**Abstract**

**Gestural Characterization of a Phonological Class: the Liquids**
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**2009**

Rhotics and laterals pattern together in a variety of ways that suggest that they form a phonological class (Walsh-Dickey 1997), yet capturing the relevant set of consonants and describing the behavior of its members has proven difficult under feature-based phonological theory (Wiese 2001). In this dissertation, I argue that an articulatory characterization of liquids is better able to reconcile the essential aspects of their phonetic and phonological behavior.

I present data from a broad survey of rhotic and lateral phonology which suggest that, cross-linguistically, the two properties most commonly associated with liquids are their interchangeability (alternation, neutralization and allophony within the class), and their shared phonotactic distribution within the syllable. Liquids act as cluster-enabling segments in complex onsets and codas, most commonly appearing closer to the nucleus than obstruents; when liquids appear adjacent to the nucleus, they often interact with it.

Ultrasound studies were conducted to examine lingual articulation in the liquid consonants which pattern together in Spanish and Russian. Although the liquids in these languages differ in their acoustic properties, manners and places of articulation, they were found to be united by a lower susceptibility to vocalic coarticulation than coronal stops. In light of previous studies showing that rhotics and laterals are produced with both coronal and dorsal (or pharyngeal) constrictions in English (Delattre & Freeman 1968; Sproat & Fujimura 1993; Browman & Goldstein 1995; Gick et al. 2006), this suggests that liquids require more global control of tongue shape than obstruents (Goldstein p.c.). In the languages examined in this study, liquid consonants are characterized by the coordinative production of coronal and dorsal gestures.

I argue that coronal liquid consonants are segments corresponding to recurrent, stable constellations of gestures in which a tongue-tip approximation is coordinated

with a dorsal constriction. Such gestural configurations are inherently sonorous – due to the vocalic nature of the tongue body constriction and the incomplete or sporadic nature of the coronal closure – and therefore afford spontaneous voicing.

I propose that asymmetries in the distribution of liquids in onset and coda clusters result from differences in the coordination of their constituent gestures with respect to the syllabic nucleus. Differences between clear and dark laterals result primarily from differences in dorsal target locations. Differences between rhotics are attributed to variation in the stiffness and degree of damping of tongue-tip and tongue body gestures – trills and retroflex rhotics being characterized by a more highly constrained dorsum, and taps by a lightly damped tongue tip. Phonological processes involving interactions between liquids and nuclei – post-vocalic deletion, coloring and lengthening – result from the blending and interaction of adjacent and overlapping tongue body gestures.

# Gestural Characterization of a Phonological Class: the Liquids

A Dissertation
Presented to the Faculty of the Graduate School
of
Yale University
in Candidacy for the Degree of
Doctor of Philosophy

by
Michael Ian Proctor

Dissertation Director: Darya Kavitskaya

December 2009

## Acknowledgements

This dissertation could not have been written without the generous help of my family, friends, teachers, and colleagues. Thank you all.

I have been inspired by the community of researchers at Haskins Laboratories, especially Chris Shadle, Khalil Iskarous, Doug Whalen, Hosung Nam, Mark Tiede and Aude Noiray, and partially supported by NIH grants NIDCD RO1 DC 006705 and NIDCD RO1 DC 02717.

Erich Round, Tine Mooshammer, and the Yale Phonetics and CLAY groups have provided great feedback and encouragement along the way, and helpful critique of presentations. I was generously assisted by Shri Narayanan, Erik Bresch, the SPAN group at USC, and by my experimental participants and language informants.

It is my great fortune to have had wonderful teachers at Yale and the University of Queensland. I would like to thank Dianne Jonas, Charles Yang, Stanley Insler, Maria Piñango, Larry Horn, Carol Fowler, Rob Pensalfini, Mary Laughren, Michael Harrington, David Lee, Lynn Wales, and especially John Ingram, for encouraging me to pursue my interest in linguistics.

