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The Organization and Structure of Rhotics in American English Rimes*

Language-specific maximal size restrictions on syllables have been defined using frames such as moraic structure. In General American English, a trimoraic syllable template makes largely successful predictions about contexts where tense/lax vowel contrasts are neutralized, but neutralization preceding a coda rhotic has not been adequately explained. We attribute the apparent special properties of coda /ɹ/ to two characteristics of its representation, informed by our articulatory investigation: sequential coordination of dorsal and coronal subsegmental units and a high blending strength specification, corresponding to high coarticulatory dominance. Phonological and articulatory characteristics of coda laterals are compared. Representations that encode respective coordination and strength of subsegmental units allow for configurations that reflect differences and shared properties across rimes with coda liquids. In this framework, mora assignment is computed over the sequencing of subsegmental units, predicting that complex segments may be bimoraic. Our account brings phonotactics for rimes with post-vocalic liquids in line with the trimoraic syllable template. It provides support for a view of phonological structure where sequencing and overlap are represented at the subsegmental level, and phonological coordination patterns are sensitive to blending strength.

1. Introduction

Syllables show language-specific size restrictions that characterize upper limits on their constituents. Such restrictions have been characterized as syllable templates, defined by a frame such as moraic structure or CV skeletal slots. A variety of phenomena have been attributed to enforcement of a syllable template in numerous languages, including closed syllable vowel shortening, degemination, epenthesis and deletion (Clements & Keyser 1983, Itô 1986, 1989, Archangeli 1991, Zec 1995).

In General American English, this kind of syllable template has similarly served as a tool for understanding limits on syllable size and cooccurrence restrictions on tautosyllabic vowels and coda consonants. A template defined by a trimoraic maximum has been employed to explain the absence of bimoraic nuclei, i.e. tense vowels and diphthongs, in syllables with a complex coda (Hammond 1999, Hall 2001, 2002). These studies note that this restriction on nuclei is not observed with complex codas ending in a coronal obstruent, which may be nonmoraic. Syllables with coda /l/ show the expected extent of maximum constituency, as illustrated in (1a) with syllables containing high front vowels. Both tense and lax vowels are possible before a simple coda /l/, but before a complex coda with /l/ followed by a noncoronal consonant, the vowel is necessarily lax (monomoraic). A syllable with a tense vowel and complex coda, such as **meelk*, is excluded because it would amount to four moras. However, the possible vocalic nuclei in syllables with coda /ɹ/ show more extreme restrictions, as illustrated in (1b). Tense/lax vowel contrasts among high front vowels are neutralized before a simple coda with /ɹ/, and all high front vowels are excluded before a complex coda containing /ɹ/ and a noncoronal consonant. In fact, before a complex coda with post-vocalic /ɹ/ and a noncoronal coda, only two distinctive vowel qualities are possible in General American English: [ɑ], as in *park*, and [ɔ], as in *pork*.

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(1) a. High front vowels before coda /l/ (mora count for rime in parentheses)

	Simple coda	Complex coda
Tense [i]	*peel* (3μ)	—
Lax [ɪ]	*pill* (2μ)	*milk* (3μ)

b. High front vowels before coda /ɹ/

<table>
<tr><th></th><th>Simple coda</th><th>Complex coda</th></tr>
<tr><td>Tense [i]</td><td rowspan="2">peer</td><td rowspan="2">—</td></tr>
<tr><td>Lax [ɪ]</td></tr>
</table>

These asymmetries in the phonotactics of syllables with coda liquids in General American English are the focus of this paper. While the neutralization of tense/lax vowel contrasts before /ɹ/ in General American English is well known, the motivation for this neutralization has not been adequately accounted before in the context of the syllable template, nor is it well understood in general. Furthermore, while previous studies have suggested an articulatory basis for the vowel qualities that may precede a complex coda with /ɹ/ (Proctor & Walker 2012, Walker & Proctor 2013), the severe reduction of vowel contrasts in this context has not been situated in a comprehensive formal account. In this paper, we leverage the trimoraic syllable frame to understand why rimes with coda /ɹ/ show these restrictions in comparison to coda /l/, despite overarching properties that are common to both liquids. We suggest that more extreme phonotactic restrictions on rimes with coda /ɹ/ are connected to the combined complex structure of this consonant and its intrinsic high coarticulatory strength. We propose that when these characteristics are properly taken into account in the phonological representation, various restrictions on vowel contrasts in rimes with coda /ɹ/ follow from a trimoraic maximum.

While our specific goal for this study is to understand the structure of syllables with post-vocalic liquid consonants in General American English, our larger goal is to contribute on several key issues involving the phonological representation of consonants, vowels, and quantity. As to the representation of complex segments, we recognize complexity on two fronts: SPATIAL COMPLEXITY, involving multiple place constrictions – corresponding to multiple subsegmental units – and TEMPORAL COMPLEXITY, involving a controlled sequencing of those subsegments. Henceforth, we will use "subsegments" to refer to the atomic units of which segments are composed, corresponding to the level represented by gestures or features. In the case of coda liquids in General American English, a dorsal articulation precedes a coronal articulation (Sproat & Fujimura 1993, Browman & Goldstein 1995, Proctor et al. 2018). This is an instance of temporal control, which more generally may take the form of abstract sequencing or synchrony over subsegments. Such control falls under the rubric of COORDINATION relations, operating directly at the level of subsegments (Browman & Goldstein 1986 et seq.), rather than at the segmental level, as in traditional approaches where root nodes govern temporal sequencing of segments and their dependent features (e.g. Clements 1985, Sagey 1986). The assignment of moras to coda consonants in our account is computed over sequential coordination among subsegments, giving rise to the possibility that temporally complex segments may be bimoraic.

The coordination of subsegments can cause overlap such that there are competing demands on articulators, as, for instance, in the case of overlap between the dorsal component of a coda liquid and that of a preceding vowel. We find support for a phonological organization of subsegments in the syllable that is sensitive to the relative STRENGTH of these competing demands and the resulting predictions for realizing vowel contrasts. We incorporate this property into the account by appealing to the concept of a specified blending strength of a subsegment, corresponding to its degree of coarticulatory dominance, as represented in a gestural approach to subsegmental representation (Saltzman & Munhall 1989, Fowler & Saltzman 1993). The degree of specified blending strength is informed by our articulatory study of liquids in General American English. We show that the coordination and strength of subsegments interact in critical ways in rimes with coda liquids. This approach both differentiates the phonotactics of rimes with post-vocalic rhotics versus laterals and incorporates what they share in common. In the larger picture, it provides a framework for representing complex segments and their potential for partial overlap with neighboring segments.

The organization of this paper is as follows. In §2 we discuss the trimoraic syllable template for General American English. We identify phonotactic predictions and identify where they appear to fall short for rimes with post-vocalic /ɹ/. In §3 we review background on the articulation of liquid consonants in General American English; we present phonetic evidence from a study on the relative coarticulatory dominance of the rhotic versus lateral, and we examine how rhotics and laterals coarticulate with vowels of different qualities in the rime. In §4 we present our analysis of rimes with post-vocalic liquids. Framed within gestural representations, our account posits that the nuclear vowel and dorsal gesture of the lateral regularly overlap, while the organization of the vowel and dorsal gesture of the rhotic depends on the vowel and its degree of similarity to the rhotic posture. As a result, a coda lateral typically gives rise to a single mora, but a coda rhotic gives rise to a single mora in some contexts and two moras in others. In the latter contexts it produces stronger neutralizing effects on the preceding vowel than other coda consonants. In §5 we discuss potential extensions to other patterns, and in §6, we present the conclusion.

2. The trimoraic maximum for General American English syllables

The dictates of a syllable template together with assumptions about segments' moraic contribution and sonority sequencing play a large part in explaining intrasyllabic phonotactics in many accounts of syllable structure. Our focus is on General American English (GenAm for short), which refers to the majority of rhotic American English varieties, such as those spoken in the American Midwest and the western United States (Wells 1982). Our discussion of phonotactic distributions in GenAm rimes with post-vocalic liquids is based chiefly on Hammond (1999) and Proctor & Walker (2012) and is confirmed by our consultation with native speakers. Additional sources are cited where applicable.

As mentioned above, GenAm syllables have been proposed to allow a maximum of three moras. "Superheavy" syllables, which contain the three-mora maximum, are positionally limited; Hall (2001, 2002) characterizes their distribution as final in the prosodic word. Our exemplification of phonotactic distributions concentrates on monosyllables, which is a context where the full range of phonotactic contrasts are evidenced. Moraic structure also has implications for stress assignment; see Hammond (1999) for an analysis of English stress with syllables that may be maximally trimoraic.

For GenAm the standard assumptions are that lax vowels are monomoraic (/ɪ, ɛ, æ, ʌ, ʊ/), while tense vowels and "true" diphthongs are bimoraic (/i, e, u, o/, /aj, aw, ɔj/) (Halle & Mohanan 1985, Hammond 1997). The vowels [ɑ] and [ɔ] show broader patterns of distribution, and may occur variously both in certain contexts where only lax/short vowels are permitted or where only tense/long vowels are allowed (Halle & Mohanan 1985, Green 2001a). Relevant for this study is that [ɑ] and [ɔ] show a distribution like that of monomoraic vowels in many closed syllable contexts of GenAm.

For consonants, the usual assumption is that each coda consonant contributes a mora with the exception of final coronal obstruents, which have the potential to be nonmoraic (e.g. Hall 2002). The special status of final coronal obstruents has been attributed to their capacity to belong to a nonmoraic syllable-final appendix when the trimoraic frame is exhausted (Hall 2002). Discussion of GenAm codas in this paper will refer only to those that do not end in a coronal obstruent, unless otherwise indicated. Nevertheless, in the future it would be valuable to examine the privileged status of coronal obstruents in light of the representations we employ here.

Apart from syllables that end in a coronal obstruent, the predictions for GenAm that emerge from the trimoraic maximum and hypothesized moraic contributions for vowels and consonants are that both monomoraic and bimoraic vocalic nuclei may occur in a rime with a simple coda, while only monomoraic vowels may occur in a rime with a complex coda. These predictions are generally borne out, as illustrated for codas containing /l/ in (2). All contrastive stressed vowels and falling diphthongs of GenAm are listed. The hypothesized number of moras for each vowel or diphthong is shown in the second column. Vowel transcriptions are based on Hammond (1999) and the Carnegie Mellon University Pronouncing Dictionary for North American English (Weide 1994) with edits and corrections by Bruce Hayes (henceforth CMUD).[1] We consider the rime in *furl* to be produced with /l/ preceded by a rhotic vowel [ɝ] or syllabic [ɹ̩] (e.g. Giegerich 1992, Ladefoged & Maddieson 1996, Ladefoged & Johnson 2015). Distributionally, [ɝ] patterns as bimoraic (Hammond 1999): it can occur before a singleton coda, as in *furl* or *firm*, but not before a final cluster (e.g. **firmp*). Because there is not a detectable V[ɹ] sequence here, we do not treat bimoraic [ɝ] as qualitatively decomposable, at least in its surface form. Shaded cells in (2) lack an attested form with the vowel quality in question. Where words are repeated in more than one cell, they are listed as variants in the CMUD. This is often the case for [ɑ] and [ɔ], whose contrast is weak and/or frequently neutralized in GenAm, especially in areas outside of the eastern United States (but including Pittsburgh) (Wells 1982: 473). As expected, the full range of vocalic contrasts is attested before a simple coda containing /l/. In a rime with a complex coda, no vowel or diphthong that is expected to exceed one mora is attested.

Despite the success of the trimoraic syllable template in explaining the absence of various vocalic contrasts in rimes with a complex coda, phonotactic restrictions on vowels in rimes with /ɹ/ appear to be considerably under-predicted, and they are quite striking when compared alongside those with coda /l/. As shown in (2), tense/lax contrasts are neutralized before a simple coda with /ɹ/. Before a complex coda with /ɹ/, only [ɑ] and [ɔ] are attested, a distributional restriction highlighted by Proctor & Walker (2012) and Walker & Proctor (2013). (We characterize the round vowel realization in this context as [ɔ], because it is monophthongal.)

