Articulatory bases of sonority in English liquids

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Abstract. Sonority is generally considered to play a primary role in governing intrasyllabic phonotactics. In this chapter, we examine the phonotactic and articulatory properties of tautosyllabic vowel-liquid sequences in American English, and consider the implications for theories of sonority. Constraints on the distribution of vowels preceding liquid codas were first examined through lexical corpus analysis, revealing that fewer vowel contrasts occur before /ɹ/ than /l/, with contrasts further reduced before complex codas compared to simple codas. To shed light on these patterns, we investigated liquid production in different syllabic contexts in American English using real-time structural MRI. For each speaker examined, /ɹ/ showed more stability than /l/ in its lingual posture across contexts. For /l/, the tongue dorsum showed the greatest convergence across different vowel contexts in codas and complex syllable margins. In general, /ɹ/ exhibited less coronal stricture than /l/, consistent with some phonetic characterizations of sonority, and with traditional sonority-based accounts of the sequencing of /ɹ/ before /l/ in codas. Yet differences in stricture do not illuminate the observed restrictions on vowel-liquid sequences. Our data point to a greater encroachment on the vowel by a liquid in a complex coda, reducing the potential for contrast in pre-cluster nuclei; furthermore, the greater articulatory flexibility of /l/ renders it compatible with a larger range of vowels than /ɹ/. We conclude that articulatory factors can have a fundamental influence on phonotactic constraints, and suggest that our understanding of sonority will be enriched by taking into account a wider scope of articulatory properties beyond stricture degree alone.

1. Introduction

When it comes to intrasyllabic phonotactics, sonority is considered to play a primary role, governing the order of segments within the syllable and accounting for various co-occurrence restrictions. In treating the intrasyllabic organization of liquids, sonority-based phonotactic theories account for the permissibility of various segmental sequences in American English. These include onset clusters containing an obstruent-liquid sequence (e.g. *plan*, *bran*), which have an ascending sonority profile, and liquid-obstruent coda sequences (e.g. *milk*, *part*), and liquid-nasal codas (e.g. *film*, *barn*), which descend in sonority. Yet there

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are other distributional properties involving liquids in syllables of English that are not accounted for in a traditional sonority approach; for instance, it is unclear why there are constraints on segments in $\mathsf{VL(C)}]_\sigma$ sequences (L = liquid), and why liquid-vowel sequences are relatively unrestrained in comparison. Also relevant are asymmetries involving post-vocalic liquids: rhotics always appear closer to the nucleus in a tautosyllabic sequence (*snarl*; but $*\text{-Vl}\text{ɹ}]_\sigma$), and fewer vowel qualities occur before tautosyllabic rhotics than before laterals. In addition, distributional constraints on American English syllables with vowel-liquid sequences raise questions about the extent to which a vowel coalesces with, or is colored by, a following liquid in English rimes.

Our goals in this chapter are to explore how the articulation of liquids sheds light on their intrasyllabic phonotactic properties with relation to nuclear vowels, paying particular attention to vowel-like postures of the tongue dorsum in liquids, and to consider the implications for the basis of sonority. We present data from an articulatory study of liquids in American English designed to investigate these phenomena in more detail. The results of our research lead us to conclude that articulatory factors play into phonotactic constraints, and suggest that the concept of sonority would benefit from enrichment in the domain of articulation.

As background to this research, we note that Parker (2011) states that "a major function of sonority is to organize (order) segments within syllables." Sonority is therefore anticipated to play a significant role in accounting for the internal organization of syllables with post-vocalic liquids and the phonotactic restrictions they show on intrasyllabic segmental sequences. Given that segments closer to the nucleus tend to be more sonorous, phenomena involving the sequencing of liquids in onset and coda clusters have traditionally been explained by asserting that rhotics have greater sonority than laterals (Wiese 2001), and that both liquids are higher on a sonority hierarchy than obstruents. Yet despite the longstanding tradition of sonority-based accounts of segmental organization in syllable structure (Whitney 1872; Sievers 1876/1893; de Saussure 1915), the concept of sonority has not been well defined. In the case of liquids, the question of a phonetic basis for sonority is especially challenging. Although several phonetic parameters have been shown to be correlated with sounds that pattern together phonotactically in some languages (Parker 2002, 2008), none has proven to be robustly associated with the diverse segments that function as liquids across languages, nor even with sets of rhotics that pattern together in the same language (Lindau 1985; Kohler 1995; Ladefoged and Maddieson 1996; Walsh-Dickey 1997; Wiese 2011). If sonority is indeed relevant to the organization of liquids in syllable structure, a central question thus remains: *from which properties of rhotics and laterals does their sonority scaling emerge?*

Many phonetic grounds for sonority have been proposed in the literature, the most common being supralaryngeal aperture or a closely related concept (see Parker (2011) for a review). We take this as our working understanding of the phonetic basis for the traditional view of sonority. However, it is not clear how this perspective on sonority illuminates restrictions on vowel-liquid sequences – phonotactic constraints that could be expected to fall within sonority's scope. Given this shortcoming, as well as the difficulties in finding a unitary basis for the diverse class of liquids, we sidestep pursuing a grounding for sonority in this vein and return to this issue later. We seek instead to find insights about sonority relationships by investigating the articulatory characteristics of liquids and nuclear vowels in General American English (GAE). The hypothesis we explore is that the high sonority of English liquids derives from their vowel-like articulation of the tongue body (Delattre and Freeman 1968; Sproat and Fujimura 1993; Harris 1994), and that asymmetries in the sonority of rhotics and laterals arise in part from differences in tongue shaping and gestural coordination. We test these hypotheses by examining liquid production by three speakers of American English using real-time Magnetic Resonance Imaging (rtMRI). We suggest that better insights into the concept of sonority can be gained by taking into account various aspects of consonantal and vocalic articulation and coarticulation.

This chapter is organized as follows. In section 2 we discuss distributional restrictions found in syllables of GAE with post-vocalic liquids, which constitute the phonotactic phenomena to be explained. In section 3, we briefly review research on the production of liquids in English rimes and some analyses of their organization into syllable structure. Taken together, this work points to a basis for the phonotactic properties of post-vocalic liquids in the overlap of a liquid's dorsal gesture with the preceding vowel. In sections 4–5, we present our investigation of the articulation of liquids in different syllable positions and different vocalic contexts. In section 6, we discuss the results, finding that traditional views of sonority fall short in explaining the patterns our study reveals, and that various factors of articulation are relevant. Section 7 concludes the paper and offers directions for future research.

2. Distributional Restrictions in American English Syllables with Post-Vocalic Liquids

In English syllables, rimes containing liquids exhibit several characteristic phonotactic properties. In consonant sequences, liquids always appear closer to the nucleus than tautosyllabic obstruents and nasals, and within the set of liquids, rhotics always appear closer to the nucleus than laterals. In vowel-liquid sequences, vocalic contrasts are reduced when a vowel is followed by a liquid in certain configurations in the rime. In particular, fewer vocalic contrasts occur before tautosyllabic rhotics than laterals, and fewer occur before a liquid followed by another tautosyllabic consonant than before a rhotic or lateral alone in the rime. Also, different subsets of English vowel contrasts are found before -ɹC and -lC rime clusters. Similar constraints exist in other Germanic languages, including Dutch (Booij 1995) and German (Wiese 2001). We detail these phonotactic restrictions in GAE below, and outline the specific questions they give rise to in our investigation. For descriptive convenience, we will refer to post-vocalic liquids in the rime as in the 'coda.' However, in doing so, we do not foreclose the question of whether some or all of these liquids might actually belong to the nucleus, as we touch on later.

In GAE,[2] Hammond (1999) observes that seven vowel qualities, including glide-final diphthongs, contrast before a simple rhotic coda,[3] but only /ɔ/ and /ɑ/ contrast before /ɹ/ when it is followed by a voiceless stop in the rime. This particular reduction of vowel contrasts is true more generally of -ɹC codas, although some additional vowels are attested when the syllable is closed by certain coronal obstruents: {/d/,/s/,/z/} (see Table 1).[4] These contrasts are more limited in tautomorphemic contexts.