Above all, I am indebted to the members of my committee – Dasha Kavitskaya, Jelena Krivocapić, Steve Anderson and Louis Goldstein – for their wisdom, criticism and guidance. Thank you all for keeping me on track, sharing your ideas, and helping me come to a better understanding of phonetics and phonology.

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# Chapter 1

# Introduction

A central concern of phonological theory is to account for the fact that certain groups of sounds pattern together within and across languages. One of the most fundamental ways in which the members of a phonological class can pattern together is in their shared phonotactic distribution within the syllable. In most languages, for example, syllabic nuclei may only by filled by a member of the class of vowels. In coda position, some languages allow only nasals (e.g. Manam, Twi, Mokilese), while languages which allow complex onsets typically constrain the ordering of consonants within the cluster according to phonological class (Sievers 1881).

A group of consonants which plays an important role in the phonotactics of the syllable is *the liquids*: a diverse set of sounds whose constituency varies from language to language, but typically includes trills, taps, and lateral approximants. Unlike more canonical major classes such as nasals, stops and vowels, there is no simple phonetic property which is universally shared by all members; however, the phonological evidence for a class of liquids is compelling. Cross-linguistically, the bulk of this evidence involves syllable-level phonotactic constraints.

For example, syllable structures differ considerably between Slavic and Romance languages, in terms of the permissible length of onsets, the consonants licensed in coda position, and the sequencing constraints at both ends of the syllable. Yet when we list all of the maximal onsets found in Russian and French (Table 1.1), we can see that despite these differences, both languages share the common property that syllable onsets of a certain level of complexity must be liquid-final.

These phonotactic parallels are even more remarkable when we consider the variety of consonants which function as liquids in French and Russian. The segments which occur in cluster-final position in the words in Table 1.1 include alveolar,

| Russian: #CCCC- | | |
|---|---|---|
| /fspl-/ | всплыть | 'come to light' |
| /fspl$^j$-/ | всплеск | 'splash' |
| /fspr-/ | вспрыснуть | 'to spray' |
| /vzbr-/ | взброс | 'upthrust' |
| /vzdr-/ | вздрогнуть | 'to shudder' |
| /vzdr$^j$-/ | вздремнуть | 'to snooze' |
| /fstr$^j$-/ | встреча | 'meeting' |
| /fskr-/ | вскрыть | 'to open' |
| /fskr$^j$-/ | вскритнуть | 'to cry out' |
| /vzgl$^j$-/ | взгляд | 'glance' |
| /vzgr$^j$-/ | взгрустнуться | 'to feel sad' |

| French: #CC- | | |
|---|---|---|
| /pʀ-/ | *précis* | 'precise' |
| /pl-/ | *placer* | 'to put' |
| /bʀ-/ | *bravo* | 'bravo' |
| /bl-/ | *blaguer* | 'to joke' |
| /fʀ-/ | *frapper* | 'to hit' |
| /fl-/ | *flatter* | 'to flatter' |
| /tʀ-/ | *tracer* | 'to trace' |
| /dʀ-/ | *drapeau* | 'flag' |
| /kʀ-/ | *craquer* | 'to crack' |
| /kl-/ | *classer* | 'to classify' |
| /gʀ-/ | *grater* | 'to scrape' |
| /gl-/ | *glacé* | 'frozen' |

Table 1.1: **Liquid-final maximal onset clusters in Russian and French**. (French examples taken from Colantoni & Steel, 2005).

palatalized and uvular trills, uvular fricatives, as well as dental, clear, palatalized and velarized lateral approximants. In both languages, rhotic and lateral realization also varies considerably with dialect, register, idiolect and speech rate. The question to be addressed in this dissertation is the following: why is it that such a diverse group of consonants patterns together in the phonological structure of languages?

## 1.1 The Class of Liquids

The phonological concept of 'liquid' has always been a variable, language-specific category. The word ὑγρός was originally used by Greek grammarians to describe a class of laterals $\{\lambda\}$, rhotics $\{\rho\}$ and nasals $\{\mu, \nu\}$. The term referred to the 'fluidity' of syllable weight in Greek prosodic structure, because two different syllabifications involving liquids were possible (Allen 1973). In Homeric Greek, because laterals, rhotics and nasals did not cluster, a preceding obstruent would be syllabified as a coda (Table 1.2). In Attic Greek, obstruent-liquid clusters were tolerated, resulting in open syllables before such clusters (Walsh Dickey 1997).

