-F1 ($\beta = 2.80$, $t = 0.97$). Identity of the preceding vowel also had a significant effect on F2-F1: laterals following [ɪ] had significantly greater F2-F1 than those following [ɛ] ($\beta = 76.43$, $t = 2.59$), but not than those following [ʌ] ($\beta = 39.30$, $t = 1.02$). Adjusting the Vowel factor so that [ʌ] is the reference showed that F2-F1 is not significantly different between laterals following [ʌ] and [ɛ] ($\beta = 37.13$, $t = 1.07$). No significant interaction between either of the Aperture measures and Vowel quality was found. Finally, a significant effect of Frequency was found, such that F1 and F2 were approximately 30 Hz closer together in high-frequency words than in low-frequency words ($\beta = 29.46$, $t = 3.82$). This effect of lexical frequency on F2-F1 proximity, independent of its effect on tongue tip aperture, is likely, at least in part, the result of a reduced acoustic

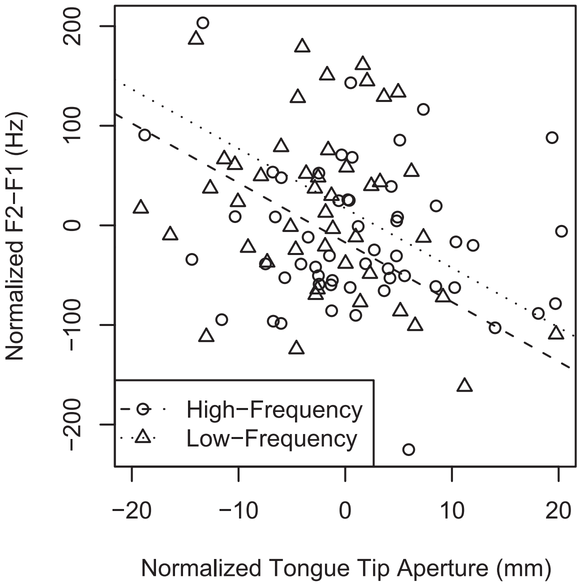

Fig. 7: Normalized mean F2-F1 values (Hz) against normalized tongue tip aperture values (mm), in high- and low-frequency words. Each data point represents the mean of all repetitions of a given word by a given speaker. (Thus, each speaker contributes 13 data points.)

vowel space in high- compared to low-frequency words (Munson and Solomon 2004). The effects of tongue tip aperture and word frequency on F2-F1 values are visualized in Figure 7, which displays F2-F1 values against tongue tip aperture values, both of which are normalized by speaker. The dotted and dashed lines representing the relationship between tongue tip aperture and F2-F1 proximity were derived from the linear mixed model run with the full, non-normalized values.

These findings suggest that reduction of the tongue tip gesture in laterals in pre-labial and pre-velar contexts in high-frequency words contributes to increased proximity of F1 and F2. The precise articulatory-acoustic relation that gives rise to this outcome is, however, not specified by our current measures. For example, although strength of the tongue dorsum constriction appears to have little impact on the difference between F1 and F2, our dorsum measures – which include constriction degree but not anterior-posterior constriction place – do not allow us to assess whether weaker tongue tip constrictions may correspond with more posterior tongue dorsum constrictions (and, consequently, decreased F2-F1 distance).

4 Discussion

This study built on previous findings that speakers of American English tend to produce a relatively weak tongue tip constriction for pre-velar and pre-labial laterals and tested whether alveolar constrictions are especially weak in high-frequency words ending in /lC_{velar}/ or /lC_{labial}/. The theoretical motivation for this extension was to investigate the phonetic underpinnings of sound changes leading to post-vocalic /l/ vocalization or loss. We predicted that a post-lateral consonantal context that does not require an alveolar constriction might contribute to alveolar reduction. Moreover, we predicted that the highly practiced articulatory routines (and, possibly, faster lexical access) for high-frequency words with final /lC_{labial}/ or /lC_{velar}/ would further contribute to alveolar reduction.

Both predictions were upheld. Consistent with the findings of Giles and Moll (1975), the place of articulation of the post-lateral consonant influenced aperture in the tongue tip and blade region: aperture was greater for laterals in labial and velar contexts than for those in alveolar contexts (Figure 3). This effect was consistently strong and held for all speakers and all word groups (e.g., *ilk* and *milk* compared to *built*; *whelp* and *help* compared to *pelt*).