The data in Table 1 were compiled from a syllabified version of the Carnegie Mellon University Pronouncing Dictionary (Weide 1994). The original 133, 746-word dictionary was first modified to remove non-nativized proper names

2. The structure of rimes and realization of liquids varies across different varieties of American English, some of which, most notably, are 'non-rhotic'. Unless otherwise stated, the phonological properties discussed in the remainder of this chapter are those of General American English, a 'rhotic' variety typified by the middle class English spoken throughout much of the Midwestern United States (see Wells (1982) for more details).
3. The rhotic vowel [ɝ] occurs followed by most of the possible coda consonants: *burp*, *blurb*, *firm*, *surf*, *curve*, *birth*, *pert*, *bird*, *burn*, *pearl*, *purse*, *burrs* (with suffixation), *birch*, *purge*, *(kirsch)*, *(concierge)*, *work*, *iceberg*; (marginal codas – those only found in a limited number of loan words – are given in parentheses). In the rimes for these words, articulatory evidence points to a rhotic vowel followed by a simple non-rhotic coda, rather than a $\text{-V}ɹ\text{C}]_\sigma$ articulatory sequence. This is consistent with treatments of the syllabic peak in a word like *purr* as a syllabic /ɹ/ (Ladefoged and Maddieson 1996: 234).
4. Speakers differ in their judgment of the syllable count for words with rimes consisting of a diphthong or non-low tense vowel followed by a liquid, e.g., *fire* and *pool*. Such forms are termed "sesquisyllables" by Lavoie and Cohn (1999), who analyze them as trimoraic monosyllables that are inherently unstable. Following their lead, we treat these forms as monosyllables in their usual form.

and compound nouns, resulting in a lexicon of 94,816 unique English words, including inflected forms. We use square brackets to identify vowel contrasts that occur before particular -ɹC codas only in morphologically complex forms. Rime sequences that are marginal in English, for instance, those that occur in only a handful of loanwords or proper names, are placed in parentheses. In this chapter, we set aside contrasts that are marginally attested. Sequences limited to syllables with -LC codas closed with a final coronal obstruent have a special status. In some previous research, the coronal obstruent is analyzed as organized into a syllable appendix (Fujimura and Lovins 1978; Fujimura 1979; Halle and Vergnaud 1980; Kiparsky 1981; Selkirk 1982), and is therefore external to the syllable rime.[5] We will concentrate chiefly on restrictions where the final consonant in a coda cluster is not a coronal obstruent.

Table 1. American English rhotic-final rimes (left column) and rhotic-initial coda clusters. (Unattested: */-ɹw/, */-ɹð/, */-ɹʒ/, */-ɹj/, */-ɹŋ/, */-ɹh/).

	-ɹ	-ɹp	-ɹb	-ɹm	-ɹf	-ɹv	-ɹθ	-ɹt	-ɹd	-ɹn	-ɹl	-ɹs	-ɹz	-ɹʧ	-ɹʤ	-ɹʃ	-ɹk	-ɹg
-i-	beer								beard			pierce	[[beer]s]					
-ɪ-																		
-eɪ-																		
-ɛ-	bare								[[bare]d]			scarce	[[bare]s]					
-æ-																		
-ʌ-																		
-ɑ-	bar	carp	barb	farm	scarf	carve	hearth	part	bard	barn	snarl	farce	[[bar]s]	arch	barge	marsh	park	(Marg)
-ɔ-	bore	warp	orb	form	wharf		forth	port	board	born	whorl	force	[[bore]s]	torch	forge	borsch	pork	morgue
-oʊ-																		
-ʊ-																		
-u-	cure								[[cure]d]				[[cure]s]					
-aɪ-	fire								[[fire]d]				[[fire]s]					
-aʊ-	hour												[[hour]s]					
-ɔɪ-																		

The reduction of vowel contrasts seen before -ɹC codas is not generally mirrored following Cɹ- sequences in the onset. For example, while just two vowel contrasts are attested before a tautosyllabic /-ɹk/ sequence, numerous vowel qualities are attested following a /kɹ-/ onset: *creep* [i], *crib* [ɪ], *crate* [eɪ], *crest* [ɛ], *crab* [æ], *crumb* [ʌ], *crawl* [ɔ], *crop* [ɑ], *crow* [oʊ], *crook* [ʊ], *crude* [u], *crime* [ɑɪ], *crowd* [ɑʊ].

A greater range of vowel contrasts are found in rimes containing postvocalic /l/ than those with post-vocalic /ɹ/. All fifteen GAE vowels and diphthongs occur before a simple lateral coda. Before an -lC coda closed with a non-coronal consonant, as many as four vowel qualities stand in contrast. Also, a different

5. Nevertheless, the special status of -LC codas closed by a coronal obstruent could provide valuable insights into coda organization, and remains to be investigated in future work.

set of vowel qualities are found before -lC coda clusters than before -ɹC codas (Table 2, using the same lexicon as for Table 1). Again, the same degree of vowel contrast reduction does not generally occur after onset clusters with a lateral. For instance, just five vowel contrasts occur before a tautosyllabic /-lk/ cluster, while most vowels and diphthongs of English are attested after a /kl-/ onset: *clean* [i], *clip* [ɪ], *claim* [eɪ], *cleft* [ɛ], *clap* [æ], *club* [ʌ], *cloth* [ɔ], *clock* [ɑ], *cloak* [oʊ], *clue* [u], *climb* [ɑɪ], *cloud* [ɑʊ], *cloy* [ɔɪ].

Table 2. American English lateral-final rimes (left column) and lateral-initial coda clusters. (Unattested: */-lw/, */-lð/, */-lɹ/, */-lj/, */-lg/, */-lŋ/, */-lh/).

	-l	-lp	-lb	-lm	-lf	-lv	-lθ	-lt	-ld	-ln	-ls	-lz	-ltʃ	-ldʒ	-lʃ	-lk
-i-	peel								field			[[peel]s]				
-ɪ-	pill			film			filth	built	gild	kiln		[[pill]s]	filch			milk
-eɪ-	pale								[[fail]ed]			[[pale]s]				
-ɛ-	bell	help		elm	elf	delve	wealth	belt	meld		else	[[bell]s]	belch		(Welsh)	elk
-æ-	pal	scalp		psalm	(Alf)	valve		[[shal]t]	[[corrall]ed]			[[pal]s]				talc
-ɝ-	pearl								world			[[pearl]s]				
-ʌ-	hull	pulp	bulb		gulf			cult	[[hull]ed]		pulse	[[hull]s]	mulch	bulge		bulk
-ɑ-	poll			palm	golf	solve			ribald			[[poll]s]				balk
-ɔ-	ball				(Rudolf)			fault	bald		false	[[ball]s]			(Walsh)	
-oʊ-	bowl							bolt	fold			[[bowl]s]				
-ʊ-	pull				wolf				[[pull]ed]			[[pull]s]				
-u-	pool								[[pool]ed]			[[pool]s]				
-aɪ-	pile								mild			[[pile]s]				
-aʊ-	fowl								[[foul]ed]			[[fowl]s]				
-ɔɪ-	boil								[[foil]ed]			[[boil]s]				

In addition to these constraints on constituency, not all vowel-consonant sequences occur with equal likelihood in English rimes. To better understand these phonotactic preferences, a lexical corpus analysis of American English was conducted. All rimes found in the lexicon we derived from the modified Carnegie Mellon University Pronouncing Dictionary were examined, and frequencies of all vowel-liquid-consonant trigrams in words of English were compiled. Estimated frequencies of rhotic- and lateral-initial codas in GAE are given in Tables 3–4. These values represent type frequencies in a corpus where each unique word of English is listed once, rather than token frequencies in a usage-based corpus.

The privileged status of the coronal obstruents /s, z, t, d/ in complex codas is apparent from the fact that they collectively account for 39.5% of all liquid-consonant combinations, due to the high functional load of these consonants in English morphology. The data reveal that the great majority of English complex codas containing rhotics occur in rimes initiated by the vowels [ɑ] and [ɔ], while complex codas with a post-vocalic lateral are more commonly initiated with one of the vowels [ɪ], [ɛ], [ʌ], [ɔ] and [oʊ].[6] The differences in frequency and the gaps in the lexicon suggest that some vowel-liquid sequences are more felicitous than others in English.

Table 3. Counts and relative frequencies of English rhotic-initial codas (number of occurrences of each rime type in a 94,816-word corpus), excluding rhotic vowel nuclei ([-ɝ]).