The Latin translation of the Greek term – *liquidus* – referred only to the consonants /l/ and /r/ because they shared distributional properties distinct from the nasals in Latin, such as *muta cum liquida* ('stop with liquid'), which also described the phonotactics of syllable onset clusters. It was the Latin conception of the class which survived into the philological literature because similar affinities between 'l-like' and 'r-like' segments were observed in many other languages (Walsh Dickey

1997).

| LANGUAGE | SYLLABIFICATION | LIQUIDS |
|---|---|---|
| Homeric Greek | *pat.ros, ep.le.to, reg.mi.ni, tek.non* | — |
| Attic Greek | *pa.tros, e.ple.to, re.gmi.ni, te.knon* | {/r/,/l/,/m/,/n/} |
| Latin | *pa.trem, du.plo*, *[$_\sigma$CN | {/r/,/l/} |

TABLE 1.2: **The language-specific constituency of the class of liquids**: contrasting syllabifications in Homeric Greek, Attic Greek and Latin.

### 1.1.1 Scope

Although the class of liquids consists of laterals and rhotics, not all lateral consonants pattern as liquids. A variety of sounds can be lateralized, including clicks (e.g. Xhosa[1] [kǁ], [ŋǁ]; Hadza [ᵏǁ], [ᵑǁ]), fricatives (Welsh, Navajo, Zulu: [ɬ], [ɮ]) and affricates (Tswana, Nahuatl: [t͡ɬ]). Because these sounds all typically involve a greater stricture of the tract than that employed in the production of lateral approximants, they may be classified as lateral obstruents. Such sounds are not especially rare: 54 (9.5%) of 567 languages surveyed by Maddieson (2008) were found to use lateral obstruents, including eight languages which use no lateral approximants.

Walsh Dickey (1997) demonstrates that lateral obstruents tend to pattern with the other obstruents, rather than the lateral approximants, in languages where they co-occur. The Semitic language Jibbali, for example, has a constraint prohibiting multiple coronal sonorants in roots, yet allows lateral obstruents and approximants to co-occur in roots such as /ɬʔl/ *'honeycomb'* and /ɮwl/ *'grumbling'* (Johnstone 1981). Most of the phonological behavior shared by lateral approximants and rhotics (examined in detail in Chapter 2 and briefly summarized below) does not typically involve lateral obstruents, and for these reason they are not considered to be members of the class of liquids.

The group of consonants which will be examined in this dissertation is the set of rhotics and lateral approximants. The term 'lateral' will be used throughout to refer to 'lateral approximants', unless otherwise indicated.

[1] References for languages cited by name only may be found in Appendix A.

## 1.2 Phonological Behavior of Liquids

It is not only in their common distribution that laterals and rhotics pattern together; other types of evidence for a class of liquids can be found throughout the phonology of many languages. Liquids pattern together in a wide range of synchronic and diachronic processes including metathesis, dissimilation, assimilation and harmonization. Historically, laterals and rhotics have merged in some languages (Maori, Campidanian Sardinian, Unua) and split in others (Avok, Maskelynes). Postvocalic liquids can become vowels, lengthen or color the preceding vowel, or disappear all together (Australian English, Dyirbal).

Some of the most compelling evidence for the class is the widespread phenomenon of liquid allophony. Rhotics and laterals often alternate with each other, or neutralize in certain environments (Cuban Spanish, Jamsay). In languages with a single liquid, this segment may be variously realized as a rhotic or a lateral, sometimes in free variation (Sentani, Jita), sometimes idiolectally, and sometimes in a phonologically conditioned manner (Gonja, Sranan, Japanese). Both free variation and phonologically-conditioned allophony are also attested amongst rhotics and laterals in languages with rich liquid inventories (Hausa, Kikongo Kituba).