(2) Vocalic contrasts preceding coda liquids

<table>
<tr><th rowspan="2">Vowel/ diphthong</th><th rowspan="2">Nuclear µs</th><th colspan="2">Coda /l/</th><th colspan="2">Coda /ɹ/</th></tr>
<tr><th>CVl]σ</th><th>CVlC]σ</th><th>CVɹ]σ</th><th>CVɹC]σ</th></tr>
<tr><td>[i]</td><td>2</td><td>peel</td><td></td><td rowspan="2">peer</td><td></td></tr>
<tr><td>[ɪ]</td><td>1</td><td>pill</td><td>milk</td><td></td></tr>
<tr><td>[eɪ]</td><td>2</td><td>pail</td><td></td><td rowspan="2">pair</td><td></td></tr>
<tr><td>[ɛ]</td><td>1</td><td>bell</td><td>elk</td><td></td></tr>
<tr><td>[æ]</td><td>1</td><td>pal</td><td>scalp</td><td></td><td></td></tr>
<tr><td>[ʌ]</td><td>1</td><td>mull</td><td>bulk</td><td></td><td></td></tr>
<tr><td>[ɝ]</td><td>2</td><td>furl</td><td></td><td></td><td></td></tr>
<tr><td>[ɑ]</td><td>1</td><td>pall</td><td>golf</td><td>bar</td><td>park</td></tr>
<tr><td>[ɔ]</td><td>1</td><td>pall</td><td>golf</td><td rowspan="2">bore</td><td>pork</td></tr>
<tr><td>[oʊ]</td><td>2</td><td>pole</td><td></td><td></td></tr>
<tr><td>[ʊ]</td><td>1</td><td>pull</td><td>wolf</td><td rowspan="2">boor</td><td></td></tr>
<tr><td>[u]</td><td>2</td><td>pool</td><td></td><td></td></tr>
<tr><td>[aj]</td><td>2</td><td>pile</td><td></td><td>pyre</td><td></td></tr>
<tr><td>[aw]</td><td>2</td><td>fowl</td><td></td><td>hour</td><td></td></tr>
<tr><td>[ɔj]</td><td>2</td><td>boil</td><td></td><td></td><td></td></tr>
</table>

Transcription of the vowel quality before simple coda /ɹ/ varies across scholars (e.g. Kenyon & Knott 1953, Wells 1982, Giegerich 1992, Hammond 1999, Ladefoged & Johnson 2015). The

[1] The edited dictionary is available at http://www.linguistics.ucla.edu/people/hayes/251English/index.htm#dictionary. It was last downloaded on October 3, 2011.

phonetic characterization of tense versus lax vowels in English is a vexed issue (Halle 1977). What is important for our aims is that the tense/lax contrast in GenAm is correlated with a phonological distinction in quantity, and tense/lax neutralization correlates with a lack of quantity contrast. We take up phonological representation in §4. Meanwhile we use "tense" and "lax" as classificatory labels.

The vowel neutralization effects witnessed in GenAm before /ɹ/ cannot be attributed to vowel-/ɹ/ sequences in general. While some reduction of vowel contrasts also occurs before intervocalic [ɹ], the most extreme reduction occurs preceding coda /ɹ/, with the strongest effect before complex codas. Contrast reduction before intervocalic [ɹ] is weaker and more variable across regions where GenAm is spoken. For instance, some GenAm speakers (but a minority) maintain a three-way vowel contrast before /ɹ/ in [meᶦɹi] *Mary*, [mɛɹi] *merry* and [mæɹi] *marry*. Others neutralize the pre-rhotic vowel in the first two words to [ɛ], i.e. [mɛɹi] corresponds to both *Mary* and *merry*. For still other speakers, all three words are homophonous (Wells 1982: §6.1.5). Furthermore, /ɹ/ does not have the same effects across a morpheme boundary within a word or internal to a compound. For instance, the first vowel in *de-restrict* and *key#ring* is [i], distinct in quality from the neutralized high front vowel in the first syllable of *clear-ing*, where the vowel-/ɹ/ sequence is not separated by a morpheme boundary (Wells 1982: 481, 2008: 223). Prosodic organization therefore appears to be an important factor in determining the contexts for restrictions on Vɹ. We focus on vocalic neutralization before unambiguous coda consonants, where neutralization is most severe.

A further observation is that liquids do not generally induce neutralizing effects on a following vowel. Almost all vocalic contrasts are attested following a complex onset containing a liquid, as shown in (3) for onsets [kl] and [kɹ] (but [bɹ] is used for the onset with a rhotic preceding [ɔj]). This pattern is consistent with the assumption that onset consonants in GenAm are not moraic.

(3) Vowel contrasts following a complex onset with a liquid

Vowel/diphthong	[ClV(C)]σ	[CɹVC]σ
[i]	*clean*	*creep*
[ɪ]	*clip*	*crib*
[eᶦ]	*claim*	*crate*
[ɛ]	*cleft*	*crest*
[æ]	*clap*	*crab*
[ʌ]	*club*	*crumb*
[ɝ]	*clerk*	
[ɑ]	*clock*	*crop*
[ɔ]	*cloth*	*crawl*
[oᵘ]	*cloak*	*croak*
[ʊ]		*crook*
[u]	*clue*	*crude*
[aj]	*climb*	*crime*
[aw]	*cloud*	*crowd*
[ɔj]	*cloy*	*broil*

The neutralizations before coda /ɹ/, namely, (i) loss of tense/lax contrasts, and (ii) greater neutralization before a complex coda, are of the very kind we could expect from a template imposing a limit on syllable size. However, if coda /ɹ/ is monomoraic, a trimoraic upper limit does not predict vocalic neutralization to the extent attested. Like rimes with coda /l/, all vocalic contrasts would be expected to be possible before simple coda /ɹ/, while all monomoraic vowels would be expected before a complex coda. If coda /ɹ/ were instead bimoraic, neutralization of tense/lax contrasts before simple coda /ɹ/ would be expected, assuming that the neutralized vowels are monomoraic. This is the approach that we will pursue here. Nevertheless, a two-fold challenge for a bimoraic representation of /ɹ/ is understanding why syllables like *park* and *pork* do not exceed three moras, and why ɹC codas are possible only with [ɑ] and [ɔ]. These are the chief questions that we tackle in this paper, along with why /ɹ/ would behave as bimoraic. We examine articulatory evidence to inform the phonological representation of GenAm rimes with liquids with the aim of understanding both why rimes with /ɹ/ show these distributions, and why those with /l/ are different.

A further issue is that rimes with a true diphthong before a bimoraic coda /ɹ/ would amount to four moras. In fact, forms with a diphthong plus coda /ɹ/ are particularly prone to give rise to syllable count judgments that amount to more than one syllable (Lavoie & Cohn 1999, Cohn & Tilsen 2015). Lavoie and Cohn refer to syllables with variable count judgments as "sesquisyllables." Such judgments have been attributed to the presence of an extra mora in the rime (Lavoie & Cohn 1999, Cohn 2003), which could be consistent with a bimoraic approach to coda /ɹ/. However, sesquisyllables present complexities: judgments are variable, it is not clear whether sequisyllabicity is a gradient characteristic, and similar effects are found with coda /l/. While sesquisyllables are not the focus of this paper, they show promise to fit within the general approach we propose, as we discuss in §5.

3. The articulation of liquids in General American English

Previous research on English /ɹ/ has revealed its complexity along two dimensions. It is spatially complex because it involves multiple constrictions, and it is temporally complex because these constrictions are not always synchronous.

The articulation of English rhotics shows considerable variation across individuals and environments (Delattre & Freeman 1968, Zawadzki & Kuehn 1980, Hagiwara 1995, Westbury et al. 1998, Guenther et al. 1999, Zhou et al. 2008, Mielke et al. 2010, 2016). Nevertheless, rhotic production typically involves three coordinated components: a labial constriction and two lingual constrictions, of which one is coronal and one pharyngeal. Our focus is on the lingual constrictions. The coronal constriction varies across (at least) three broad categories of execution, involving retroflexion or tip-up or tip-down bunching (Espy-Wilson et al. 2000, Gick et al. 2003), and ranges in location from alveolar to palatal (Zhou et al. 2008; Alwan et al. 1997). The pharyngeal constriction engages the posterior part of the tongue dorsum or the tongue root (Delattre & Freeman 1968, Alwan et al. 1997, Gick 2002). The magnitude and timing of articulations is sensitive to the position of the rhotic in the syllable. In a study of Canadian English speakers, Campbell et al. (2010) found that in syllable-final rhotics, the pharyngeal constriction preceded the coronal constriction, which had a reduced magnitude. In syllable-initial context, the tip-blade articulation preceded the pharyngeal constriction, and the lingual articulation in the pharyngeal region was reduced.

These asynchronous multi-constriction properties of coda /ɹ/ may bear on its potential to pattern as bimoraic in the syllable template; like bimoraic consonant clusters, /ɹ/ would involve a sequence of articulations. In turn, a weight-occupying articulatory sequence for coda /ɹ/ would enforce a monomoraic nuclear vowel, which would explain neutralization of the quantity-related tense/lax contrast before /ɹ/. Nonetheless, sequential production of component lingual constrictions in a coda consonant does not always correlate with the expected pattern for bimoraic status in GenAm rime phonotactics. First, a complex coda with /ɹ/ is possible after [ɑ] and [ɔ] (as in *park*, *pork*), which seems to indicate that /ɹ/ adds only a single mora to rimes with these vowels. In other words, it seems as if the weight contribution of coda /ɹ/ is sensitive to the quality of the preceding vowel. This could be related to the finding of Proctor & Walker (2012) that the posterior articulation of /ɹ/ resembles that of [ɑ] and [ɔ]. Second, production of GenAm /l/ in coda also involves sequential lingual constrictions, but tense/lax vowel contrasts are maintained before coda /l/, suggesting that /l/ adds just one mora in these contexts.

English laterals resemble rhotics in their spatial and temporal complexity. Similar to /ɹ/, /l/ involves dual lingual constrictions: a coronal consonant-like tongue-tip raising and a vowel-like tongue body retraction in the velar, uvular or pharyngeal region (Giles & Moll 1975, Sproat & Fujimura 1993, Browman & Goldstein 1995, Gick 1999a). In coda laterals, the formation of the tongue body constriction precedes the tongue tip constriction (Sproat & Fujimura 1993, Browman & Goldstein 1995, Krakow 1999, Gick et al. 2006, Scobbie & Pouplier 2010). For some varieties of English, the coronal constriction of coda laterals is (variably) reduced in magnitude, so that the lateral may be 'vocalized' (Gimson 1980, Wells 1982, Hardcastle & Barry 1989). Yet despite these broad similarities in the organization of multiple articulations in coda rhotics and laterals, they do not show identical patterning with respect to quantity-related neutralization in the rime. Relevant to this, a qualitative comparison of rhotic and lateral production, based on a study of three speakers of GenAm, has suggested that rhotics show more convergence in lingual posture across vowel and syllable contexts than laterals (Proctor & Walker 2012).

Summing up the discussion thus far, we find that the neutralizing effects of lingual constriction sequencing in the rime vary with the particular liquid as well as the preceding vowel in question. Specifically, a greater propensity for vocalic neutralization is found before /ɹ/ than /l/, and the weight contribution of coda /ɹ/ appears to be lesser following the vowels [ɑ] and [ɔ].

To shed more light on the surrounding issues, we conducted a real-time structural magnetic resonance imaging (rtMRI) study to further investigate the articulatory properties of rhotics and laterals in different syllabic positions in GenAM (Proctor et al. 2018). The findings of this investigation are important for our phonological analysis, because they inform us about the temporal and spatial properties of the vocal tract constrictions involved in GenAm liquids as well as the coarticulatory interaction between vowels and different liquids in onsets and codas. Therefore, the study is briefly summarized here.