	-ɹp	-ɹb	-ɹm	-ɹf	-ɹv	-ɹθ	-ɹt	-ɹd	-ɹn	-ɹl	-ɹs	-ɹz	-ɹʧ	-ɹʤ	-ɹʃ	-ɹk	-ɹg	Total	
-i-								37			3	62						102	11.0%
-ɛ-								34			1	65						100	10.8%
-ɑ-	5	9	6	1	2	2	70	117	11	3	6	35	6	6	2	19		300	32.3%
-ɔ-	3	2	12	2		4	68	121	46	1	38	53	3	5	1	9	2	370	39.9%
-u-								19				15						34	3.7%
-aɪ-								6				12						18	1.9%
-aʊ-												4						4	0.4%
	8	11	18	3	2	6	138	334	57	4	48	246	9	11	3	28	2	928	100%

Table 4. Counts and relative frequencies of English lateral-initial codas (number of occurrences of each rime type in a 94,816-word corpus).

	-lp	-lb	-lm	-lf	-lv	-lθ	-lt	-ld	-ln	-ls	-lz	-lʧ	-lʤ	-lʃ	-lk	Total	
-i-								13			21					34	6.5%
-ɪ-			1			1	12	20	2		23	3			4	66	12.5%
-eɪ-								16			23					39	7.4%
-ɛ-	3		3	4	3	3	10	27		1	28	3		1	1	87	16.5%
-æ-	1		1	2	1		1	1			7				2	16	3.0%
-ɝ-								6			11					17	3.2%
-ʌ-	3	1		2			10	18		3	11	2	3		5	58	11.0%
-ɑ-			3	3	8			6			3				1	24	4.6%
-ɔ-				1			12	19		2	26			1		61	11.6%
-oʊ-							6	28			34					68	12.9%
-ʊ-				1				2			5					8	1.5%
-u-								8			12					20	3.8%
-aɪ-								14			15					29	5.5%
-aʊ-								4			5					9	1.7%
-ɔɪ-								8			8					16	3.0%
	7	1	8	13	12	4	51	190	2	6	232	8	3	2	13	527	100%

The phonotactic properties of post-vocalic coda liquids that we have outlined in this section raise questions about the organization of rhotic and lateral liquids in syllable structure, the relationship between vocalic contrast and a following

6. [ɔ] and [oʊ] occur before an -lC coda primarily when the final consonant is a coronal obstruent. We return to this in section 6.2.

liquid, and how sonority figures in these patterns. The specific questions that form the focus of our investigation are as follows.

(1) a. why are fewer vowel contrasts supported before /ɹ/ than /l/?
b. why are vowel contrasts reduced when a post-vocalic liquid is followed by another consonant in the coda?
c. what determines which vowel qualities survive before a complex coda?
d. what do these data tell us about the basis of sonority?

3. Previous Research

A central challenge presented by these data is determining the structural relationship between a syllable nucleus and the following consonants. The data presented in section 2 suggest that post-vocalic liquids and the preceding vowel enter into a close relationship, with the potential to impact the realization of the vowel's distinctive properties. Such phenomena have implications for theories of syllable structure in general, and bases of sonority in particular.

Important insights into the structure of rimes that contain liquids have been obtained through phonetic study of their production. Delattre and Freeman (1968) and Zawadzki and Kuehn (1980) observed that the many varieties of American English /ɹ/ all make use of both a coronal and a pharyngeal constriction. Hardcastle and Barry (1989), Sproat and Fujimura (1993) and Browman and Goldstein (1995) found evidence that American English /l/ is also produced with two coordinated components: a vowel-like dorsal gesture, and a consonantal coronal gesture.

Most importantly, these studies and others have found articulatory commonalities between coda liquids and the nuclei with which they interact. Giles and Moll (1975) observed that lingual dorsum shaping in American English /l/ was similar to that observed in vowels, and Baker, Mielke and Archangeli (2005) observed vowel-like tongue postures in pre-liquid positions in English codas, where an "excrescent schwa" is sometimes perceived. Gick, Kang and Whalen (2002) demonstrated that American English /ɹ/ involves a low-back dorsal articulation, and in /l/, the dorsal articulation is pharyngeal and more constricted.

Another insight gained from these studies is that English liquid allophony may result from differences in the timing and interaction of their constituent gestures with surrounding segments. Sproat and Fujimura (1993) observed that in syllable-final 'dark' laterals, the dorsal gesture preceded the coronal gesture, and was lower and more retracted than for 'clear' onset laterals.

These findings are consistent with the analyses of Harris (1994) and Green (2001), who have argued that in GAE, so-called 'coda' liquids are better analyzed as forming diphthongs within the nucleus. The close affiliation of liquids with preceding vowels is also reflected in some Government Phonology analyses, where post-vocalic liquids have the capacity to form part of a rime but post-liquid 'coda' consonants are organized into the following onset (Botma, Ewen and van der Torre 2008; Ewen and Botma 2009). In his case study of English /ɹ/, Harris relates its capacity to occupy the syllable nucleus to its approximant realization and its dorsal gesture which resembles that of a vowel. See Cyran (2008) for a different perspective on final LC 'codas' in Government Phonology which emphasizes the liquid's relation to the post-liquid consonant and a following empty nucleus.

In summary, a core aspect of the production of liquids in English is that they involve coronal *and* dorsal articulations, the latter being vowel-like in nature. Furthermore, the close relationship between vowels and following 'coda' liquids has been reflected in some formal analyses of syllable structure in terms of a diphthong structure or the liquid forming a nuclear complement. Building on this work, we hypothesize that the dorsal gesture of liquids has the capacity to overlap significantly with a preceding tautosyllabic vowel, and that the phonotactic properties of liquids outlined in the previous section are related to their dorsal gestures and their degree of coproduction with the preceding vowel. We investigate these issues further in an articulatory study of English syllables with post-vocalic liquids.

4. Phonetic Investigation of English Liquid Production

We conducted a phonetic study of liquid production in GAE in onsets and codas – in both simple and complex syllable margins and across different vocalic environments – with the aim of comparing the location of the liquids' constriction formation in these contexts and effects of coarticulation. This constitutes a wider range of phonological environments than have been examined in previous articulatory studies on this topic. Using real-time structural magnetic resonance imaging (Narayanan et al. 2004), we are able to resolve the midsagittal plane of a speaker's upper airway. Because it images the whole vocal tract, rtMRI provides insights into the dynamic articulation and coordination of the tongue dorsum which are not easily obtained using other phonetic methodologies, but which are key to the understanding of liquid production, articulatory coordination, and possible phonetic bases of sonority.

4.1. Subjects and Stimuli

Data were acquired from three adult male native speakers of GAE. Subject ages ranged from 27 to 31 years (Table 5). None of the subjects spoke any other language fluently, or had lived outside the United States for a significant amount of time. Both parents of each of the subjects are fluent speakers of American English. None of the speakers reported abnormal hearing or speaking development or pathologies. Male subjects were recruited to eliminate gender as source of phonetic variability.

Table 5. Study Participants – Demographic Details.

ID	Gender	Ethnicity	Age	Birthplace
M1	Male	White	29	Buffalo, NY
M2	Male	White	31	Eau Claire, WI
M3	Male	White	27	Rochester, NY

Liquids were elicited in onset, onset-cluster, coda, and coda-cluster positions, in a range of vocalic environments (Table 6), so that lingual articulation across different vowel contexts could be observed. Only real words of English were used. Wherever possible, words with labial or glottal consonants were chosen to reduce lingual coarticulatory effects on the target liquid consonant. In three stimuli (*solve*, *beard*, *cured*), lingual obstruents were used because a word with a labial or glottal consonant for that vowel context was not available. Subjects were familiarized with all words before the experiment, and target pronunciations for any unfamiliar words were discussed. Each target word was elicited three times, in a short carrier phrase constructed from glottal fricatives, labials, and symmetrical vowels, to minimize coarticulatory influence on the target segments. The full set of stimuli presented to subjects is listed in the Appendix. Recordings were audited to verify that vowels were produced as expected; tokens that were not produced with the intended target vowel were excluded from the analysis.[7]

7. Because the low back vowel /ʌ/ is not attested before coda rhotics in English, tokens containing the closest available vowel quality – the rhoticized vowel /ɝ/ – were elicited instead, in order to complete the experimental paradigm and to investigate whether a vowel-liquid sequence is produced in this context. Although we do not present our findings on these tokens in this paper, the production of these forms was consistent with the analysis that they contain a syllabic /ɹ/ or rhotic vowel alone.

Table 6. Stimuli design – laterals and rhotics targeted in onset and coda positions.