A comprehensive cross-linguistic review of the phonology of liquids is presented in Chapter 2. Typological surveys of liquid phonology have previously been used to argue for the existence of a universal natural class of liquids (Walsh Dickey 1997). In fact, this body of data demonstrates only that different groups of rhotics and laterals constitute different types of phonological classes in many languages. Sometimes rhotics and laterals pattern together exclusively, and sometimes they act as members of a broader set of sonorants. Not all languages allow syllabic liquids, for example, and many of those that do also allow syllabic nasals (e.g. Czech).

Nevertheless, despite differences in the way that laterals and rhotics pattern with the other sonorants, liquids repeatedly exhibit many of the same fundamental properties across languages. The picture which emerges from a cross-linguistic examination of liquid behavior is that of a group of consonants which are broadly characterized by three important properties:

i. *a capacity to facilitate clustering* in onsets and codas
ii. *an affinity for the nucleus*, observed in their distribution in clusters and ability to function as syllabic consonants
iii. *a degree of interchangeability within the class*, manifest in allophony, neutralization and other phenomena

Given that laterals and rhotics share such fundamental properties, the next question to be considered is how they might be collectively captured. Our concern here is to arrive at a phonological representation which not only selects the appropriate set of consonants, but does so in a way which best accounts for the shared properties of the class.

## 1.3 Capturing the Class of Liquids

Capturing classes of liquids and describing the behavior of their members has proven difficult under feature-based phonological theory. Liquids resist phonological description in two main ways. Because different groups of consonants pattern together as liquids in different languages, it is difficult to find a single set of well-motivated features which will select all of but only the participating consonants in any given language. Secondly, the features which have been proposed to describe liquid consonants, and the hypothesized relationships between them, have not proven adequate to describe the range of behaviors which characterize the class.

### 1.3.1 The Feature [sonorant]

In many languages, the class of liquids can be captured using the feature set {+cons, +son, -nasal}. This is the case in Brabant Flemish, for example, where the lateral approximant /l/ and coronal trill /r/ function as a natural class by virtue of their common distribution in onset clusters.[2] In the southern Netherlands, many Dutch speakers use an uvular fricative rhotic /ʁ/ rather than an alveolar trill (Verstraeten & Van de Velde 2001). Since the fricative in these dialects patterns with the lateral in exactly the same ways, the set {/l/,/ʁ/} constitutes a functionally identical class of liquids to {/l/,/r/}; however, it cannot be captured using the same feature set because, by definition, it contains an obstruent.

Similar problems arise when trying to describe liquids in varieties of French, German, Portuguese, and other languages which use fricative rhotics, since the relevant class cannot be captured by making reference to the feature [sonorant]. Although the uvular fricatives [ʁ] and [χ] commonly alternate with the sonorant trill [ʀ] via phonetically transparent processes, capturing an underlyingly 'obstruent' rhotic, while excluding the other voiced fricatives which do not pattern with the lateral, is fundamentally problematic under an approach to liquid classhood which is predicated exclusively on distinctive features.

2 For example, all three-consonant onsets in Dutch end with either a lateral or rhotic (Table 2.5).

### 1.3.2 The Feature [approximant]

Padgett (1995) proposed that stricture features are not bound to a global root node, but rather are associated with individual articulators. Under this approach, a class of liquids may be defined over any group of segments with an oral articulator node bearing the feature specification {+cons, +approximant}. However, it is still impossible, even under Padgett's geometry, to collectively define a class of liquids using stricture features if that class includes a fricative.[3] In Chapters 5 and 8, I propose a phonological model of liquid consonants which bears similarities to Padgett's representation in that specifications for stricture are localized, rather than global, but differs in the important respect that these specifications are neither binary nor privative.