New to this study is the finding that the more frequent the word ending in /lC_{velar}/ or /lC_{labial}/ clusters, the greater the aperture in the alveolar region for lateral productions (Figure 5). This lexical frequency effect, while significant, was small. For example, the largest average aperture difference between high- and low-frequency words for an individual speaker (S006) was roughly 1.73 mm (although aperture differences within specific high- and low-frequency word pairs were often substantially larger). Moreover, the size of the frequency effect on the anterior constriction for the lateral differed considerably across the eight participants. Speaker-specific differences were evident in the random coefficients for the relation between speaker and frequency (Table 2), and are illustrated as well in Figure 8 for speakers S003 and S009. Both of these speakers' lateral productions were among those most influenced by lexical frequency. For speaker S003, tongue tip aperture differed sharply for alveolar and non-alveolar contexts, and the added effect of frequency resulted in laterals in some high-frequency words (e.g., *milk*) that lacked clear evidence of tongue tip raising. In contrast, speaker S009 routinely raised her tongue tip; for this speaker, context and frequency had considerably smaller effects on lateral alveolar constrictions, most of which were produced within the aperture range of 0 to 1.0 mm, even in high-frequency words.

Despite the (unsurprisingly) small and variable nature of the effects of lexical frequency on alveolar reduction, the overall finding of weaker alveolar constrictions for laterals in high-frequency words is consistent with the results from pho-

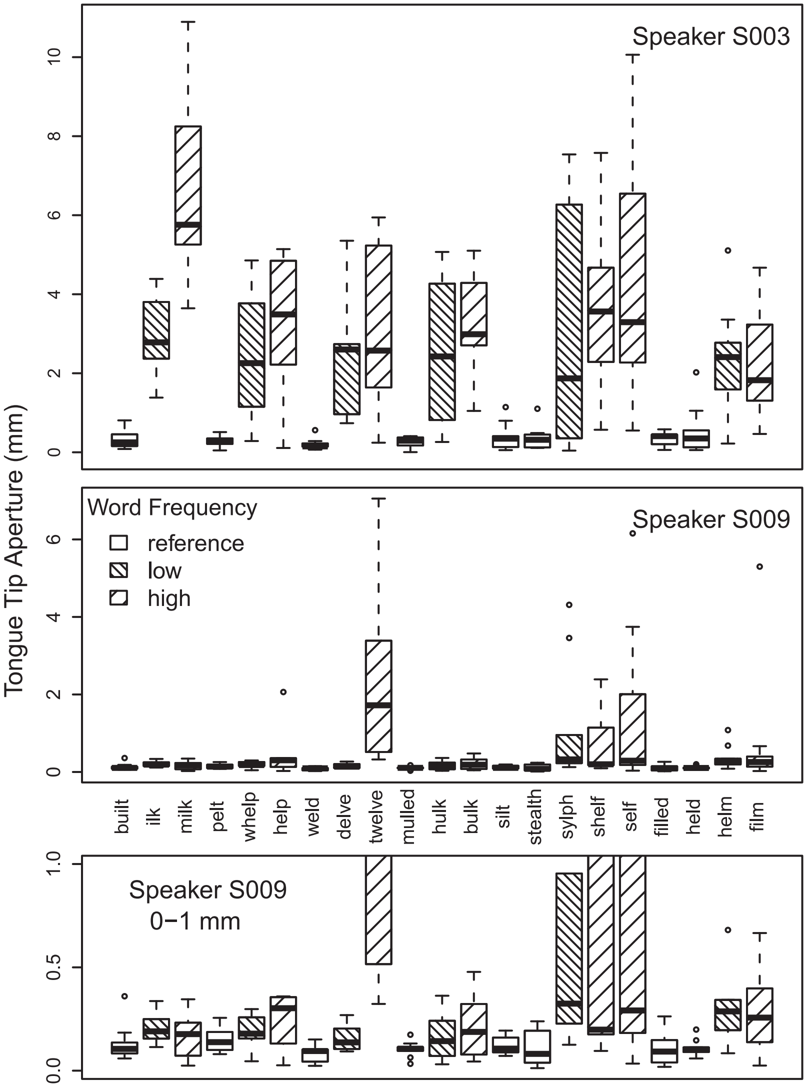

Fig. 8: Tongue tip aperture (mm) for speakers S003 (top) and S009 (middle), by word. Bottom plot reproduces data from S009 with the y-axis enlarged but restricted (0–1.0 mm) for visual clarity.

netically transcribed corpora (e.g., Bybee 2000; Coetzee and Kawahara 2013) and acoustic studies (e.g., Pluymaekers et al. 2005; Gahl 2008) showing that high-frequency words are more likely than low-frequency words to exhibit reduction phenomena. Moreover, our own investigation of the Buckeye Corpus (Pitt et al.