Onset	#l-	#ɹ-	#Cl-	#Cɹ-
[i]	leap	reap	bleep	brief
[ɑ]	lob	rob	plop	prop
[u]	loop	room	plume	prove
[oʊ]	lobe	robe	blow	probe
[ʌ]	love	rum	plum	from

Coda	-l#	-ɹ#	-lC#	-ɹC#
[i-ɪ]	peel	beer	film	beard
[ɑ]	ball	bar	solve	barb
[u-ʊ]	pool	moor	wolf	cured
[oʊ-ɔ]	pole	bore	Rolf	form
[ʌ]	hull		pulp	
[ɝ]		fur		firm

4.2. Image and Audio Acquisition

MRI data were acquired at Los Angeles County Hospital on a Signa Excite HD 1.5T scanner, using a custom upper airway receiver coil array. Subjects' upper airways were imaged while they lay supine in the MRI scanner. Stimuli were presented in fixed order, in large text on a back-projection screen which subjects could read from within the scanner bore without moving their head. Sentences were presented one at a time, elicited at a natural speaking rate. A spiral gradient echo pulse sequence was used to acquire a 5 mm midsagittal slice with image resolution 68 × 68 pixels over a 200 × 200 mm field of view (Fig. 1). Image data were reconstructed as 33.2 frame per second video sequences (Bresch et al. 2008). Audio was simultaneously recorded at a sampling frequency of 20kHz inside the MRI scanner while subjects were imaged, using a custom fiber-optic microphone noise-canceling system (Bresch et al. 2006).

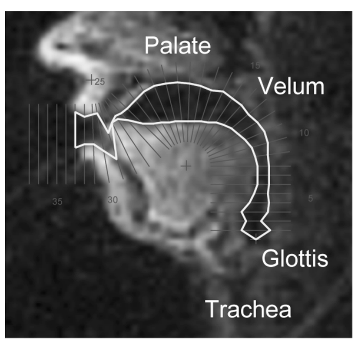

Figure 1. **Real-time Magnetic Resonance Imaging of midsagittal vocal tract**. Image frame captured at onset of lateral closure in low vowel context [ɑlɑ] (Subject M3). Semi-polar vocal tract analysis grid (dark radial lines) and vocal tract outline generated by semi-automatic segmentation of air-tissue boundaries (light solid lines) superimposed on Magnetic Resonance Image. (Color figures available online at http://sail.usc.edu/span/papers/codaliquids).

4.3. Analysis

For each utterance, the midpoint of liquid production was estimated by locating the image frame in which maximal lingual elongation – measured between the points of maximal coronal and pharyngeal constriction – was observed (Fig. 2). A 300 to 350 msec interval centered on that frame was identified, corresponding to the entire interval of liquid production: the V(C).CV sequence for tokens containing simple onsets, the VC.CV sequence for simple codas, the V(C).CLV sequence for complex onsets, and the VLC.CV sequence for complex codas. Start and endpoints for each interval were chosen to be the articulatory midpoints of the context vowels, estimated by locating the frame in which the tongue dorsum was maximally static in the vicinity of the target constriction for the vowel.

For each frame in the image sequence, tongue posture in the midsagittal plane was captured by automatically identifying air-tissue boundaries (Proctor, Bone and Narayanan 2010), and manually correcting the tongue outline where the algorithm failed to locate the edges of lingual tissue with sufficient accuracy (Fig. 1). In other figures in this paper, air-tissue boundaries like those identified by the light solid lines in (Fig. 1), are displayed without the background of the

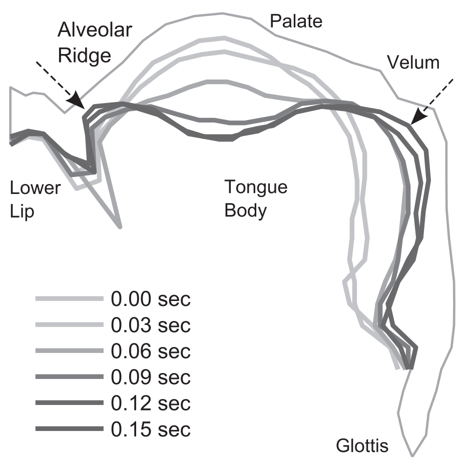

Figure 2. **Analysis of articulatory movement in rtMRI data**. Sequence shown: [-iɫ]. Each curve corresponds to the location of the midsagittal tongue edge at one point in time. Tongue edge curves are indexed in time by darkness of shading. Tongue position captured at 30 msec intervals in transition from midpoint of nuclear vowel (t = 0 msec: lightest shaded curve) to coda consonant (t = 150 msec: darkest shaded curve). Arrows indicate constriction targets achieved by tongue tip and tongue dorsum at point of maximum elongation of tongue during lateral articulation.

magnetic resonance image. The sequence of tissue boundaries provides a dynamic record of lingual articulation during liquid production in each phonological environment – a 33 frame per second 'movie' depicting tongue movement between the consonant and vowel of interest (Fig. 2). Because subjects' heads remained stationary throughout the acquisition session, tongue position can be compared across tokens for each subject.

5. Results

5.1. Lateral Articulation

Lateral articulation is illustrated in Fig. 3, which compares lateral onset and coda production in the same two vowel contexts. In the onset panels (left column), the superimposition of midsagittal tongue positions captured at successive 30 msec intervals shows the transition from onset lateral to the following

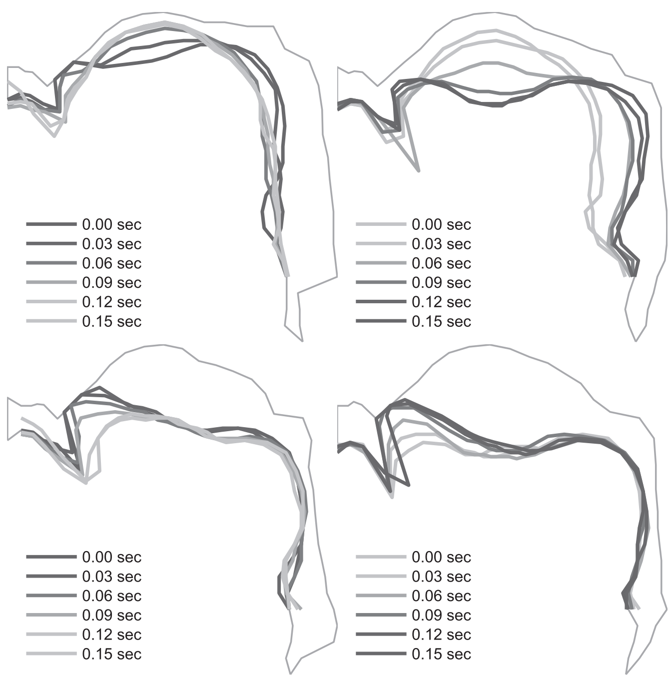

Figure 3. **Onset and coda lateral production** in two vowel contexts by Subject M2. Top left: [li-]; Top right: [-iɫ]; Bottom left: [lʌ-]; Bottom right: [-ʌɫ]. Midsagittal tongue position captured at 30 msec intervals. Light lines: mid-vocalic; dark lines: mid-consonantal frame.

vowel; in the coda panels (right column), change in tongue position is shown from the midpoint of the vowel into the coda lateral.[8]

The data reveal considerable asymmetries between laterals produced in onset and coda positions, and in different vowel contexts. Before a high front vowel, onset laterals are produced with a higher, more advanced tongue body posture (see Fig. 3, top left) than coda laterals after the same vowel, where a lower, more retracted tongue body is evidenced, and in some cases, an undershot or asymmetrically articulated coronal gesture (Fig. 3, top right). Comparing the movement of the tongue body between vocalic and consonantal postures, there is more movement when a lateral is produced in the context of a high front vowel in both positions in the syllable (see two upper panels in Fig. 3) than when it is in the context non-high non-front vowel, where very little tongue body movement can be observed in the transition between the consonant and the vowel, in either onset or coda environments (see two lower panels in Fig. 3).

5.1.1. The Effect of Vowel Context on Lateral Production

We can gain more insights into these articulatory differences by directly comparing laterals produced in the vicinity of different vowels. Mean tongue position was calculated across two of the three productions by each subject of each lateral in each phonological environment.[9] Tongue positions captured at the point of mid-consonantal production (see section 4.3), for laterals elicited in onset and coda positions, are compared in Fig. 4.[10] Note that the panels in Fig. 4 compare the posture of the tongue in production of a lateral consonant at a single point in time across vowel contexts rather than showing tongue positions at successive intervals in forming a lateral entering into or out of an adjacent vowel, as in Fig. 3.