Rhotic and lateral consonants were elicited from four native speakers of GenAm in simple onsets and codas in CVC words. The experimental corpus included all phonotactically possible combinations of vocalic nuclei adjacent to a liquid in a syllable margin (4). In addition to words with a liquid onset or coda, the same vowels were elicited in monosyllabic contexts where both onset and coda were labial or labiodental.[2]

(4) Stimuli for experimental corpus

<table>
<tr><th>Vowel</th><th>σ[ɹ</th><th>ɹ]σ</th><th>σ[l</th><th>l]σ</th><th>Interlabial</th></tr>
<tr><td>/i/</td><td>reap</td><td rowspan="2">beer</td><td>leap</td><td>peel</td><td>beep</td></tr>
<tr><td>/ɪ/</td><td>rip</td><td>lip</td><td>pill</td><td>bib</td></tr>
<tr><td>/e/</td><td>rave</td><td rowspan="2">bare</td><td>lame</td><td>bail</td><td>babe</td></tr>
<tr><td>/ɛ/</td><td>rep</td><td>Lev</td><td>bell</td><td>pep</td></tr>
<tr><td>/æ/</td><td>rap</td><td></td><td>lap</td><td>pal</td><td>bam</td></tr>
<tr><td>/ʌ/</td><td>rum</td><td></td><td>love</td><td>mull</td><td>pub</td></tr>
<tr><td>/ɑ/</td><td>rob</td><td>bar</td><td>lob</td><td>ball</td><td>bob</td></tr>
<tr><td>/ɔ/</td><td></td><td rowspan="2">bore</td><td></td><td></td><td></td></tr>
<tr><td>/o/</td><td>robe</td><td>lobe</td><td>pole</td><td>foam</td></tr>
<tr><td>/ʊ/</td><td></td><td rowspan="2">boor</td><td>loof</td><td>pull</td><td>boof</td></tr>
<tr><td>/u/</td><td>rube</td><td>loop</td><td>pool</td><td>boom</td></tr>
</table>

The entire vocal tract was imaged in the midsagittal plane using rtMRI (Narayanan et al. 2004, Bresch et al. 2008) while participants produced each word in the corpus. Tongue postures were compared

[2] Empty cells in (4) correspond to contexts that lacked a reliable contrast for our speakers. Three of our participants reported a full or partial merger of back round vowels to [ɔ] before coda /ɹ/. Nevertheless, they attempted to produce *boor* with a vowel approximating a high back vowel. In this monosyllabic corpus, onset position is conflated with word-initial position and coda position is conflated with word-final position. The extent to which the results generalize to word-medial syllables remains for future investigation.

at key articulatory landmarks: i) rhotic coronal target, ii) rhotic dorsal target, iii) rhotic labial target, iv) lateral coronal target, v) lateral dorsal target, vi) vowel target adjacent to each liquid, and vii) interlabial vowel target. Consonant targets were defined to be the image frame in which the maximal constriction was achieved by the articulators associated with the gesture of interest; vowel targets were located at the center of the stable interval of dorsal articulation associated with the primary vocalic lingual goal. "Dorsal" is used broadly here to include the posterior lingual articulation of the rhotic. We review three key sets of findings from this study: i) articulatory coordination, ii) tongue dorsum posture in coda rhotics and preceding vowels, and iii) cross-positional stability and coarticulation.

First, articulatory coordination in these liquids in large part followed the same patterns that have previously been reported. In coda rhotics, the dorsal target preceded the coronal target. No evidence of a labial constriction was found in coda rhotics. In onset rhotics, the labial target was reached prior to the coronal and dorsal targets, and the latter two targets were synchronous. In coda laterals, the dorsal target was achieved before the coronal target, but in onset laterals the reverse order was found. In coda laterals, tongue tip closure was often not achieved, resulting in (semi-)vocalized productions. Despite these commonalities, both rhotic and lateral consonants showed speaker-specific postures: the specific location of the coronal and dorsal constrictions varied, as did the degree of bunching or retroflexion of the tongue in rhotics.

Second, lingual articulation for liquids was examined in different vowel contexts. Due to our focus on rimes with /ɹ/, we concentrate here on the posture of the tongue in the pharyngeal region during coda rhotics and preceding vowels. Overall, less movement was observed from non-high back vowels [ɑ] and [ɔ] into the pharyngeal constriction for the rhotic than from other peripheral vowels, confirming the observations of Proctor & Walker (2012). However, some speaker-specific variation was found in the location of tongue dorsum constriction in the rhotic and the vowel. Lesser movement between non-high back vowels and the rhotic pharyngeal constriction could be expected, because these vowels involve a pharyngeal constriction. These effects are illustrated qualitatively in Figure 1 with vocal tract outlines corresponding to rimes with coda /ɹ/ for speaker W1.[3] Each panel superimposes the vocal tract outline for each pre-rhotic vowel target posture (green) on the outline for the coda rhotic dorsal target (blue) following that vowel. The outlines for the vowel and rhotic are closer in the region of the pharynx where the rhotic constriction is formed for [ɑɹ] and [ɔɹ] rimes (third and fourth panels) than for [ɪɹ] and [ɛɹ] rimes (first and second panels). Outlines represent characteristic midsagittal postures for the targets in question, derived from mean tongue positions across three tokens. Corresponding figures for the rimes with /ɹ/ for the other three speakers are shown in the Appendix. The location of greatest constriction in the pharynx for rhotics varied across speakers from low pharyngeal (W1) to mid-pharyngeal (W2, W3) to upper pharyngeal (M1).

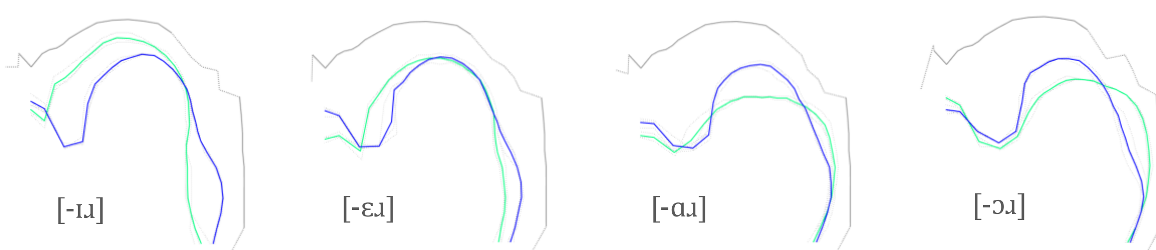

Figure 1: Target postures of pre-rhotic vowels (green tongue outlines: *'beer'*, *'bare'*, *'bar'*, *'bore'*), and coda rhotics following each vowel, captured at dorsal target (blue outlines: *'beer'*, *'bare'*, *'bar'*, *'bore'*). Mean tongue postures shown for Speaker W1; see Appendix for other speakers.

[3] Figure 1 shows rimes for which vocalic contrasts were regularly maintained across our participants. The majority of our participants reported full or partial merger of back round vowels to [ɔ] preceding coda /ɹ/.

The third relevant area of findings from this study involves lingual stability across different syllable positions and coarticulatory behavior. As to stability, greater consistency in lingual posture was found in rhotics than laterals across onset and coda contexts, consistent with previous research. Coda laterals showed greater retraction of the tongue dorsum than in onsets, and they showed a lower front of the tongue dorsum. A difference in coronal articulation was observed for some speakers, with a tendency for vocalization to occur in lateral coda contexts. Lesser differences were found in the articulation of rhotics in onset versus coda position.

Two aspects of the coarticulatory dominance of liquids were examined: the degree of coarticulatory resistance of liquids to articulation of the neighboring vowel (i.e. influence of vowel on liquid; Bladon & Al Bamerni 1976, Recasens 1985), and the degree of coarticulatory aggression of liquids on articulation of the neighboring vowel (i.e. influence of liquid on vowel; Farnetani 1990, Recasens & Espinosa 2009). Coarticulatory resistance (cf. Recasens et al. 1997) was quantified by measuring displacement in the midsagittal plane from the mean tongue posture for each liquid produced before and after a common set of context vowels. Coarticulatory aggression was quantified by measuring total lingual displacement of vowels produced adjacent to liquids, compared to the 'intrinsic' posture of the same vowels produced in inter-labial environments. In codas, rhotics showed higher coarticulatory resistance to the diverse articulations of tautosyllabic vowels than laterals. The same was true for three of the four speakers for onset rhotics versus laterals (one speaker showed the reverse effect in onset). Furthermore, vowels were overall significantly more displaced adjacent to rhotics than laterals. Greatest displacement was found in the context of coda rhotics, consistent with exertion of the greatest coarticulatory influence on a neighboring vowel of all liquids in syllable margins.[4]

In summary, key findings for our investigation that emerge from this study are given in (5).

(5)
i. For both coda /ɹ/ and coda /l/, the dorsal target was reached before the coronal target.

ii. Less movement in the pharyngeal region was observed from the vowel target to the rhotic dorsal target in rimes with non-high back vowels than with other peripheral vowels.

iii. The rhotic showed overall greater coarticulatory dominance than the lateral, and it showed greater articulatory stability across syllable positions.

4. The structure of rimes with post-vocalic liquids

Our analysis centers on the phonological representation of rimes with post-vocalic liquids. We concentrate on three dimensions of the abstract representation: i) specification of subsegmental units, ii) temporal structure, and iii) quantity.

Our proposal aims to bring the apparently special properties of the phonotactics of rimes with coda /ɹ/ in GenAm in line with the standard trimoraic template by making certain representational assumptions that are informed by the articulatory evidence described in the preceding section. In overview, first, we posit that liquids are specified for both coronal and dorsal subsegments, represented as gestures. Second, we assume that phonological temporal organization is represented at the subsegmental level in the form of coordination relations that govern overlap and ordering, and that the moraic contribution of consonants in the rime is tied to such relations. This assumption makes available the possibility that sequenced subsegments belonging to the same segment could give rise to a bimoraic status. Third, we hypothesize that the greater coarticulatory

[4] Because various vowel contrasts are neutralized before coda rhotics, it is conceivable that vowels show less peripheral articulations in this context than in contexts where contrasts are not neutralized, such as before coda laterals. In other words, we cannot rule out that positional lack of contrast has an effect on articulation apart from coarticulatory influence of the rhotic.

dominance of GenAm rhotics versus laterals corresponds to a stronger specified blending strength in the phonological representation for rhotics' dorsal component. We propose that this stronger blending strength causes the dorsal gesture for /ɹ/ to be organized in sequence to that of the nuclear vowel when the dorsal gestures are substantially different, but it overlaps the vowel's dorsal gesture when they are relatively similar. We suggest that these differences in organization give rise to the phonotactic restrictions on tautosyllabic vowel-/ɹ/ sequences and their differences from those involving coda /l/.

Our account will thus make critical use of subsegmental coordination relations and blending strength in the phonological grammar. A general claim underscored by our study is that these are essential components of any theory of subsegmental representation – we will refer to this as the COAST approach for short (Coordination And Strength). Our assumption of gestures as the atoms of representation is precisely because they encode both of these properties. They will be important both for representing the temporal complexity of liquids and for the outcome of overlap among the dorsal subsegments of liquids and vowels. In developing our account, we first detail our assumption of gestures as the representation of subsegmental units and show how these representations encode coordination relations within and across vowels and consonants in the syllable. We next discuss how moraic assignment operates in these representations. In this context, we address the phonotactics of rimes with a post-vocalic liquid, showing how a difference in blending strength for /ɹ/ versus /l/ can produce a difference in temporal organization for subsegments in the rime. A constraint-based analysis is presented, exhibiting how these representations are obtained by the phonological grammar.