### 1.3.3 The Feature [liquid]

Because it has proven difficult to capture the liquids with the same features used to describe other major classes, a number of additional features have been proposed. Walsh Dickey (1997), for example, proposes the major class feature [liquid] in order to distinguish nasalized and non-nasalized trills, which are contrastive in Igbo: *ịrị́* 'to creep' / *ịr̃ị́* 'to climb' (Dunstan 1969). I suggest that the need to stipulate additional features of this type in order to account for a single contrast found in small number of languages reveals more about the limitations of distinctive feature theory than the nature of liquids. Although there is no broad phonological or phonetic evidence for the feature [liquid], there is nevertheless a "necessity for (the) new feature" (Walsh Dickey 1997: 150) under a theoretic framework in which phonological classhood is exclusively defined over sets of universal distinctive features. In Chapter 9, I present an account of liquid nasalization which is compatible with overlapping, gesturally-defined classes of nasal and liquid sonorants.

The examples of Dutch and Igbo demonstrate that the problem of describing the class of liquids bears on a fundamental issue in phonological theory: whether phonological primitives should be phonetically grounded (Fant 1960; Jakobson et al. 1952; Stevens et al. 1986), or pure abstractions reflecting phonological organization independent of phonetic principles (Fudge 1967; Anderson 1981). Features which have been proposed to describe more canonical classes – such [voiced] and [nasal] – satisfy both schools of thought because they are phonetically well-motivated and also reflect universal principles of phonological organization. Features such as [liquid] (Dixon 1972; Walsh Dickey 1997; Hall 2009), on the other hand,

3 According to Cruz Ferreira (2004), for example, the liquid phonemes of European Portuguese are {/l/,/ɾ/,/ʁ/}. See Wiese (2001a,b) for further discussion of the problem of representing fricative rhotics.

are essentially stipulative because they are neither grounded in phonetic principles nor justified by a broad cross-linguistic body of phonological data.

## 1.4 Phonetic Characterization of Liquids

Having seen that liquids resist collective classification under feature-based phonological theory,[4] we now consider whether these consonants might be characterized more successfully in the phonetic domain. Before considering the phonetic properties of the class of liquids as a whole, we must first examine the phonetics of rhotics and laterals.

### 1.4.1 Phonetic Properties of Rhotics

Because of the great diversity of *r*-like segments which pattern together, phonetic characterization of rhotics is especially problematic. A wide variety of manners (fricatives, trills, taps, approximants and vowels) and places of articulation (dental, alveolar, retroflex, uvular and pharyngeal) are used in consonants which function as rhotics in the phonology of various languages. The consonants most commonly classified as rhotics are shown in Figure 1.1 (Magnuson 2007). Although the phonetic differences between segments occupying adjacent nodes on the graph might be minimal ([ʐ]–[ɻ] primarily differ in stricture), differences between consonants on peripheral nodes can be radical ([ʊ]–[ʀ̥] differ in place, manner and voicing).

The search for acoustic properties shared by all consonants considered to be phonological members of this heterogeneous class has proven elusive. For example, Lindau (1978) proposed that rhotics might be characterized by a lowered 3rd formant, but Ladefoged & Maddieson (1996) concluded that a low F3 serves as an acoustic correlate to particular set of articulatory configurations which characterize many types of rhotic, but not uvulars nor dentals. In Chapters 4 and 7, the acoustic properties of Spanish and Russian rhotics will be examined in greater detail, where it will be shown that neither F3, nor any other acoustic property appears to be invariant across the complete set of rhotics which pattern together in either language.

In the case of English, the search for common articulatory characteristics among rhotics has proven to be more fruitful than the quest for acoustic invariants. Although Delattre & Freeman (1968) found at least six different types of American English /ɹ/, two broad articulatory configurations – bunched and retroflex – were

[4] For additional critique of feature-based approaches to capturing the class of liquids, see Wiese (2004) and Mielke (2005, 2008).