The data reveal that coronal articulation is largely consistent across all vowel contexts and in both syllabic margins, whether simple or complex, but dorsal articulation varies between lateral tokens. For all three subjects, greater variation in dorsal posture can be observed between vowel contexts in onset position (left

8. Data shown for Subject M2; laterals produced by Subjects M1 and M3 showed the same fundamental patterns of articulation as those described for M2.
9. The 1st and 2nd repetitions of each of the simple onset laterals were analyzed because a third repetition of these items was not available. For all other tokens, the 2nd and 3rd repetitions of each utterance were selected for analysis, for which the subject was more accustomed to the scanner. Tongue outlines are constructed from the mean coordinates of air-tissue boundaries sampled across both utterances.
10. Data shown for Subject M3; laterals produced by Subjects M1 and M2 showed the same fundamental patterns of articulation as those described for M3.

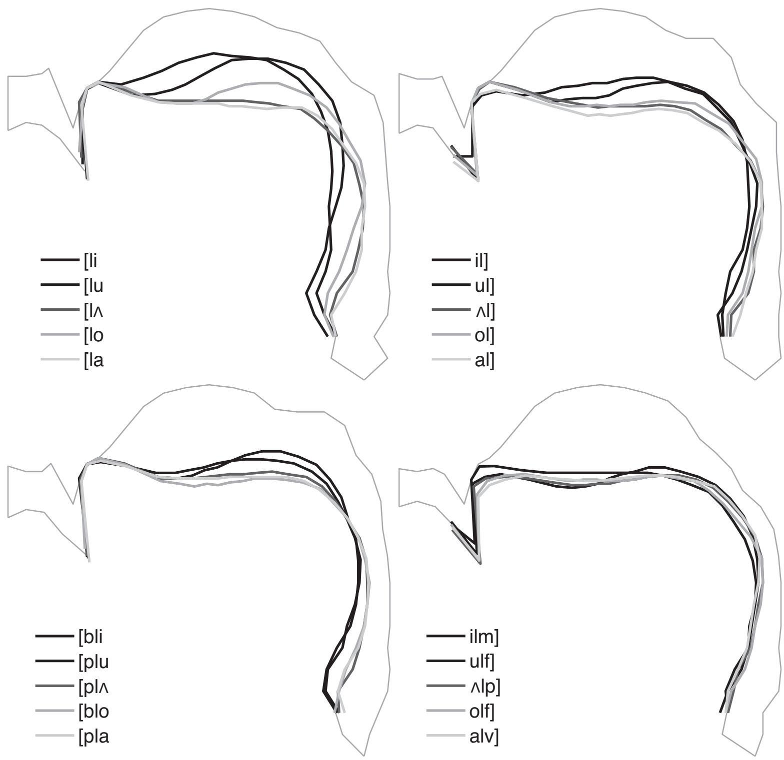

Figure 4. **Midsagittal tongue posture during lateral production in five different vowel contexts**. (Mean tongue edge captured at consonantal midpoint of two lateral productions by Subject M3). Top left: onset laterals; Top right: coda laterals; Bottom left: onset cluster; Bottom right: coda cluster.

panels) than for coda laterals (right panels). For all three subjects, the tongue dorsum is more retracted, and exhibits less displacement due to vocalic coarticulation in coda position. Mean pharyngeal posture calculated across lateral tokens uttered by all subjects[11] was 4.3 mm more retracted (pharyngealized) for simple coda laterals than in simple onsets. Mean pharyngeal aperture, measured at the point of maximal midsagittal constriction across all tokens with simple onsets and codas produced by all speakers, is 7 mm more constricted for coda laterals produced in a high front vowel context, compared to onset laterals produced in the same vocalic environment. Since high front vowels are not expected to exhibit pharyngeal constriction, this difference is particularly

11. Degree of pharyngealization was estimated by locating the x-coordinate of the most posterior point of the tongue dorsum in the midsagittal plane for each token.

indicative of the greater dorsal retraction induced by laterals in coda position. Furthermore, based on our qualitative analysis of superimposed tongue postures, we find a continuum of convergence for the tongue body position of the lateral across different vowel contexts as follows: -VlC]$_\sigma$ > -Vl]$_\sigma$ > $_\sigma$[ClV- > $_\sigma$[lV-, where greatest convergence for the tongue dorsum occurs with postvocalic /l/ in a coda cluster (Fig. 4, bottom right) and the least convergence with prevocalic /l/ in a simple onset (Fig. 4, top left).

5.2. Rhotic Articulation

Coda rhotic articulation is illustrated in Fig. 5, where it is compared with onset rhotic production in the same two vowel contexts. For onset rhotics (left column), superimposed midsagittal tongue positions captured at successive 30 msec intervals show the lingual transition from syllable-initial consonant into the

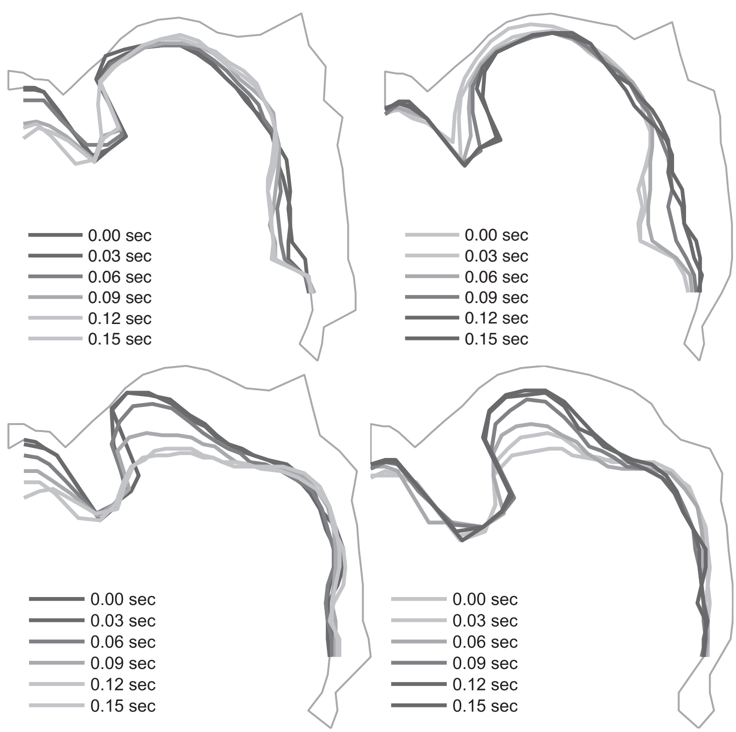

Figure 5. **Onset and coda rhotic production** in two vowel contexts by Subject M2. Top left: [ɹi-]; Top right: [-iɹ]; Bottom left: [ɹɑ-]; Bottom right: [-ɑɹ]. Midsagittal tongue position captured at 30 msec intervals. Light lines: midvocalic; dark lines: mid-consonantal frame.

following vowel; for coda rhotics (right column), superimposed tongue edges show the change in midsagittal tongue position from the midpoint of the nuclear vowel into the following consonant.[12] These data reveal a greater overall symmetry in tongue shaping between onset and coda rhotics than was observed for laterals (Fig. 3). Although the extent of ‘bunching’ and degrees of coronal and pharyngeal stricture differ between phonological environments and speakers, for any given vowel context (compare within rows in Fig. 5), midconsonantal lingual postures are broadly similar for all rhotics, whether they occur in onset or coda position.

5.2.1. The Effect of Vowel Context on Rhotic Production

Coda rhotic articulation was examined further by directly comparing consonants produced in the vicinity of different vowels. Mean tongue position captured at the point of mid-consonantal production, for rhotics elicited in simple and clustered onset and coda positions, are compared in Fig. 6.[13] Similar to Fig. 4 for laterals, these panels compare the posture of the rhotic consonant at a single point in time across different vowel contexts. Each subject exhibited a different articulatory posture for /ɹ/ – M1 using the most ‘bunched’ tongue shape, and M3 the most ‘retroflexed’ (Delattre and Freeman 1968; Hagiwara 1995; Alwan, Narayanan and Haker 1997). Despite these characteristic differences in articulation (Fig. 7), the most important observation to be made from these data is that rhotics produced by all three subjects show a remarkable consistency in articulatory configuration across all four syllable structure environments, whether in an onset or coda or in a simple or complex margin. In particular, the onset rhotics exhibit much less influence from vocalic coarticulation than the onset laterals produced by the same speakers (compare especially the top left panels in Figs. 4 and 6). Although not as pronounced as for the laterals, small production differences due to position in the syllable can also be observed in these data: coda rhotics (right column in Fig. 6) are produced with a more central tongue body, a less apical coronal articulation, and a more open constriction at the point where the tongue most closely approximates the palate than onset rhotics (left column in Fig. 6).