4.1 Gestural representations

The core of our proposal is that phonotactic properties of coda liquids are related to their coordination relations and differences in strength. We assume that GESTURES are the atomic units of phonological representation (Browman & Goldstein 1986 et seq., Pouplier 2011). Gestures are specified for various parameters that include a constricting organ and associated articulator set (lips, tongue tip, tongue body, tongue root, jaw, velum, glottis) and a goal articulatory state, defined in terms of a constriction location and constriction degree (e.g. tongue tip closure at alveolar ridge, velum wide). Temporal structure is explicitly encoded both within gestures, which have an intrinsic duration, and between gestures, which may be in a synchronous or sequential coordinative relationship.

A key property of gestures is that they are specified for a blending strength, which can serve as a representation of differences in coarticulatory dominance (Saltzman & Munhall 1989, Fowler & Saltzman 1993). When two temporally overlapping gestures impose conflicting demands on an articulator, their goal states are blended. The blended outcome is the weighted average of the goal articulatory states, with the weighting for each based on their specified blending strength α, where a higher α corresponds to a higher coarticulatory contribution for that gesture (Iskarous et al. 2012, Smith 2018). The intrinsic temporal properties of gestures are determined by their interval of activation and stiffness k, which affects the speed of constriction formation and release. Vowel gestures have a lower stiffness than consonantal gestures, and different stiffness parameter settings may distinguish between other temporally contrastive gestures, such as vowels and glides (Browman & Goldstein 1992). We will indicate a high consonant-like stiffness setting for a gesture using the label "C", an intermediate glide-like stiffness setting with "G", and a low vowel-like stiffness setting with "V". In many cases, these settings will be predictable from a gesture's constriction degree, but they will be important for glides and liquids, which involve gestures at the cusp of the vocalic/consonantal boundary. The availability of three phonological stiffness settings is consistent with Padgett's (2008) proposal (using features) for a three-way phonological distinction between vowels, semivocalic glides and consonantal glides.

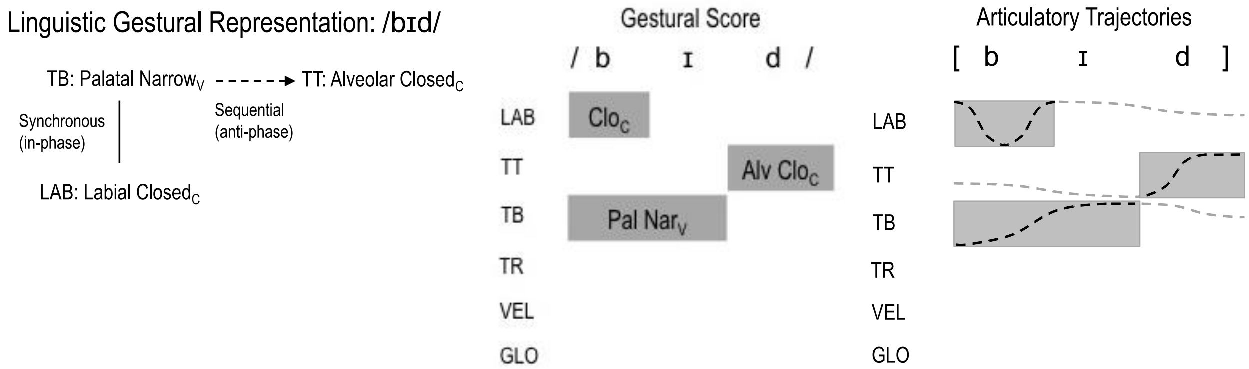

Figure 2: Three levels of gestural computation for the word *bid.* L-to-R: Linguistic gestural representation (coupling graph); Gestural score; Articulatory trajectories generated by task dynamic model.

We assume that the temporal coordination of gestures is governed by phonological grammar (e.g. Gafos 2002, Davidson 2003, Smith 2018). The level of representation that phonological grammar may manipulate is the LINGUISTIC GESTURAL REPRESENTATION, or COUPLING GRAPH, consisting of gestures with parametric specifications (for articulator set, goal articulatory state, blending strength, and stiffness) and temporal coordination relations between them (synchronous or sequential). The temporal arrangement of gestures which results from these phonological specifications is represented in a GESTURAL SCORE, which specifies the duration for which each gesture is active and its timing relationships with all other, possibly overlapping, gestures in the utterance. The gestural score forms the input to the TASK DYNAMIC MODEL, which generates the ARTICULATORY TRAJECTORIES. Our aim is to identify the appropriate linguistic representation for vowel-liquid rimes in GenAm, including the gestures involved, their temporal coordination, and the relation to moraic structure. Nonetheless, as we will discuss, other levels of computation in the model may factor into selection of the optimal linguistic gestural representation.

The different levels of gestural computation are illustrated in Figure 2 for the word *bid* [bɪd]. The linguistic gestural representation consists of three gestures: (i) the labial closure associated with /b/; (ii) the palatal tongue body (TB) approximation of /ɪ/; and (iii) the alveolar tongue tip (TT) closure required for /d/. The labial and vocalic gestures are synchronously coordinated (in-phase, indicated by a solid line), while the TT gesture is sequentially coordinated with that of the vowel (anti-phase, indicated by a dashed arrow pointing to the gesture that follows). These coordinative relationships – synchronous onset and vowel but sequential vowel and coda consonant – define basic principles of temporal organization within the syllable (Browman & Goldstein 1988, 2000; Nam et al. 2009). The gestural score indicates the interval of activation for each gesture, and the articulator set involved in executing it. Where boxes overlap in the vertical space, their respective gestures are simultaneously active. Possible resulting articulatory trajectories are illustrated schematically in Fig. 2; the actual articulations used to realize any particulate utterance of 'bid' would be a function not only of individual gestural specifications and their blending parameters, but also other factors such as speech rate and prosodic context.

Assuming the grammatical framework of Optimality Theory (OT; Prince & Smolensky 2004), we follow Smith's (2018) assumption that GEN executes changes in gestural representation at the level of the coupling graph i.e. the linguistic gestural representation, and phonological constraints governing gestures are therefore enforced only through selection among candidates differing in their coupling graph and the presence or absence of gestures. Nevertheless, the outputs evaluated by constraints contain not only the coupling graph, but also information about the gestural score, articulatory trajectories and acoustic output that are calculated from it. For example, it is possible for phonological constraints to reference whether a given linguistic gestural representation will result in certain gestures being simultaneously active, but the grammar cannot directly govern a gesture's duration. The latter is a continuous variable that is not part of the linguistic representation but rather is computed in the gestural score based on the gesture's parametric specifications. Similarly, a phonological constraint may reference the result of blending two overlapping gestures with specific blending strengths, but it cannot alter the computation of the blending outcome that is the product of those specifications. This understanding enables phonological markedness and contrast to be sensitive to the effects of gestural blending and to structure gestural overlap accordingly.

For the gestural representation of GenAm liquids, we assume two coordinated lingual gestures, and in the case of onset rhotics, also a labial gesture. Following Proctor et al. (2018), we posit a TT gesture and a TB gesture for GenAm rhotics and laterals. For the coronal articulation of /ɹ/, a glide-like TT gesture is specified for the constriction [Palatal] and constriction degree [Narrow].[5] Even though the blade and even the front of the tongue may be involved in realizing the coronal articulation in addition to the tongue tip, the abstract TT articulator is broadly interpreted. We suggest the TT articulator is most suitable for representing an articulation that may involve tip-up or tip-down bunching or retroflexion. For the pharyngeal articulation of /ɹ/, a glide-like TB gesture is specified for the constriction location [Pharyngeal] and constriction degree [Narrow]. We follow Browman & Goldstein (1989) in assuming the TB articulator executes articulations even extending into the pharyngeal region. Onset rhotics will also have a vocalic [LAB: Protruded Narrow] gesture. GenAm /l/ will consist of two gestures: consonantal [TT: Alveolar Closed] and glide-like [TB: Uvular Narrow].

In coda context, the gestures of GenAm liquids will be in a sequential relation, with the TB gesture ordered before the TT gesture. The output linguistic gestural representation for the GenAm rhotic and lateral in coda are illustrated in Figure 3. Note that the specifications in Figure 3 characterize goals for the midsagittal tract configuration. In the case of the lateral consonant, for instance, it is possible that additional goal(s) govern activity in another plane. We assume that segments are defined as formal sets of gestures, where those sets are given in the input and may be modified in the output (Walker 2017, Smith 2018). Gestures belonging to the same segment will thus

Coda rhotic	Coda lateral
TB: Pharyngeal Narrow$_G$ - - - - - -► TT: Palatal Narrow$_G$	TB: Uvular Narrow$_G$ - - - - - -► TT: Alveolar Closed$_C$

Figure 3: Gestural representation of a coda rhotic (left) and coda lateral (right) in GenAm

be identified by membership in the same set, rather than by hierarchical organization under a root node. Particular coordination relations among gestures belonging to the same segment will be driven by grammatical constraints on phonological outputs; however, as is customary in OT, those constraints are ranked and violable.[6]

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[5] Further testing is needed to confirm whether the TT gesture of GenAm rhotics should be represented as glide-like or consonantal. Proctor's (2009) cross-linguistic study of liquids suggests that the gestural structure of coronal liquids prototypically involves a consonant-like TT gesture and a vowel-like TB gesture (we treat the latter as glide-like). Yet an articulatory study of Canadian English /ɹ/ by Campbell et al. (2010) assumes both lingual gestures to be vowel-like, but with allophonic differences in the realization of each gesture based on syllable position, affecting magnitude.

[6] The idea that segments (tend to) involve gestures in specific temporal relations is shared with an approach to segments as gestural constellations (Browman & Goldstein 1986). A difference of the set-based approach adopted here is that segments are defined as gestural sets independent of intergestural coordination relations. Further, the phonological grammar governs how the set of gestures that compose a segment will be coordinated in the output.

4.2 Representation of quantity
As discussed in §2, the syllable template for GenAm has been framed in terms of moras. We assume a mora-based approach to quantity in the linguistic representation (Hyman 1985, Hayes 1989). Moras represent abstract units of weight, distinct from the continuous variable of duration, which is calculated in the gestural score.

The weight of vowels and consonants can be distinctive. Of relevance here is the representation of weight in tense/lax vowel pairs in GenAm. Building on previous work on GenAm syllable structure (see §2), we assume that contrasts among tense/lax vowel pairs primarily involve a phonological distinction in quantity. In contexts where tense and lax vowels contrast, tense vowels will be bimoraic in the input, and therefore long, while lax vowels will be monomoraic or lack a mora in the input and are therefore represented as short in the phonological output, with one mora. In our analysis, we assume that the gestural specifications for a tense/lax (i.e. long/short) vowel pair will be the same in the linguistic representation, though their difference in moraic structure will have some effect on their quality realization, such as diphthongization of non-low long vowels, which we abstract away from here. This assumption is not crucial, however. If evidence were to support a difference in intrinsic gestural specification in tense/lax pairs, the phonological analysis would necessarily correlate this difference with a quantity difference.

Weight can be coerced in specific contexts. Coerced weight refers to moras whose presence in the output is predictably enforced by a constraint, rather than exhibiting a contrastive distribution. WEIGHT-BY-POSITION (WBP) is responsible for the assignment of moras to coda consonants (Hayes 1989, Morén 1999, 2000). We assume a version of WBP where a mora is assigned to each gesture that is in a sequencing relation following the primary gesture of a vowel in a syllable (building on proposals of Browman & Goldstein 1988, 2000, Nam 2007). We will assume that the lingual gesture of a vowel is primary, though this is not crucial.

The moraic structures for two words, *bid* and *bead*, are illustrated in Figure 4. Following Hall (2002), we assume the [d] is moraic here, because it does not exceed the three-mora maximum. For *bid*, a mora will be enforced for the gesture for lax [ɪ] by constraint (see §4.4). In addition, WBP will enforce a mora for the TT gesture of the coda consonant, because it is sequenced after a vowel. The association of moras with gestures is indicated with dotted lines to keep them distinct from intergestural coordination relations. In *bead*, the gesture for the tense vowel is associated with two moras (due to a bimoraic input), and the gesture for coda [d] is assigned a mora through WBP. Since the distinction between the tense and lax vowels is encoded in terms of weight, we henceforth transcribe their phonemic contrast as involving quantity rather than quality, e.g., as /iː/ (*b<u>ea</u>d*) versus /i/ (*b<u>i</u>d*).