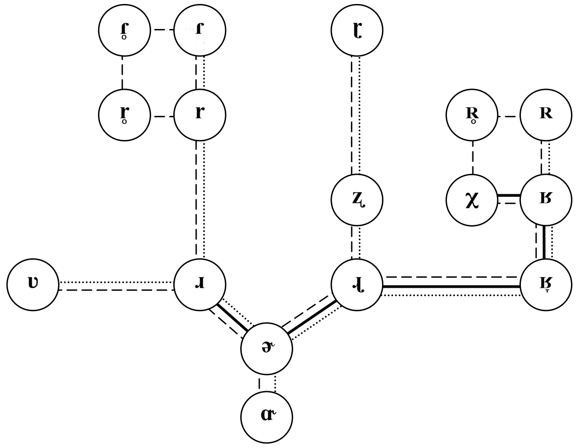



FIGURE 1.1: **Consonants which function as rhotics**, organized according to the phonetic associations between them (Magnuson 2007, after Lindau 1978).

identified, both of which employ a coronal and a pharyngeal constriction. Cineradiographic studies by Zawadzki & Kuehn (1980) supported the characterization of American English /ɹ/ as a coronal-pharyngeal approximant, and Gick et al. (2003) found that English /ɹ/, despite its great variation, is invariably produced with three components: a labial, anterior lingual, and tongue root gesture. By allowing for greater freedom in the degree, rather than the place of constriction of each of these constituent gestures, the authors make the case for a common articulatory characterization of the diverse set of rhotics found in American English.

### 1.4.2 Phonetic Properties of Laterals

As with the rhotics, laterals in many languages display a considerable degree of allophonic and acoustic variation, yet here too, research has indicated that, at least in the case of English, these consonants may be characterized more easily in articulatory terms.

In a cineflurographic study of American English /l/, Giles & Moll (1975) found that the lingual dorsum shape was essentially constant for all of the allophones which they studied, and that the dorsal contours were similar to those observed in vowels. In an EPG study on the vocalization of syllable-final /l/ in Southern British English, Hardcastle & Barry (1989) concluded that dark-/l/ is defined by two articulatory components, each with a corresponding acoustic correlate.

Based on the findings of these studies, and their own examination of American English X-ray microbeam data, Sproat & Fujimora (1993) proposed a unified model of /l/ as a complex segment consisting of two coordinated gestures: a vocalic dorsal gesture, and a consonantal coronal gesture. Asymmetries were observed in the relative timing of these components: the vocalic gesture preceded the consonantal gesture in codas, and lagged in onsets. The authors argue that the clear/dark allophony of English /l/ results from these timing differences, as well as the "greater retraction and lowering of the tongue dorsum" observed in darker variants of /l/.

### 1.4.3 Phonetic Properties of Liquids

While numerous studies have addressed the individual phonetics of laterals and rhotics, relatively little investigation has been made into the phonetic properties of liquids as a class. If rhotics and laterals can both be characterized in terms of multiple coordinated lingual gestures, then this suggests that the class of liquids might be defined in similar terms.

In an MRI study of American English, Gick et al. (2002) showed both [ɹ] and [ɫ] to be produced with coronal and dorsal components. The data revealed that the dorsal constriction in both liquids strongly resembles those of low back vowels (Fig. 1.2).

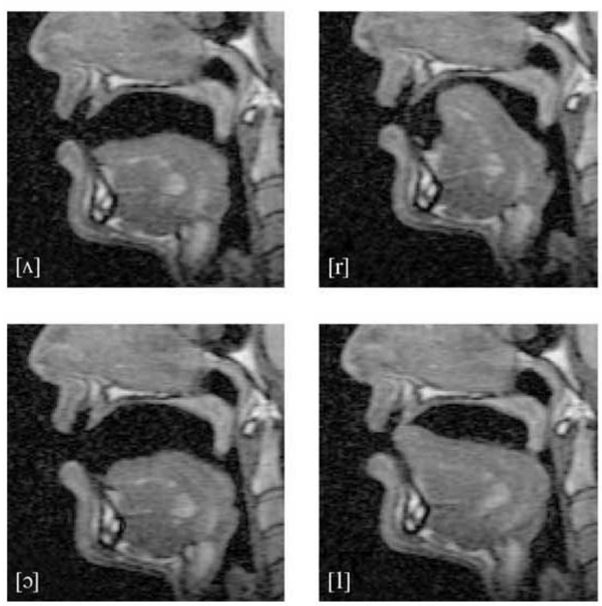



FIGURE 1.2: **Articulatory commonalities between English liquids and vowels**. Midsagittal MRI of male speaker of American English showing [ɹ] and [ɫ] to be produced with coronal and vowel-like dorsal constrictions (Gick, Kang & Whalen 2002).