12. Data shown for Subject M2; rhotics produced by Subjects M1 and M3 showed the same fundamental patterns of articulation as those described for M2.
13. Data shown for Subject M3; rhotics produced by Subjects M1 and M2 showed the same fundamental patterns of articulation as those described for M3. Mean midsagittal lingual postures calculated from two of the three productions elicited from each subject.

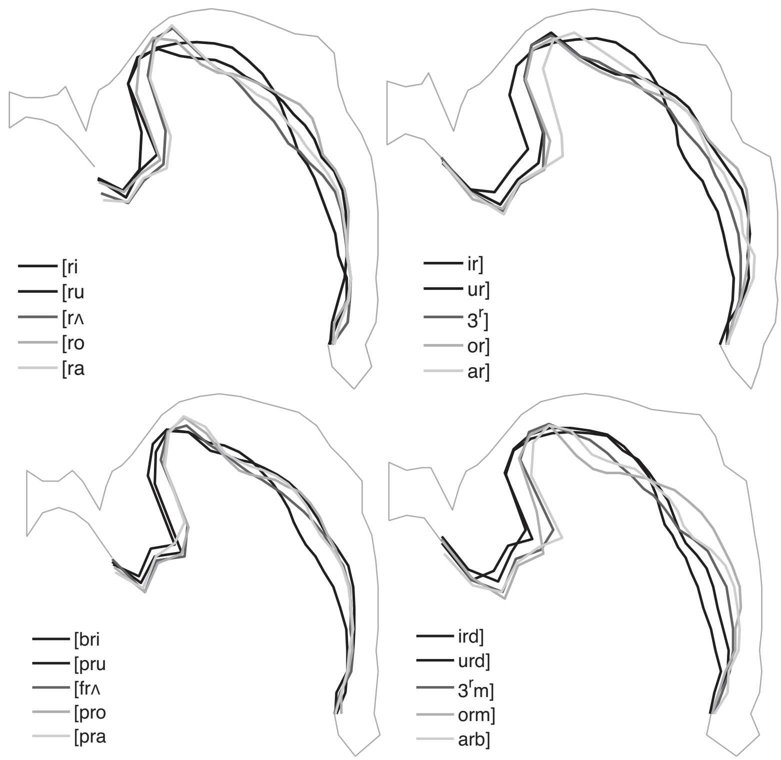

Figure 6. **Midsagittal tongue posture during rhotic production in five different vowel contexts**. (Mean tongue edge captured at consonantal midpoint of two rhotic productions by Subject M3). Top left: onset rhotics; Top right: coda rhotics; Bottom left: onset cluster; Bottom right: coda cluster.

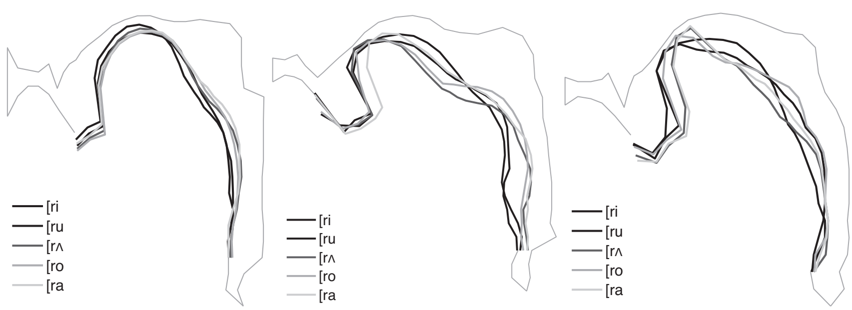

Figure 7. **Subject-specific tongue shaping in rhotic production**: Mean tongue postures captured at consonantal midpoint of onset rhotic production in five vowel contexts. Left: Subject M1 most bunched; Center: Subject M2 most 'frog'-like; Right: Subject M3 most retroflexed.

5.3. Liquid production in low back vowel contexts

For all three subjects, a remarkable lack of tongue movement was observed during the production of liquids in non-high, non-front vowel contexts. Maximal dorsal stability was observed when laterals were produced in [ʌ], [oʊ] and [ɔ] contexts (Fig. 3, bottom row; Fig. 8, top row); and when rhotics were produced in [ɔ] and [ɑ] contexts (Fig. 5, bottom row; Fig. 8, bottom row).

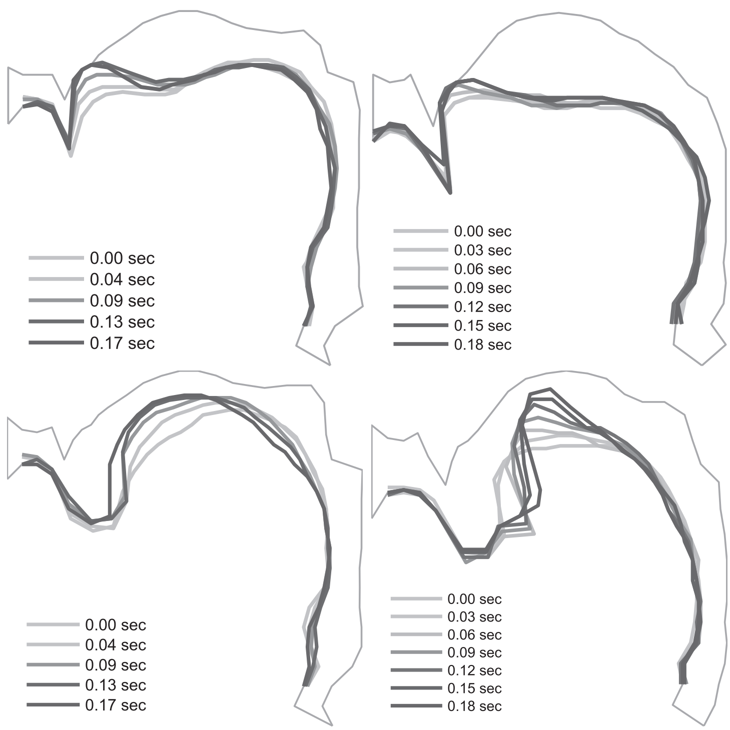

Figure 8. **Coda liquids produced in non-high non-front vowel contexts exhibit maximal dorsal stability**. Top left: [-oʊɫ] (M1); Top right: [-ʌɫ] (M3). Bottom left: [-ɔɹ] (M1); Bottom right: [-ɑɹ] (M3); Midsagittal tongue position captured at 30 msec intervals. Light lines: mid-vocalic; dark lines: mid-consonantal frame.

5.4. Summary of Results

In summary, the key findings of our phonetic study are as follows:

1. Greater differences between onsets and codas – in both dorsal location and global tongue shaping – are observed for /l/ than for /ɹ/.

2. For /l/, there is a continuum of tongue dorsum convergence across different vowel contexts as follows: -VlC]$_\sigma$ > -Vl]$_\sigma$ > $_\sigma$[ClV- > $_\sigma$[lV-.
3. Although there is variation across speakers in their execution of /ɹ/ as bunched or retroflex, within speakers /ɹ/ shows more convergence in its lingual posture across syllabic contexts (onset/coda, simple/complex margin) than /l/ does.
4. In coda position, the target posture of the tongue dorsum during the production of /ɹ/ strongly resembles that of [ɑ] and [ɔ], whereas for /l/, the posture of the tongue dorsum is similar to that observed during the production of [ʌ], [oʊ] and [ɔ].

The asymmetries between liquids indicate that /ɹ/ is more resistant to coarticulatory effects from a tautosyllabic vowel than /l/ is, that is, /ɹ/ is more stable overall in its articulatory posture across different vocalic contexts. This more consistent type of execution for /ɹ/ signals that its tongue shaping properties are more intrinsically dominant than those of /l/, and it is more vowel-like in this regard.

6. Discussion

The data presented in section 5 are problematic for some theories of sonority. English laterals and rhotics involve both coronal and dorsal constrictions. As we discuss below, a view of sonority that is grounded exclusively in overall vocal tract aperture fails to characterize differences in stricture in different regions of the vocal tract that are fundamental to liquids' individual behaviors in different syllable contexts. Also, many other physical properties that have been proposed as the basis for sonority do not explain phonotactic restrictions on vowel-liquid sequences in the rime. Nevertheless, our data suggest some phonetic bases to the phenomena identified in section 2. English laterals and rhotics were observed to have intrinsic articulatory differences, and different ways of interacting with tautosyllabic vowels in different positions in the syllable. We will suggest that these findings have important implications for our understanding of sonority.