2007) shows that the frequency effect found here for laterals produced in a laboratory setting is also present in more casual speech. In the Buckeye corpus analysis, we extracted all words from that corpus that ended phonologically in /l/ followed by a consonant and had at least 10 occurrences in the corpus. Lack of transcribed [l] was interpreted as evidence that the token was produced without an audible lateral (and possibly with vocalization). For each word, we calculated the proportion of utterances produced with no audible /l/, and determined the linear correlation between these proportions and the frequency of the words in the corpus (log transformed at base 10). The results showed a strong positive correlation ($r^2 = 0.28$, $p = 0.0097$): the more frequent the word is in the corpus, the less likely it is to be produced with (audible) /l/. The deletion/vocalization proportions range from zero for infrequent words, like *result* and *wild,* to 22% for the most frequent word, *old*.

Measures of the tongue dorsum constriction for laterals further inform our interpretation of reduction of the alveolar gesture. Relevant to our interest in drawing parallels between variable, phonetic alveolar reduction and the historical processes of vocalization and lateral loss is whether greater alveolar reduction in high-frequency words is exclusively or largely a consequence of more general reduction in high-frequency compared to low-frequency words, or whether reduction is restricted to the anterior constriction. (If phonetic alveolar reduction is an early precursor to vocalization, for example, we would expect reduction to be largely restricted to the anterior constriction.) The results, though, point to a more complex situation than that suggested by either of these two alternatives. The tongue dorsum data do show evidence of reduced constrictions in more frequent lexical items (Figure 6); the effect, although small, is present for each speaker's lateral productions (Table 3). This outcome, when combined with the effect of frequency on tongue tip constrictions (Figure 5), would seem to be indicative of general reduction of lingual gestures in more frequent lexical items. Nonetheless, the frequency effect is not simply one of overall smaller magnitude of lingual constrictions in high-frequency words, as shown by the finding that, for a given high-frequency word (in relation to its low-frequency counterpart), tongue tip and tongue dorsum apertures were not correlated. For these data, then, reduction of the tongue tip constriction is not tied to reduction of the tongue dorsum constriction.

The synchronic and historical evidence for English dialects reviewed in the Introduction indicated an especially high likelihood of vocalization (and, less often in the cited studies, /l/ loss) in pre-consonantal position when that consonant requires a non-coronal constriction. The effect of consonantal place on the lateral productions of speakers in this study is consistent with this evidence. Our articulatory data on lingual constrictions in /Vl$C_{alveolar}$/, /VlC_{labial}/, and /VlC_{velar}/ sequences do not determine whether the reduced alveolar constrictions in the latter two contexts are due to lack of an independently required alveolar constriction for C, or to coordination of the lateral with another, temporally overlapping, supralaryngeal constriction, or to other factors. However, for all speakers in this study, the gestures for /l/ and C substantially overlapped, as indicated by the timing of the anterior lateral constriction in relation to the corresponding acoustic signal (see Section 2.4). (We inspected the acoustic signal because we lack articulatory data for the post-lateral labials and have not yet analyzed constriction data for post-lateral velars.) For example, in most /VlC_{labial}/ productions, maximum tongue tip constriction for the lateral occurred during the acoustic labial (closure for /p/, nasal murmur for /m/, or frication for /f/). The relative timing of /l/ and /k/ (in /VlC_{velar}/ productions) is more difficult to determine due to the tongue dorsum constriction for /l/, but here again the most constricted position of the anterior portion of the tongue was typically achieved during the voiceless portion of the signal, suggesting that it overlapped with the /k/ closure.

Irrespective of the precise source of the robust place effect in these data, we interpret the less constricted alveolar region for laterals in labial and velar contexts as a likely articulatory impetus for new pronunciation norms in which earlier /l/ has vocalized to a back vowel or approximant or been lost altogether. In drawing this link between apical weakening or undershoot and lenition processes, we are not making a novel claim, but rather providing further data in support of earlier proposals of the possible articulatory origins for these sound changes (e.g., Straka 1968; Hardcastle and Barry 1989; Recasens 1996 and elsewhere; Gick, Kang, and Whalen 2002).