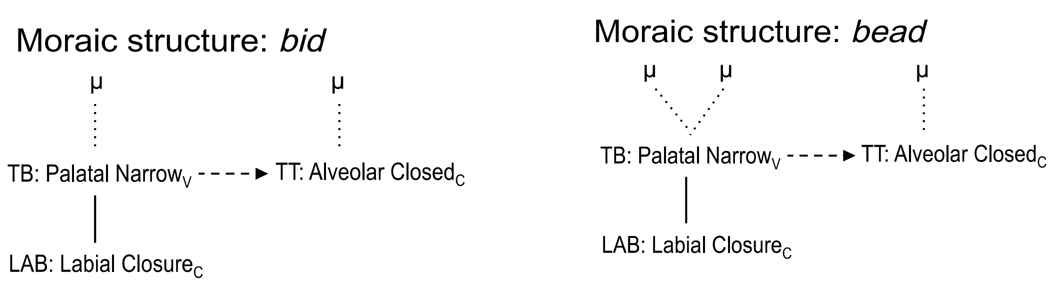

Figure 4: Linguistic gestural representation and moraic structure for *bid* (left) and *bead* (right).

4.3 Representations: Explaining rimes with a post-vocalic liquid
We now return to answering two central questions in (6) about the phonotactics of GenAm rimes with /ɹ/ versus /l/ – both spatially and temporally complex liquids.

(6) i. Why is the vowel length contrast (which distinguishes tense/lax pairs) neutralized in rimes with a simple coda consisting of /ɹ/ but not /l/?

ii. Why are [ɑ] and [ɔ] the only vowels possible in a rime with a complex coda containing /ɹ/, while all short (lax) vowel contrasts are potentially available before a complex coda with /l/?

In addressing these questions, we present the temporal organization of gestures that we propose for rimes with post-vocalic /l/ versus /ɹ/, and the rationale that gives rise to them.

With respect to vowel length contrasts, rimes with post-vocalic /l/ show phonotactics in conformity with the majority of GenAm consonants, so we begin with these structures. In rimes with a simple coda /l/, quantity contrasts are preserved (e.g. *peel*, *pill*), while in rimes with a complex coda containing post-vocalic /l/, only short vowels are possible (e.g. *milk*, **meelk*), but all short vowels are possible in this context. In all of these rimes, /l/ patterns as monomoraic; therefore, a word like, *ill* [ɪl], with a short vowel, will have just two moras, while a word like *eel* [iːl], with a long vowel, will have three moras.

The output linguistic gestural representation that we propose for *ill* is shown in Figure 5. For ease of interpretation, we have labeled the three gestures as follows: "i" is the gesture for the nuclear vowel, realized as short [ɪ], "l-dor" is the dorsal gesture of the lateral, and "l-cor" is the coronal gesture of the lateral. Relevant parameter settings for each are shown. A coda lateral in GenAm consists of l-dor [TB: Uvular Narrow$_G$] sequenced before l-cor [TT: Alveolar Closed$_C$] (the α value for l-dor is discussed below). In addition, the gesture of the nuclear vowel will be in a sequential coordination relation with the coda lateral. We propose that this relation exists between the nuclear vowel and the consonantal l-cor gesture. Thus, both the gesture of the nuclear vowel and the glide-like l-dor gesture are coordinated to precede l-cor; however, no direct temporal coordination exists between the l-dor gesture and the gesture of the vowel. The lack of a sequencing relation between the vowel and l-dor gesture is important, because it means that a coda lateral will give rise to only one mora. The sequencing relation between the vowel and l-cor will cause a mora to be assigned to l-cor through WBP, but l-dor is not moraic, because it is not sequential to the vowel.

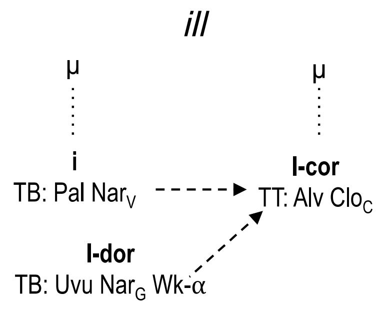

Figure 5: Output linguistic gestural and moraic representations for *ill*.

As a result of these coordination relations, the nuclear vowel and the TB gesture of the lateral will overlap. In the implementation of these relations, the release of the gesture of the vowel and of the TB gesture of the lateral will each be controlled to coincide with the TT target gesture. Studies of English laterals by Gick (1999b) and Krakow (1999) provide related insights about the timing of component gestures of coda liquids, though the specific proposal about the phonological structure of laterals is original here, to the best of our knowledge. The form of overlap we propose between the vowel and TB gesture of a coda lateral differs from synchronous gestures that are coordinated to begin in near-simultaneous fashion. A representation of this kind, which lacks direct coordination between a vowel and one of the gestures of a multi-gestural coda consonant, is likely not unique to GenAm laterals. Byrd et al. (2009) tentatively proposed a similar temporal coordination structure for a nuclear vowel and coda [n] in English, such that the vowel and velum lowering gesture both precede the TT closure gesture.

Because coda /l/ contributes only a single mora, distinctively long vowels are possible preceding a simple lateral coda. A word like *eel* [iːl], with a long vowel, will have three moras, two owing to the vowel and one to /l/ (Fig. 6, left). A word like *ilk* [ɪlk], where post-vocalic /l/ is part of a complex coda, will also have three moras. The short vowel contributes one mora, and WBP causes a mora to be assigned to each of l-cor and k-dor, the dorsal gesture for /k/ (Fig. 6, right).[7] In a VlC rime, long vowels are excluded, because the syllable would otherwise exceed the trimoraic maximum allowed for GenAm.

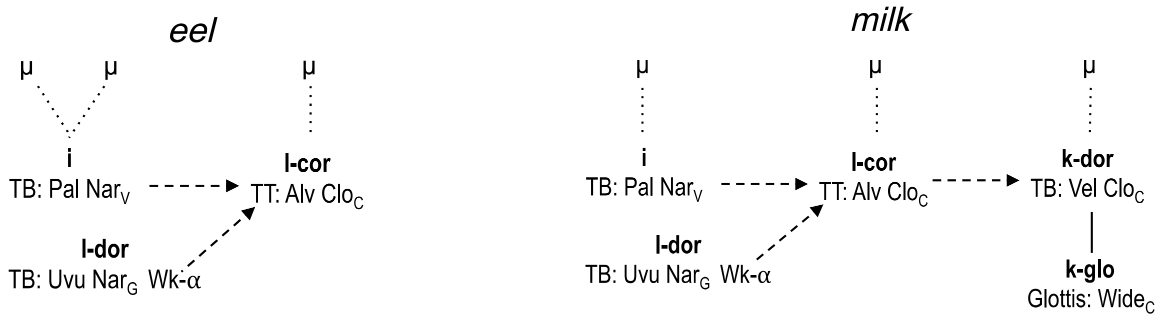

Figure 6: Output linguistic gestural and moraic representations for *eel* (left) and *milk* (right).

The question of partial overlap of a coda consonant and a nuclear vowel arises for /l/ but not /d/ (compare Fig. 4), because multi-gestural /l/ has internal sequencing of its gestures but mono-gestural /d/ does not. During the period where l-dor and the vowel overlap, the goal states for these gestures will be blended, with the relative contribution of each gesture dictated by its specified α value. A key finding of the study by Proctor et al. (2018) was that GenAm laterals have a lower coarticulatory dominance than rhotics, which we interpret as corresponding to a lower specified blending strength (α value) for laterals than rhotics. We suggest that the weaker blending strength of the lateral enables l-dor to overlap with the vowel without significantly compromising contrasts in vowel quality. However, in the case of /ɹ/, which has a higher blending strength, the implications for gestural overlap are different, as we discuss below. We will characterize the critical difference in blending strength of the liquids with a specification of "weak" (Wk) for α in l-dor and "strong" (Str) for α in ɹ-phar (referring to the dorso-pharyngeal gesture of /ɹ/ formed with the TB). We focus on the blending strength of these gestures in particular, because they are sequenced before the TT gesture in each liquid, and are therefore in a context for potential overlap with the vowel. Weak versus strong specifications for gestural blending strength have been proposed to play a role in phonological patterning in other studies (Smith 2018, Smith & Blaylock 2017), supporting a distinction along these lines in the linguistic gestural representation.

[7] Observe that k-dor is in a sequencing relation that causes it to follow the vowel in the syllable, so it will be assigned a mora; however, k-glo, the glottal gesture for /k/, is not coordinated in a sequential relation (rather it is synchronous with k-dor), so it is not relevant for WBP.

Like the lateral, the coda rhotic involves a sequence of two gestures (§4.1): ɹ-phar preceding ɹ-cor. When the nuclear vowel involves lingual control that differs significantly from that of ɹ-phar, the strong blending strength of the ɹ-phar gesture has potential to interfere with the distinctive quality of the vowel if it substantially overlaps with the vowel gesture. Such interference is avoided if ɹ-phar is sequenced to follow the gesture of the vowel, as shown for the word *ear* in Figure 7. In this temporal organization, the rhotic gives rise to two moras, one for ɹ-phar sequenced after the gesture for /i/ and one for ɹ-cor sequenced after ɹ-phar. Due to the trimoraic maximum in GenAm syllables, a vowel in this context must be phonologically monomoraic. This prediction is consistent with the neutralization of vowel quantity (tense/lax) contrasts preceding coda /ɹ/.

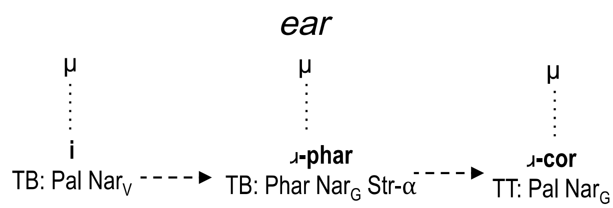

Figure 7: Output linguistic gestural and moraic representations for *ear*.

Nevertheless, in rimes containing a non-high, back vowel [ɑ] or [ɔ], post-vocalic /ɹ/ may be part of a complex coda, and only with these vowels. The pharyngeal constriction for /ɹ/ was found to most closely resemble that of these peripheral vowels. Because of their similarity, we propose that [ɑ] and [ɔ] can significantly overlap with ɹ-phar without compromising distinctive quality, despite the high blending strength of the rhotic. This enables a representation for *are* in which ɹ-phar and the gesture for [ɑ] are each sequenced before ɹ-cor, but they are not in a direct temporal relation with each other (Fig. 8, left). Since ɹ-phar is not sequenced after the gesture for [ɑ], *are* will give rise to just two moras, one for the vowel and one for ɹ-cor. The potential for overlap between [ɑ]/[ɔ] and ɹ-phar thus makes possible an additional coda consonant, as shown for *ark* (Fig. 8, right). In this case, the sequential relation between ɹ-cor and k-dor causes WBP to assign a third mora. By contrast, a complex coda is not possible with post-vocalic /ɹ/ for other vowel qualities, because the sequencing of ɹ-phar after the vowel gesture – to avoid neutralizing overlap – causes the Vɹ sequence to occupy the maximal three moras.