6.1. Sonority and Aperture

Some sonority scales group liquids together so that they have the same sonority rank, while others make one or more subdivisions within the class of liquids (Parker 2011). An approach where all liquids have the same sonority value does not necessarily imply that they have a common factor in their articulation, provided the basis for sonority ranking is not defined in articulatory terms;

however, it does predict that liquids will pattern together phonologically with respect to sonority-based phenomena. This prediction is not borne out, at least for Germanic languages. General treatments of the phonological behavior of liquids are offered by Yip (2011) on laterals and Wiese (2011) on rhotics. Both point to phonotactic evidence that the rhotics of Germanic languages (German and English) are more sonorous than laterals.

A long-standing and pervasive idea in the literature is that sonority corresponds to (supralaryngeal) aperture (e.g. Bloomfield 1914; de Saussure 1915; Lass 1984). One issue for an aperture-based view of sonority, at least pertaining to oral occlusion, is that nasals have complete oral occlusion, while fricatives do not, but nasals pattern as higher in sonority than fricatives. A proper quantification of the relative apertures of /l/ and /ɹ/, would require the calculation of tract volume in all dimensions (not just the midsagittal plane), and is therefore beyond the scope of this study. Nonetheless, the data presented here signal that a fuller treatment of the behavior of /l/ and /ɹ/, both within and across different syllabic contexts, requires a more complex characterization of constrictions in the vocal tract than that afforded by a single aperture-based phonetic correlate. Previous research has shown (see section 3), and our study has confirmed, that coronal and dorsal articulations are each fundamental components of /l/ and /ɹ/ in GAE. A comparison of midsagittal strictures formed by the tongue body or root reveals some important asymmetries. We observed pharyngeal stricture to be greater on average for laterals in the rime than for onset laterals (Fig. 4) – a position where laterals are more prone to exhibit phonological behavior associated with high sonority, such as vocalization (Hardcastle and Barry 1989; Sproat and Fujimura 1993). In addition, many laterals were produced by the subjects in this study with mid-oral regions of much greater midsagittal opening than the more evenly constricted rhotics produced in the same contexts (Figs. 4, 6). Predicating sonority purely in terms of overall tract aperture fails to characterize these differences in English liquids.

Despite these shortcomings of *gross* tract aperture as a basis for sonority in complex consonants such as English liquids, coronal stricture does seem to be a correlated factor for some aspects of the phonotactic distribution of these consonants. For the speakers of GAE analyzed in this study, rhotics were typically produced with a more centralized, vowel-like tongue posture, while laterals were produced by the same speakers with a more consonant-like coronal constriction. In most phonological environments, these articulatory differences between rhotics and laterals will typically give rise to measurable differences in many of the physical properties which have been proposed as correlates of sonority, including total acoustic energy (Heffner 1969), band-limited resonant energy (Catford 1977), and relative sound pressure levels (Parker 2008). The differences in degree of coronal constriction observed between English liquids would also place laterals higher than rhotics on the impedance hierarchy proposed by Hume and Odden (1996), by virtue of their increased resistance to supraglottal airflow through the vocal tract.[14] Nevertheless, identifying a single phonetic variable that obtains sonority scaling effects across all languages and phonological patterns has proven difficult, especially when it comes to sonorant consonants (Parker 2008, 2011), and some researchers have questioned this enterprise (e.g. Kiparsky 1979; Ohala 1990; Harris 1994; Wright 2004).

Despite the potential capacity for such correlates to obtain a higher sonority ranking for English /ɹ/ than /l/, it is not clear how they could offer insight on restrictions on tautosyllabic vowel-liquid sequences. In traditional sonority accounts, not every phonotactic pattern is necessarily based in sonority. For example, many languages, English included, exhibit onset clusters /pl-/, /bl-/, /kl-/, /gl-/ but not /tl-/, /dl-/. Rather than being grounded in sonority, this cooccurrence restriction has often been attributed to the obligatory contour principle (OCP) (e.g. Borowsky 1986), that is, a restriction holding over adjacent elements that are identical in some specific respect. Yet the range of restrictions on vowel-liquid sequences do not fall within the scope of the OCP. It is possible that these restrictions have a basis besides sonority or the OCP, but given the extensive role attributed to sonority in explaining phonotactic patterns, it is worth considering whether the concept of sonority could be augmented to obtain them. We will suggest that the intrinsic articulatory properties of liquids are critical to understanding the properties of syllables with post-vocalic liquids and this points to a benefit of a view of sonority that incorporates factors of articulation.

6.2. Intrinsic Liquid Asymmetries

A robust and fundamental difference between the laterals and rhotic approximants analyzed in these data is that they involve different patterns of lingual coordination and gestural control. English lateral production requires the coordination of a central alveolar closure with a dorsal retraction, elongating the tongue along the midsagittal plane and creating side channels for airflow (Ladefoged and Maddieson 1996). The coronal gesture was observed to be largely similar across different contexts in this study in the location and degree of constriction (other than some undershoot or asymmetrical lateralization in some tokens), but the dorsal articulation of laterals varied considerably amongst speak-

14. The same is likely true of the obstruence-based scale, proposed by Clements and Osu (2003), defined in terms of the buildup of oral air pressure. Measurements of intraoral air pressure for segments of English and Spanish are given by Parker (2002).

ers and across syllable position and vowel context. Rhotic production, on the other hand, was found to be more invariant across different phonological environments: the same broad patterns of articulation were observed in all environments, and lingual shaping was shown to be more resistant to coarticulatory effects than for laterals.

These results are consistent with earlier findings on the phonetic characterization of English liquids. Sproat and Fujimura (1993), following Hardcastle and Barry (1989), observed that the dorsal constriction of /l/ varies in both location and timing with respect to the coronal constriction. This differs from the articulatory patterns observed for English /ɹ/, whose constituent gestures, although differing between individuals, appear to be more tightly coordinated in the respect that they vary less in inter-gestural coordination and location according to phonological environment (Delattre and Freeman 1968; Zawadzki and Kuehn 1980).[15]

It has been suggested that liquid consonants are produced with more global control of tongue shape than some obstruents (Proctor 2009). The differences between /ɹ/ and /l/ point to a stricter control of dorsal posture in English rhotic approximants than in laterals, causing /ɹ/ to show greater coarticulatory resistance from a tautosyllabic vowel than /l/. This could be modeled as differences in the weightings that govern the blending of coproduced gestures (Saltzman and Munhall 1989), such that the dorsal gesture for the rhotic is more heavily weighted and that of the lateral less so.

The differences in production of liquids observed in these data also sheds some light on other aspects of their phonological organization. One of the questions that we set out to investigate is why English has fewer vowel contrasts before tautosyllabic /ɹ/ than /l/ (Tables 1–2). If /ɹ/ shows greater resistance to coarticulation, the realization of tautosyllabic vowels will be affected more by the rhotic than the lateral. In rimes that contain a post-vocalic liquid, we therefore expect a greater range of vowel qualities to occur preceding a lateral. This predicts that pre-rhotic vowels should be more vulnerable to reduction of contrast than those that precede a lateral.

The observed articulatory configuration and stability for /ɹ/ also aligns with its greater propensity to function as syllabic across languages (Bell 1978). We

15. The issue of timing has not been addressed in this paper, primarily because the temporal resolution of the rtMRI data presented here does not allow for fine quantification of articulatory coordination. Although initial analyses do not reveal any duration differences between the liquids elicited in these tokens, it may be the case that there are fine differences in timing, not evident at these frame rates, which have a bearing on the relative sonority of rhotics and laterals and their differential behaviors in onsets and codas.

found that /ɹ/ is overall more vowel-like in its production than /l/. In particular, it tends to show a lesser degree of coronal constriction, both its coronal and dorsal gestures involve approximant-type stricture, that is, a constriction degree that is wider than that of a fricative, and it exhibits a more intrinsically dominant tongue shape in coproduction.