Word frequency effects on leniting sound changes are characteristically viewed as contributing to the propagation of these changes through the lexicon. Bybee (2000, 2002), Phillips (1984, 2001), and Pierrehumbert (2001), for example, all cite the tendency of processes of lenition (assimilations, reductions, deletions) to affect more frequent words before less frequent words. We apply a similar lexical diffusion interpretation to the finding that, in the lateral productions of the speakers in this study, high-frequency words exhibited weaker alveolar constrictions than did low-frequency words. We emphasize that our data do not demonstrate an influence of lexical frequency on an ongoing process of vocalization or /l/ loss, but rather exhibit small to moderate frequency effects on what are quite possibly established patterns of gradient articulatory variation. However, consistent with the view that these articulatory gradients serve as the seeds of sound change (e.g., Ohala 1993), it is reasonable to speculate that, should pronunciation norms begin to shift and alveolar reduction for /l/ become exaggerated, high-frequency words would be at the forefront of that shift. Moreover, we interpret the combined influences of word frequency and place of the post-lateral consonant on the lingual constrictions to be especially consistent with these influences being potential precursors to vocalization. If these influences were instead phonetic precursors to /l/ loss – that is, absence of both the alveolar and dorsal gestures – we might expect that the influences of lexical frequency on reductions of the anterior and posterior constrictions would be tied to each other, and that the posterior (unlike anterior) constrictions would not be very nearly the same across place (compare Figures 4 and 3). (That the dorsum constriction does not reduce in the velar context may be due to the need to form a dorsum closure for the following /k/. However, that dorsum apertures did not differ significantly in the velar and labial contexts is suggestive of a relatively stable dorsum constriction for these speakers' lateral productions.)

For reduction of the lateral alveolar constriction in high-frequency words to serve as the impetus for *sound* change, it follows that the reduced gesture must have acoustic consequences. These data provide evidence of small, but nonetheless reliable, acoustic consequences of the size of the alveolar constriction: weaker alveolar constrictions (larger tongue tip apertures) in post-vocalic laterals resulted in closer F2-F1 proximity. Although the acoustic effects are so small (on average, 6 Hz per mm reduction in alveolar constriction) as to be imperceptible in most cases, of possible relevance especially to vocalization is that, in some vowel contexts, F2-F1 proximity in laterals is approaching a distance within which integration may occur for these formants. Chistovich (1985), among others, has shown that when two formants are within a critical distance of each other – usually estimated to be within 3 to 3.5 Bark – their proximity results in perceptual formant averaging. Stevens (1989) proposed that this critical F2-F1 spacing may provide an auditory basis for back, as opposed to front, vowels. Our acoustic data show that the average F2-F1 difference in laterals in high-frequency words is 3.6 Bark following /ɛ/ and 3.3 Bark following /ʌ/, that is, near or within the critical distance. (In comparison, Syrdal and Gopal [1986] report F2-F1 differences of 7.6 and 3.8 Bark for /ɛ/ and /ʌ/, respectively, in an /h_d/ context.) The crucial point here is that, in certain vowel contexts, small changes in F2-F1 proximity due to reduced tongue tip constriction may result in disproportionately large perceptual shifts. If further alveolar reduction in high-frequency words were to contribute to yet greater proximity of the first two formants, the listener might reanalyze the syllable rhyme as containing a back (rounded) vowel or /Vw/, instead of /Vl/, particularly if the alveolar constriction were so weak as to not yield clear vowel-to-consonant formant transitions.

Thus, the ultrasound evidence of reduced alveolar constrictions for laterals in labial and velar contexts, especially in high-frequency words, and the (small) acoustic consequences of that reduction can be interpreted as providing the phonetic material for sound changes in which post-vocalic laterals lenite in non-coronal contexts. A limitation of this account is that the non-coronal context for lateral change, although well documented for many varieties of English, does not hold for some other languages, especially for the history of Romance languages. For example, pre-consonantal vocalization occurred only – or initially – in dental/alveolar contexts in many varieties of Old and present-day Italian, Old Catalan, Old Provençal, and some Occitan dialects (Recasens 1996, 2009, 2012; Müller 2011). What might be the phonetic impetus in consonantal contexts that are not, as shown by the articulatory data reported here and elsewhere (e.g., Giles and Moll 1975; Hardcastle and Barry 1989; Recasens 2009), conducive to reduction of the anterior constriction? Recasens (2012) has suggested that a possible articulatory trigger in dental and alveolar contexts could be gestural merger between a (shortened) /l/ and the following homorganic consonant, an outcome that could lead to the longer, /w/-like dorsal gesture being the only acoustic information for the lateral. Alternatively, an auditory trigger also considered by Recasens (1996, 2012) is that if listeners attribute the velarized quality of /l/ to following labials and velars but not to following dentals/alveolars (because the former but not the latter share with velarized laterals a low-frequency F2), then the acoustic information for the dorsal constriction would be perceptually more prominent in dental/alveolar contexts. (See Müller [2011: 81–83] for yet another account of vocalization in Romance languages.) Unfortunately, the current findings and our interpretation of those findings, while not incompatible with these proposals concerning change in dental/alveolar contexts, do not further inform them. According to our account, reduction of the anterior gesture for laterals is especially likely to occur in high-frequency words in which that gesture must be coordinated with a following labial or velar constriction, and serves as one – but is by no means the only – precipitating factor for sound changes involving /l/ lenition.

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