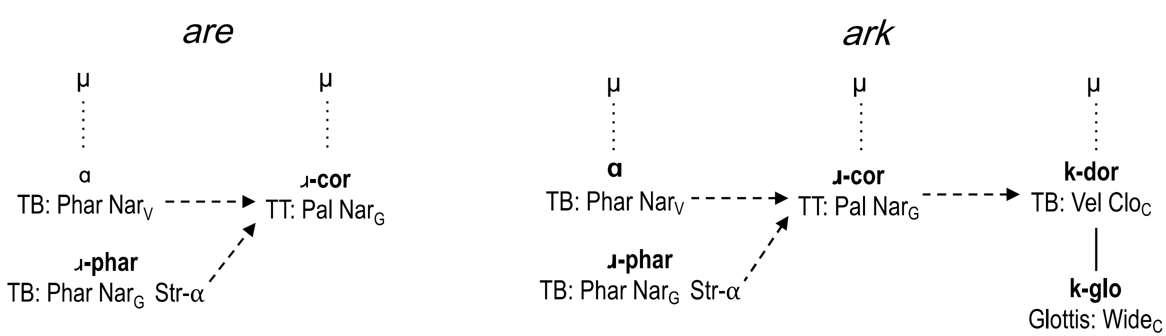

Figure 8: Output linguistic gestural and moraic representations for *are* (left) and *ark* (right).

A summary of our primary claims about the representation of rimes with post-vocalic liquids is provided in (7). In the COAST approach, differences in the organization of rimes with /ɹ/ versus /l/ involve manipulation of coordination relations, largely driven by differences in the blending strength of their TB gesture.

(7) i. Coda /l/ and coda /ɹ/ each involve a sequence of two lingual gestures, with the more posterior gesture ordered before an anterior gesture (in line with the findings of previous studies and our own).

ii. Coda /l/ adds only one mora to a syllable. The weak blending strength of the l-dor gesture enables it to overlap with the nuclear vowel lingual gesture without compromising distinctive vowel quality.

iii. Coda /ɹ/ adds one or two moras to a syllable, depending on the quality of the nuclear vowel. This owes to the strong blending strength of ɹ-phar. If the vowel is non-high and back (/ɑ/ or /ɔ/), ɹ-phar can overlap with the vowel, because the gestures are highly similar. However, ɹ-phar is sequenced to follow the lingual gesture of other vowels, with the result that ɹ-phar does not interfere with distinctive nuclear vowel quality.

The representations that we propose are abstract and hypothetical, but they are grounded in research on the articulation of rimes with post-vocalic liquids, including the formation of constrictions for the vowel and liquid, the sequencing of lingual gestures that compose the liquid, and the coarticulatory properties of liquid articulations. Our account makes predictions about the coordination of the nuclear vowel and gestures of post-vocalic liquids that can be tested in future articulatory studies (cf. Marin & Pouplier 2014).

Our proposal about the temporal organization of liquids in rimes has some affinity with previous work proposing that post-vocalic liquids are high in sonority and form a diphthong with a preceding tautosyllabic vowel in the syllable nucleus (Harris 1994, Green 2001b, see also related work by Botma et al. 2008, Ewen & Botma 2009). Our study of GenAm vowel-liquid phonotactics, contextualized in relation to articulatory research, suggests that a glide-like dorsal/pharyngeal component of liquids has the capacity to share temporal space with the nuclear vowel. However, different from prior analyses, details of overlap of the glide-like component of the liquid with the vowel or its diphthongal-like sequencing depend on specific articulatory properties of the liquid, namely its coarticulatory dominance, and its articulatory similarity to the nuclear vowel. As discussed by Proctor & Walker (2012), articulatory factors contribute to understanding liquid-specific and vowel-specific restrictions in GenAm rime phonotactics, beyond a traditional diphthongal treatment of post-vocalic liquids.

4.4 Constraint-based analysis

We now turn to an OT analysis that derives the gestural coordination relations and moraic assignment that we propose for GenAm rimes. Numerous OT analyses have been proposed that represent grammars operating over gestural representations (Gafos 1996, 2002, Davidson 2003, Hall 2003, Bradley 2005, 2007, Casserly 2012, Tejada 2012, Smith 2016, 2018), though with some differences, such as whether coordination is enforced at the level of the coupling graph or gesture-internal landmarks. As mentioned above, we follow Smith (2018) in broad-based assumptions about the nature of structure that may differ among candidates produced by Gen and the levels of computation available in the constraint evaluation. We also follow Smith in supposing that inputs may contain a linear ordering over segments (conceived of as sets of gestures; see §4.1), and constraints select the appropriate coordination structure for gestures in the output.

We deal first with the constraints and ranking involved in deriving the appropriate basic temporal coordination and assignment of moras for gestures within syllables of GenAm. The relevant faithfulness constraint is MAX-GEST-IO, which penalizes deletion of a gesture (in the formalism of

McCarthy & Prince 1995).[8] Three markedness constraints are defined in (8). On referencing the primary or head gesture in consonants and vowels, see Gafos (2002) and Smith (2018).

(8) a. SYNC(CV): Assign a violation mark for any primary consonantal gesture that is not synchronous with the primary gesture of the nearest following vocalic gesture.

b. COORD(C): Assign a violation mark for any primary consonantal gesture that is not in a coordination relation with a gesture of another segment.

c. WBP: Assign a violation to every gesture that lacks an associated mora where that gesture is in a sequencing relation following the primary vowel gesture in the syllable.

SYNC(CV) enforces the synchronous coordination of an onset consonant and following vowel. The vowel follows the onset in that its peak stricture is computed to be reached after that of the consonant. This constraint is equivalent to COUPLE(C, V), proposed by Smith (2018). We have changed the constraint name here to highlight the type of coordination relation it enforces, namely, a synchronous relation, as opposed to a sequential one. This constraint is violated in outputs of some languages, such as when the first consonant of an intervocalic cluster is not in a synchronous coordination relation with the following vowel, i.e. when VCCV is syllabified as VC.CV with a coda rather than V.CCV with a complex onset. See Davidson (2003) for discussion in connection with a constraint that is similar in spirit, ASSOC-CV. COORD(C) enforces a coordination relation between a consonant and the gesture of another segment; it is essentially the equivalent of ASSOC(C), proposed by Davidson (2003). This constraint serves to syllabify a post-vocalic consonant as a coda, i.e. coordinated as sequential to a preceding vowel, as a last resort. It comes into play when the consonant is word-final or cannot be syllabified into the onset of the following syllable by synchronous coordination with a following vowel. Possibly this constraint should belong to GEN (Smith 2018: 25). Finally, WBP is responsible for assignment of moras to gestures in coda contexts.

The operation of these constraints is demonstrated in (9) for *bead*. The input consists of three segments, in this case each consisting of a single gesture. These are numerically indexed for their linear order. To enhance interpretability we represent the phonemic transcription in the tableau heading with numeric subscripts, which may be matched with the affiliated gestures in the input. In addition, we continue our practice of using short-form labels for the gestures, though we indicate their fuller specifications in parentheses in the input.

[8] Questions remain about the division of labor between MAX-GEST and MAX-SEG, where the latter punishes deletion of the set of gestures that compose a segment. Similar questions arise in feature theory with the constraint MAX-[F]. We leave this issue for future research.

(9) Tableau for /b$_1$iː$_2$d$_3$/ *bead*

b-lab$_1$ i-TB$_2^{\mu\mu}$ d-cor$_3$ (= {LAB: Lab Clo$_C$}$_1$ {TB: Pal Nar$_V^{\mu\mu}$}$_2$ {TT: Alv Clo$_C$}$_3$)	SYNC(CV)	COORD(C)	WBP	MAX-GEST
a. ☞ i-TB$^{\mu\mu}$ - -> d-cor$^{\mu}$ | b-lab				
b. b-lab - -> i-TB$^{\mu\mu}$ - -> d-cor$^{\mu}$	*!W			
c. i-TB$^{\mu\mu}$ d-cor | b-lab		*!W		
d. i-TB$^{\mu\mu}$ - -> d-cor | b-lab			*!W	
e. i-TB$^{\mu\mu}$ | b-lab				*!W

The input in (9) has two moras associated with the TB gesture of the vowel, because it is distinctively long. The gesture for /d/ has no mora in the input here. This is not crucial, but it enables illustration of how WBP enforces mora insertion for the coda consonant. To conserve space, moras associated with gestures are shown with superscripted μs in tableaux. Candidate (a) [biːd$^{\mu}$] is the winner, with a moraic coda consonant. It obeys all of the constraints shown. Following Campos-Astorkiza (2003), we assume that moras inserted to represent non-geminate coda weight do not violate DEP-μ. All of the other candidates violate one of the constraints shown. Candidate (b) violates SYNC(CV), because i-TB is in a sequential relationship with b-lab. COORD(C) is violated in (9c), because d-cor is not in a coordination relation with another gesture. WBP is violated by (9d), where d-cor is in a sequential relation to the vowel gesture but is not moraic ($^{\varnothing}$): [biːd$^{\varnothing}$]. Candidate (e) bypasses violations of COORD(C) and WBP by deleting d-cor, which violates MAX-GEST, yielding [biː].

For a short vowel, as in *bid*, the TB gesture for the vowel will either have a single associated mora in the input, or no mora. The vowel will be guaranteed assignment of a mora in the output through the constraint V/μ, which assigns a violation to every primary vowel gesture that lacks an associated mora (Rosenthall 1994).

We assume two LINEARITY constraints, which prevent the effects of metathesis (building on McCarthy & Prince 1995).

(10) a. LINEARITY-SEQ: Assign a violation mark for any pair of primary gestures in a sequential coordination relation that is opposite to their precedence in the input.

b. LINEARITY-SYNC: Assign a violation mark for any pair of primary gestures in the input with precedence X > Y that are in a synchronous relation in the output where the peak constriction for X is computed to occur after Y.

LINEARITY-SEQ prevents gestures with an input precedence relation X > Y from being sequenced as Y > X in the output, but it permits overlap of X and Y, as in the synchronous relation between a vowel and onset consonant in a syllable. LINEARITY-SYNC prohibits a consonant gesture that is ordered after a vowel gesture in the input from being in a synchronous relation with that vowel gesture in the output, preventing a post-vocalic consonant from becoming an onset to that vowel. These constraints are not violated in the candidates considered in tableaux here, and they are assumed to be ranked in the top tier for the patterns under focus in GenAm.

Coda liquids in GenAm are complex segments realized with internal sequencing of gestures. We propose two constraints relevant to this representation. SYNC(sub-seg), in (11), will enforce a synchronous beginning (directly or by transitivity) for gestures belonging to the same segment, as identified by membership in the same set. Conflicting with this constraint is SEQ(liq), in (12), which demands that the TT gesture of a coda liquid be sequenced after its TB gesture. A coda liquid can be defined as a liquid with a gesture that is in a sequential coordination relation with the preceding vowel.

(11) SYNC(sub-seg): Assign a violation mark for any pair of gestures belonging to the same segment that are not synchronous.

(12) SEQ(liq): Assign a violation mark for any coda liquid whose TT gesture is not in a sequential coordination relation with its TB gesture, such that TB > TT.

SEQ(liq) must dominate SYNC(sub-seg) to obtain sequential coordination of the lingual gestures in a coda liquid. In tableaux to follow, only candidates with this coordination will be considered.

We demonstrate how the grammar selects appropriate structures for coda rhotics first and then for laterals. The constraint 3μ, defined in (13), enforces the trimoraic maximum in syllables (Hammond 1999, Hall 2002). Pertaining to rimes with /ɹ/, SEQ(Vɹ) enforces sequencing between the TB gesture of coda /ɹ/ and that of a preceding non-pharyngeal vowel (see (14)). SEQ(Vɹ) is a cover constraint for constraints on contrast that penalize the insufficient distinction in quality between vowels with a pharyngeal TB gesture ([ɑ], [ɔ]) and that of other vowels when they phonologically overlap with ɹ-phar, due to the high blending strength of the pharyngeal gesture in the rhotic. Phonological overlap would arise if the vowel's TB gesture and the TB gesture of the rhotic were both in a sequential coordination relation with the TT gesture of /ɹ/, but were not directly coordinated with each other, as in Figure 8. Dispersion-theoretic constraints can enforce contextual restrictions on contrast (Flemming 1995, 2004, Padgett 1997, Ní Chiosáin & Padgett 2001), and contextual effects can be affected by blending strength. For reasons of space, we do not elaborate the details of the constraint interactions that derive the effect of SEQ(Vɹ).