Another question that we sought to investigate was what determines which vowels survive before rhotics and laterals that are part of a complex coda in English. The articulatory data acquired in this study reveal a close resemblance in the posture of the tongue dorsum between /ɹ/ and the vowels /ɑ/ and /ɔ/ (Figs. 5, 8); and likewise for /l/ and the vowels /ʌ/, /ɔ/, and /oʊ/ (Figs. 3, 8), consistent with the findings of Gick, Kang and Whalen (2002) and Giles and Moll (1975). These results indicate that the vowel qualities that occur or are favored before a liquid-initial complex coda are influenced in part by the particular tongue shape of each liquid. Before /ɹ/, the vowels [ɑ] and [ɔ] are most frequent (Table 3), and are essentially the only possible vowels (excluding syllables closed with a coronal obstruent: Table 1). This contrast is consistent with a dorsal posture approximating a non-high back vowel with differentiation in lip rounding. Before /l/, [ʌ], [ɔ] and [oʊ] are amongst the most frequent vowels exploited in English phonotactics – nuclei whose targets are compatible with the articulatory characterization of English laterals suggested by the data presented in section 5.1.1.[16] However, unlike in rhotic codas, a greater subset of vowels are also attested in the pre-lateral context (Table 2). This difference in the range of vowel contrasts preceding the rhotic and lateral is consistent with /l/ presenting weaker coarticulatory resistance in its coproduction with the preceding vowel.

6.3. The Structure of Rimes with Liquids

Aside from various differences found in the phonotactic properties of English rhotics and laterals, liquids as a class show shared behavior in their organization in syllable structure, which we turn to next.

One of the questions driving our investigation is why vowel contrasts are reduced when a post-vocalic liquid is followed by another consonant in the rime. We have already discussed why certain vowel qualities are favored before particular liquids, but not why fewer vowel contrasts would occur before liquids in general when they belong to a complex coda. The contrast reduction

16. Almost all -lC coda clusters preceded by [ɔ] and [oʊ] end in a coronal obstruent. This is because /l/ underwent vocalization in early Modern English when preceded by these vowels and followed by a non-coronal consonant, as in words like *talk* and *folk* (Borowsky 2001).

is consistent with a greater overlap in the articulations of the liquid and tautosyllabic vowel in this context. This increase in articulatory overlap was evidenced most clearly in our comparison of the production of /l/ across different syllabic contexts: we found that the articulatory dorsal posture for /l/ showed greatest convergence with that of the tautosyllabic vowel when /l/ was post-vocalic and followed by another consonant in the rime (section 5.1.1).

The continuum in convergence for the tongue dorsum posture in /l/ and a tautosyllabic vowel across onset/coda and simple/clustered contexts (Fig. 4) points to a less clear-cut boundary between a nuclear vowel and consonants in the syllable margin than a traditional syllabic structure consisting of an onset, nucleus, and coda (and perhaps a rime) would suggest. Our data reveal that liquids that are traditionally analyzed as belonging to the onset or coda encroach more on the nucleus when they belong to a complex syllable margin rather than a simple one, and in post-vocalic context this encroachment has effects on the vowel's contrast. Understanding the reduction in vowel contrast preceding a liquid-initial complex coda involves reference to the mechanics and timing of the coproduction of liquids and tautosyllabic vowels. We leave as an open question whether such details of the scheme for speech production should be part of the phonological representation of syllables (e.g. Saltzman and Munhall 1989; Browman and Goldstein 1989; Nam, Goldstein and Saltzman 2009). Certainly, traditional approaches to syllable structure cover a considerable extent of phonological patterns pertaining to syllables. However, the vowel contrast effects in question suggest the possibility that aspects of the architecture for syllables be augmented so as to take into account the different coordination of consonants belonging to simple and complex margins. Segmental organization in the syllable periphery has been modeled in terms of gestural coordination and recoverability (Browman and Goldstein 1995, 2000; Chitoran, Goldstein and Byrd 2002), which has proven fruitful in accounting for asymmetries between onset and coda clusters, as well as typological differences in phonotactic structure.

A related issue concerns whether post-vocalic liquids in a syllable rime actually belong to the syllable coda or the nucleus. The latter organization is proposed in treatments of tautosyllabic vowel-liquid sequences as diphthongs, like those of Harris (1994) and Green (2001), mentioned above. Other research supporting the organization of liquids into the syllable nucleus in English includes MacKay (1978), Stemberger (1983) and Treiman (1984). Our data demonstrate the capacity of post-vocalic liquids to produce considerable coarticulatory effects in a preceding vowel, and post-vocalic liquids produced greater effects than pre-vocalic liquids. These data indicate that post-vocalic liquids form a closer relationship with the vowel in their production; whether this warrants characterizing post-vocalic liquids as forming part of a diphthong within the nucleus is a question that we leave for further research. On this matter it is interesting that the largely overlapped vowel-liquid sequences in our data did not seem to demonstrate a marked articulatory transition, as is usually seen with vocoid-based diphthongs. Rather, the vowel and liquid tended to converge on similar articulatory postures, especially for the tongue dorsum, minimizing the transition (Figs. 3, 5, 8). This suggests a coalescence of the vowel and following liquid, possibly with blending of their gestures, rather than realization as a sequential diphthong.

Further research on the question of diphthongization or coalescence has the potential to find connections with research on the phonology of glides that concludes they are gesturally complex and involve a dorsal articulation. Nevins and Chitoran (2008) propose that [j] is characterized by coronal and dorsal articulations, whereas [w] involves labial and dorsal articulators. Levi (2008) also hypothesizes a dorsal articulation for glides that are derived from vowels. The evidence our study has found in support of liquids fundamentally involving both coronal and dorsal strictures suggests an affinity with glides and vowels in the approximant-like dorsal component of their articulation. We regard this property as key in understanding these high sonority segments' relative compatibility with the syllable nucleus.

7. Conclusion: The Outlook for Sonority

In this chapter, we have presented evidence for an articulatory basis to some phonotactic properties of English syllable structure, characteristics that have traditionally been attributed to differences in sonority. Our rtMRI data suggest that phonotactic constraints on liquid codas result in part from the felicity with which the intrinsic tongue body gestures of the liquid consonants can combine with those of the tautosyllabic vowels. Under this account, the fact that there are more restrictions in English on rimes containing rhotics, compared to lateral codas, is consistent with the articulatory characterization of English /ɹ/ as more intrinsically vocalic than /l/. The reduction of vowel contrasts before a liquid-initial complex coda is consistent with our finding of greater articulatory overlap between the vowel and liquid in this context. Furthermore, the vowel qualities that are prone to survive in this context are those that largely align with the dorsal posture of the tongue for the following liquid.

These phonotactic properties of liquids in rimes of English are not well explained by traditional approaches to sonority where it stands as a single hierarchical property of segments. While such approaches can often obtain some of the broad sequencing effects, they miss the mark when it comes to many of the systematic nuances in the relationship between the vowel and following liquid. These include sequencing restrictions in syllables with complex codas, asymmetries in the number of vowel contrasts that are supported before /l/ versus /ɹ/, and the particular vowel qualities that are sustained in the context of particular liquids. These gaps can be filled by taking into consideration the interaction of several factors, namely, the characteristic lingual articulations of English liquids, especially their dorsal component, the degree of their stricture, intrinsic differences in the articulatory stability of /ɹ/ versus /l/, and the coordination of gestures within a rime. If, in accounting for the phonotactics of English syllables, we need to supplement the traditional view of sonority in this way, it is worth asking whether our understanding of sonority should be revisited by taking into account more articulatory factors. We propose that the development of an expanded concept of sonority, informed by phonetic data and capable of explaining a greater range of phonological phenomena, is a worthy pursuit.

Appendix: List of Experimental Stimuli

hee leap hee	hee reap hee	hee peel hee	hee beer hee
ha lob ha	ha rob ha	ha ball ha	ha bar ha
who loop who	who room who	who pool who	who moor who
hoe lobe hoe	hoe robe hoe	hoe pole hoe	hoe bore hoe
hum love hum	hum rum hum	hum hull hum	her fur her
hee bleep hee	hee brief hee	hee film hee	hee beard hee
ha plop ha	ha prop ha	ha solve ha	ha barb ha
who plume who	who prove who	who wolf who	who cured who
hoe blow hoe	hoe probe hoe	hoe Rolf hoe	hoe form hoe
hum plum hum	hum from hum	hum pulp hum	her firm her

Abbreviations

C	consonant
GAE	General American English
kHz	kilohertz
L	liquid consonant
mm	millimeter
MRI	magnetic resonance imaging
msec	millisecond
NY	New York
OCP	Obligatory Contour Principle
rtMRI	real-time magnetic resonance imaging
t	time
V	vowel
WI	Wisconsin

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