(13) 3μ: Assign a violation to any syllable with more than three moras.

(14) SEQ(Vɹ): For any coda /ɹ/ and immediately preceding vowel with a non-pharyngeal TB gesture, assign a violation to the vowel's non-pharyngeal TB gesture if it is not in a sequential coordination relation with the pharyngeal TB gesture of /ɹ/.

These constraints have the potential to conflict with MAX-μ-IO, which penalizes deletion of a mora, as in the case of shortening a long vowel shown in the tableau for *ear* in (15). The hypothetical input here has bimoraic /iː/. To facilitate interpretation, an approximate phonetic realization is notated beside candidates that includes the phonological weight of coda consonants.

(15) Tableau for /iː₁ɹ₂/ *ear*

<table>
<tr><th>i-TB$_1^{μμ}$ ɹ-phar$_2$ ɹ-cor$_2$
(= {TB: Pal Nar$_V^{μμ}$}$_1$ {TB: Phar Nar$_G$ Str-α, TT: Pal Nar$_G$}$_2$)</th><th>3μ</th><th>WBP</th><th>MAX-GEST</th><th>SEQ(Vɹ)</th><th>MAX-μ</th></tr>
<tr><td>a. ☞ μ μ μ
[ɪɹ^{μμ}] | | |
i-TB ⇢ ɹ-phar ⇢ ɹ-cor</td><td></td><td></td><td></td><td></td><td>*</td></tr>
<tr><td>b. μ μ μ μ
[iːɹ^{μμ}] \/ | |
i-TB ⇢ ɹ-phar ⇢ ɹ-cor</td><td>*!W</td><td></td><td></td><td></td><td>L</td></tr>
<tr><td>c. μ μ μ
[iːɹ^{μ}] \/ |
i-TB ⇢ ɹ-phar ⇢ ɹ-cor</td><td></td><td>*!W</td><td></td><td></td><td>L</td></tr>
<tr><td>d. μ μ μ
[iːɑ̯^{μ}] \/ |
i-TB ⇢ ɹ-phar</td><td></td><td></td><td>*!W</td><td></td><td>L</td></tr>
<tr><td>e. μ μ μ
[i^{ɑ}ːɹ^{μ}] \/ |
i-TB ⇢ ɹ-cor
ɹ-phar ⇢</td><td></td><td></td><td></td><td>*!W</td><td>L</td></tr>
</table>

The winning candidate, in (15a), shortens the vowel by deleting a mora, earning a violation of MAX-μ. This allows the ɹ-phar gesture of the coda rhotic to not overlap the vowel and still remain within the trimoraic syllable maximum. Candidate (15b) is ruled out because it has four moras. In (15c), WBP is violated, because ɹ-cor is not assigned a mora despite being sequenced after the vowel in the syllable. In (15d), a violation of WBP is avoided by deleting ɹ-cor; however, this violates MAX-GEST. In this case, /ɹ/ would resemble a pharyngeal glide, which we represent as [ɑ̯]. In (15e), the pharyngeal gesture of /ɹ/ overlaps the vowel's TB gesture, indicated by [ᵅ], which interferes with vocalic contrast maintenance. This is ruled out by SEQ(Vɹ).

The tableau in (16) shows how a different coordination structure is selected for *ark*. The glottal gesture for /k/ is not shown here since it is not relevant to issues under focus. Again, the hypothetical input contains a bimoraic vowel.

(16) Tableau for /ɑ$_1$ɹ$_2$k$_3$/ *ark*

ɑ-phar$_1^{\mu\mu}$ ɹ-phar$_2$ ɹ-cor$_2$ k-dor$_3$ (= {TB: Phar Nar$_V^{\mu\mu}$}$_1$ {TB: Phar Nar$_G$ Str-α, TT: Pal Nar$_G$}$_2$ {TB: Vel Clo}$_3$)	3μ	WBP	MAX-GEST	SEQ(Vɹ)	MAX-μ
a. ☞ μ μ μ [ɑɹ$^{\mu}$k$^{\mu}$] | | | ɑ-phar- - -> ɹ-cor - -> k-dor ɹ-phar- - ↗					*
b. μ μ μ μ [ɑːɹ$^{\mu}$k$^{\mu}$] \\/ | | ɑ-phar- - -> ɹ-cor - -> k-dor ɹ-phar- - ↗	*!W				L
c. μ μ μ μ [ɑɹ$^{\mu\mu}$k$^{\mu}$] | | | | ɑ-phar- -> ɹ-phar - -> ɹ-cor - -> k-dor	*!W				*
d. μ μ μ [ɑɹ$^{\mu}$k$^{\mu}$] | | | ɑ-phar - -> ɹ-phar - -> ɹ-cor - -> k-dor		*!W			*
e. μ μ μ [ɑːɹ$^{\mu}$] \\/ | ɑ-phar- - -> ɹ-cor ɹ-phar- - ↗			*!W		L

The vowel in *ark* is pharyngeal; therefore SEQ(Vɹ) does not prohibit it from overlapping with ɹ-phar, as in the winner in (16a). Here, coda [ɹ] contributes only a single mora. Nevertheless, to accommodate the weight contributed by two coda consonants, the vowel must become monomoraic; compare (16b). If ɹ-phar instead were sequenced to follow [ɑ], the trimoraic maximum would be exceeded even with a shortened vowel, as in (16c), or WBP would be violated, as in (16d). MAX-GEST >> MAX-μ excludes (16e), where a coda consonant is deleted to preserve a second mora in the vowel.

In words with a lateral coda, SEQ(Vɹ) does not come into play. In the case of *eel*, a representation where l-dor overlaps the TB gesture of the vowel is optimal (17a). This configuration does not violate any of the constraints under consideration. Each of the alternatives in (17) are ruled out by a violation of one of the constraints shown.[9]

[9] For *ill*, coordination relations like that in (17a) and (17b), but with a monomoraic vowel, would tie on the constraints shown. We posit that a markedness constraint *LONGC, which penalizes bimoraic consonants, is the tie breaker in favor of overlap like that in (17a). *LONGC would be ranked alongside MAX-μ to ensure selection of bimoraic coda [ɹ] in *ear* (see (15)).

(17) Tableau for /iː$_1$l$_2$/ *eel*

i-TB$_1^{\mu\mu}$ l-dor$_2$ l-cor$_2$ (= {TB: Pal Nar$_V^{\mu\mu}$}$_1$ {TB: Uvu Nar$_G$ Wk-α, TT: Alv Clo$_C$}$_2$)	3μ	WBP	MAX-GEST	SEQ(Vɹ)	MAX-μ
a. ☞ [iːl$^\mu$] μ μ μ \ / | i-TB - - -> l-cor l-dor - - ->					
b. [iːl$^{\mu\mu}$] μ μ μ μ \ / | | i-TB - -> l-dor - -> l-cor	*!W				
c. [iːl$^\mu$] μ μ μ \ / | i-TB - -> l-dor - -> l-cor		*!W			
d. [iːɣ̯$^\mu$] μ μ μ \ / | i-TB - -> l-dor			*!W		
e. [ɪl$^{\mu\mu}$] μ μ μ | | | i-TB - -> l-dor - -> l-cor					*!W

The case of *ilk* is shown in (18). The input in this tableau contains a hypothetical long vowel. Again, overlap between the vowel and l-dor is favored; however, higher ranking constraints drive a violation of MAX-μ, because the vowel must become short to accommodate a second coda consonant.

(18) Tableau for /i$_1$l$_2$k$_3$/ *ilk*

i-TB$_1^{\mu\mu}$ l-dor$_2$ l-cor$_2$ k-dor$_3$ (= {TB: Pal Nar$_V^{\mu\mu}$}$_1$ {TB: Uvu Nar$_G$ Wk-α, TT: Alv Clo$_C$}$_2$ {TB: Vel Clo}$_3$)	3μ	WBP	MAX-GEST	SEQ(Vɹ)	MAX-μ
a. ☞ [ɪl$^\mu$k$^\mu$] μ μ μ | | | i-TB - - -> l-cor - -> k-dor l-dor - - ->					*
b. [iːl$^\mu$k$^\mu$] μ μ μ μ \ / | | i-TB - - -> l-cor - -> k-dor l-dor - - ->	*!W				L
c. [iːl$^\mu$k$^\varnothing$] μ μ μ \ / | i-TB - - -> l-cor - -> k-dor l-dor - - ->		*!W			L
d. [iːl$^\mu$] μ μ μ \ / | i-TB - - -> l-cor l-dor - - ->			*!W		L

The coordination and weight representations for rimes with coda liquids thus are selected by a grammar in which 3μ, WBP, MAX-GEST and SEQ(Vɹ) dominate MAX-μ, in concert with the additional constraint rankings discussed earlier in this section.

4.5 Summary
This concludes our account of the representation of rimes with post-vocalic liquids and the explanation it affords for understanding their phonotactics. In overview, our analysis involves the following elements, built around the COAST approach.

(19) Primary elements of the analysis of GenAm rimes:

i. GenAm syllables have a trimoraic maximum, consistent with previous proposals about the syllable template.

ii. Coda liquids involve a sequence of two lingual articulations, with potential for the first, more posterior articulation to overlap the vocalic nucleus. Overlap and blending of subsegmental components is represented with gestures, which encode coordination relations at the subsegmental level and incorporate specification of blending strength.

iii. The temporal coordination of gestures in rimes with post-vocalic liquids is sensitive to blending strength and similarity in specified goal articulatory state. This can result in sequencing of the nuclear vowel and posterior lingual gesture of a liquid where overlap would interfere with maintaining certain vocalic contrasts.

iv. Enforcement of gestural sequencing in the rime can neutralize vocalic quantity contrasts (e.g. long/short vowel contrasts before a rhotic or a complex coda).

v. GenAm rhotics have a higher blending strength than laterals, leading to a greater propensity for vocalic neutralization before coda rhotics. Yet rhotics' pharyngeal gesture can overlap similar non-high back vowels, permitting an additional coda consonant in the rime only with these vowels.

vi. A constraint-based grammar governs the coordination relations and non-distinctive weight assignment, operating to derive the phonotactic distributions under study.

5. Directions for extensions to other patterns

The ramifications of representing temporal structure at the subsegmental level rather than at the root node invite reexamination of various phonological phenomena, especially those involving complex segments and partial cross-segmental overlap. As an example, our investigation finds resonance with a study of ambisyllabic /l/ in British English by Scobbie & Pouplier (2010), who observe that separate gestures of /l/ enter into distinct syllabification and coordination relations rather than behaving uniformly over the segment. Various other patterns may be amenable to an account along the lines we have proposed, both in English and in other languages. We highlight some of these here as directions for extending the application of subsegmental coordination and strength to phonotactics in the rime.

Within English, a few branches of inquiry are particularly promising: sesquisyllables and dialectal variation in vowels before liquids. We discuss these in turn, with particular attention to the first, since it is a characteristic common to GenAm. As mentioned in §2, sesquisyllables are forms with a liquid coda that are plausibly monosyllabic but variably judged by native speakers as greater than one syllable. The study of sesquisyllables by Cohn and Tilsen investigated syllable count ratings for target stimuli with rimes containing [aj], [ɑ], [i], [ɪ] (or a neutralized high front vowel contrast before /ɹ/). This study found that words most likely to be rated as >1σ contain [aj] followed by a liquid (e.g. *pile, pyre*). A similar but considerably weaker effect was found for words with a liquid preceded by a high front vowel that is tense or where a tense/lax distinction is neutralized (e.g. *peel, beer*). For both rimes with [aj] and high front vowels, variation in syllable count judgment was found across participants, words, and tasks. In contrast, forms with other vowels in a rime with a liquid coda are usually judged to be one syllable (e.g. *pill* [ɪ], *ball* [ɑ], *par* [ɑ]).

We speculate that these forms may receive an account in terms of our approach if the glide [j] in GenAm is represented with a higher blending strength than vowels, such as [i] or [ɪ]. We have not examined the blending strength of glides in diphthongs of GenAm, nor are we aware of any studies that have directly investigated this issue. Nevertheless, Recasens (1985) found that glides [j] and [w] in Catalan showed evidence of a high degree of articulatory constraint.

On the account we have proposed for the gestural organization of coda /ɹ/, a rating of words with [ajɹ] rimes as >1σ is unsurprising. The diphthong is expected to give rise to two moras, and coda /ɹ/ is expected to contribute two moras, because its pharyngeal gesture is not sufficiently similar to [j] to allow significant overlap. A count of four moras is consistent with the interpretation of Lavoie & Cohn (1999) and Cohn (2003) that sesquisyllables have an extra mora, exceeding a stable maximum for English. For [ajl] rimes, it is conceivable that the dorsal gesture of [l] is likewise sequenced after the diphthong rather than overlapping it, yielding a four-mora rime. We speculate that this sequencing could occur if the glide in the diphthong has greater blending strength (corresponding with higher coarticulatory dominance) than the vowel [i]. Data from Gick (1999b) are suggestive that a sequencing account is on the right track. Gick's interpretation of measurements of the temporal lag between TB and TT gestures in [ajl] rimes supports the notion that TB targets for /j/ and /l/ conflict with each other and delay achievement of the lateral's TB gesture (see also Gick & Wilson 2006).

As for rimes with a high front vowel, Lavoie & Cohn (1999: 111) observed that diphthongized tense vowels tend to lead to a disyllabic interpretation of sesquisyllables. A potential direction in terms of our approach is for variation in representation between [iːl] ~ [ijl] and [iɹ] ~ [ijɹ]. The diphthongal rimes would be expected to correspond with a tendency for >1σ judgments and the others to correspond to =1σ judgments. The gestural organization for [iːl] and [iɹ] rimes were illustrated in §4.3, each amounting to three moras. In the case of diphthongal [ijl] and [ijɹ], the glide in the diphthong could be sequenced before the TB gesture of the liquid. This representation would fit with Cohn and Tilsen's finding that rimes with high front vowels and liquids that are associated with >1σ judgments are longer in mean rime duration than those associated with =1σ judgments.

Finally, we note that the lack of >1σ judgments for lax vowels and low vowels is consistent with our account, as these vowels are not expected to contribute more than a single mora to a rime and they do not generally have a diphthongal production available.

Further research is warranted to test our tentatively hypothesized representations for sesquisyllables, both in terms of coordination and blending strength. We see this as a promising direction to pursue, especially intersecting with dialect variation. Wells (1982: 484–5) notes reports of English varieties spoken in the American midland where [aj] undergoes monophthongization before coda liquids. This can cause words like *tire* and *tar* to be identical, or they may be distinct, with *tire* pronounced as [taɹ] and *tar* as [tɑɹ]. Monophthongization could potentially be understood as a means of modifying the rime structure so that it does not exceed three moras.

Another phenomenon in American English varieties that could receive understanding from our approach is the reduction of vowel contrasts before coda /l/. Various varieties show merger or near-merger of tense/lax contrasts in this context. For example, merger of [iː] and [ɪ] in word pairs like *feel* ~ *fill* has been found among speakers in regions of the southern United States, and merger of [uː] and [ʊ] in word pairs like *fool* ~ *full* is prevalent among speakers in western Pennsylvania (Labov et al. 2006). Near-mergers or F1/F2 contrasts for tense/lax vowel pairs before /l/ are reported for numerous other regions, including Albuquerque and the Salt Lake Valley (Di Paolo & Faber 1990, Labov et al. 1991, Labov 1994). Like the rhotic, the coda lateral has a TB gesture sequenced before a TT gesture. For GenAm, which maintains tense/lax contrasts before coda /l/, we have analyzed l-dor as overlapping the TB gesture of the vowel in the rime. This overlap is permissible because the blending strength of l-dor is weaker than that of the rhotic's TB gestures, but /l/ will still produce coarticulatory effects on the vowel. Language varieties could vary in the perceptual distance enforced between vowels, with the result that significant overlap between the vowel and the TB gesture of the lateral is not tolerated, yielding a coordination structure like that of the rhotic following front and/or high vowels. It is also possible that the blending strength of the lateral's TB gesture varies across varieties, which likewise could give rise to sequencing between the TB gesture of the vowel and that of /l/ in cases where l-dor had a strong α specification

In future work, it would also be fruitful to examine patterns involving vocalization or loss of coda liquids in English varieties. Vocalization of coda laterals is attested both historically and as a variable present-day pattern in a number of English dialects (e.g. Wells 1982, Borowsky 2001, Horvath & Horvath 2002, Labov et al. 2006, Lin et al. 2014). Pre-rhotic breaking, along with vocalization and loss of coda rhotics occurred in sound changes in a number of English varieties (e.g. Wells 1982). These patterns are potentially amenable to understanding in terms of final weakening, blending, and differences in coordination among the components of the TB gesture of the liquid and the vowel in the rime, building along the lines discussed by McMahon et al. (1994) for rhotics. In another vein, our observation of the articulatory affinity of GenAm /ɹ/ and [ɑ]/[ɔ] is consistent with contexts for intrusive [ɹ] in certain non-rhotic dialects of English. In hiatus contexts, [ɹ] is inserted following [ɑ], [ɔ] or [ə], but [j] or [w] are inserted after high vowels, a pattern suggested to have an articulatory basis (Wells 1982, McMahon et al. 1994, Gick 1999a, Gick et al. 2002, Uffmann 2007).

Other languages show patterns where vowel length is affected in the context of a post-vocalic coda liquid. A number of dialects spoken in northern Italy show evidence of a sound change where stressed vowels lengthen before a coda liquid (Prieto-Vives 1994). In Dutch, high vowels [i, y, u] are long when followed by a rhotic in the same foot (Gussenhoven 2009). Vowel lengthening in these contexts could potentially be understood in terms of the kind of analysis we have proposed as a phonological means of preserving vowel quality contrasts in the context of post-vocalic liquid. Lengthening the vowel would increase the period where the vowel quality was less influenced by the liquid, which might partially overlap with it. In the larger picture, nasal consonants are another type of complex segment whose phonological patterning in rimes may benefit from further examination in light of these representations (Byrd et al. 2009).

6. Conclusion and further issues

Our account of the phonotactics of rimes with a post-vocalic liquid in GenAm has implications for phonological representation on two fronts: temporal structure and blending strength.

On the first point, our study supports representing temporal coordination relations directly between subsegmental units rather than indirectly through a segmental root node. Sequencing of subsegments *within* a segment is necessary to characterize the sequential realization of the dorsal(-pharyngeal) and coronal components of liquids in GenAm rimes, which has the potential to give rise to two moras. Further, partial lack of sequencing *across* segments is crucial to characterize those contexts where a coda liquid gives rise to only a single mora, due to partial overlap with the preceding vowel. A segment-based view of temporal ordering predicts that the subsegments within a segment will be deployed uniformly rather than showing evidence of independent coordination.

On the second point, our study finds support that subsegmental organization can be impacted by the specified blending strength of a gesture, a representation corresponding to its degree of coarticulatory dominance. Avoidance of overlap involving a gesture with high blending strength promotes sequential ordering of the vowel's lingual gesture and the rhotic's TB gesture in GenAm. However, just in the case of non-high back vowels, where the lingual gesture of the vowel and the TB gesture of the rhotic are similar in location and degree of constriction, overlap is permissible. This understanding brings explanation to the variable weight contribution of coda /ɹ/ in GenAm: it contributes two moras when its TB gesture is sequenced after the vowel, as in the case of front and high vowels, but it contributes a single mora when its TB gesture overlaps the vowel, as in the case of non-high back vowels.

The concepts of subsegmental coordination and blending strength are not new to this work; they have been supported by a variety of other studies (see §1, §4.1, Zsiga 1997, Smith 2018, etc.).

Our study serves to underscore that they are essential to achieving a simple understanding of something as well studied as the phonological structure and phonotactics of GenAm rimes. We envision that future work incorporating these properties in subsegmental representation can shed new light on other previously challenging phonological patterns.

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Appendix

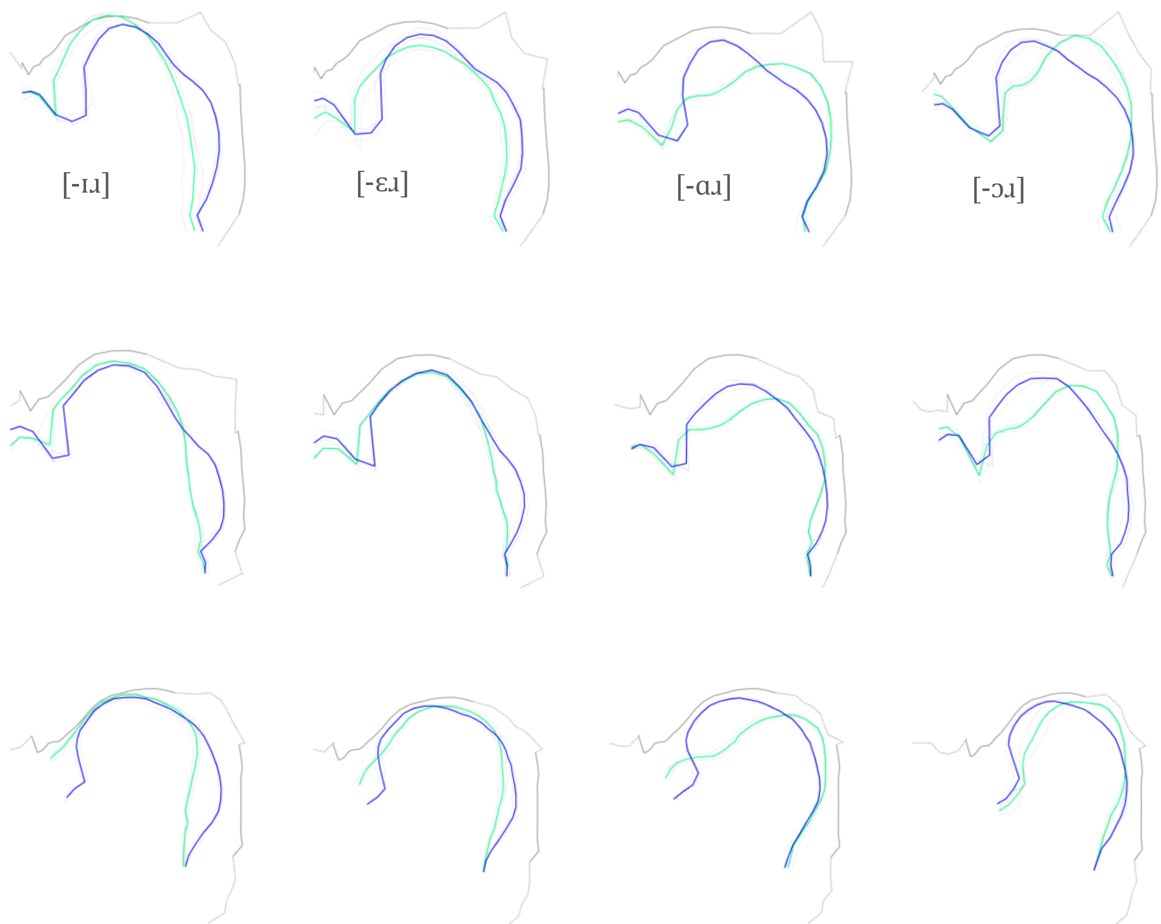

Figure 9: Target postures of pre-rhotic vowels (green tongue outlines), and coda rhotics following each vowel, captured at dorsal target (blue outlines). Left to right: : *'beer'*, *'bare'*, *'bar'*, *'bore'.* Top row: Speaker W2; Second row: Speaker W3; Bottom row: Speaker M1.