In one of the few cross-linguistic studies of the phonetics of liquids, Gick et al. (2006) identified some common tendencies in Salish, Serbo-Croatian, Korean, Mandarin and English. Post-vocalic liquids in each of these languages were invariably found to have a measurable dorsal constriction, and multiple simultaneous gestures were observed during the production of liquids in intervocalic positions. These findings are consistent with the idea that the class of liquids might be characterized in articulatory terms; however, in order to test this claim further, a much broader body of phonetic data is required.

The bulk of the phonetic data on liquids has been obtained from American English speakers, yet from a typological perspective, the liquid system of English is atypical. Only 7% of languages surveyed by Maddieson (1984) use an approximant rhotic, while tongue-tip trills occur in 41% of all languages, and in 55% of languages which feature at least one rhotic (75% of all languages).

English also uses a smaller set of liquids than many languages: 18% have at least two rhotics, 31% contrast more than one lateral phoneme, and some (Kaititj, Diyari) use as many as four different lateral liquids (Austin, 1981; Ladefoged & Maddieson, 1996). Even among the many languages which use a two-liquid system, there is a tremendous variety in the segments which are contrasted. A better understanding of the phonetic similarities and differences between these consonants is critical to a proper understanding of the nature of liquids. To begin to address this deficit, this dissertation presents articulatory and acoustic data obtained from speakers of two languages with diverse liquid inventories: Spanish and Russian.

## 1.5 Representing Liquids in the Articulatory Domain

In order to formally characterize the class of liquids in articulatory terms, we require a theoretical framework in which there is a principled relationship between articulation and phonological primitives. One such approach, which will be the primary framework used throughout this dissertation, is the program of articulatory phonology, represented in the work of Browman & Goldstein (1986, 1992, 2000), Goldstein & Fowler (2003), Saltzman (1986), Saltzman & Munhall (1989), Byrd (1996), Nam et al. (in press), Gafos (1999, 2002) and others. In the following sections, the main principles of articulatory phonology are briefly summarized.

### 1.5.1 Gestural Primitives in Phonology

The central claim of articulatory phonology is that the basic units of production, perception, and mental representation of speech are one and the same, and that these units are coordinated dynamic actions of the vocal tract, or articulatory gestures. Utterances are hypothesized to consist of coordinative structures, or 'constellations' of gestural primitives. Gestures represent both the most primitive linguistically-significant actions of the vocal tract, and the most primitive informatic units of phonology.

### Coordinative Structures of Gestures

In articulatory phonology, the phonological representation of an utterance consists of a set of gestures and the coordinative relationships between them, rather than strings of segments or tiers of features. This phonological structure can be represented with a *coupling graph* (Nam et al. in press) which indicates the constituent gestures and the coordinative relationships between them. If the phonological system is modeled as an undamped system of oscillators, as any coupled coordinative system may be (von Holst 1973, Turvey 1990), then these relationships can be expressed in terms of the relative phasing of the timing cycles of each gesture (Browman & Goldstein 1992). Gestures which are coupled in-phase (0°) represent synchronous events; all other phase relationships represent asynchrony between the coupled gestures – the greater the phase, the greater the degree of asynchrony.

The phonological structure of the English word *bad*, for example, can be represented in the coupling graph shown in Fig 1.3. The word is produced with a labial closure gesture which is synchronously coordinated with a vocalic tongue body gesture, so these gestures are modeled as being in an in-phase coupling relationship, represented by an edge in the graph. The alveolar tongue-tip closure which produces the coda consonant begins later than the vocalic and labial onset gestures – a timing relationship which is modeled as an asynchronous coupling to the nucleus, indicated using a dashed edge in the coupling graph.

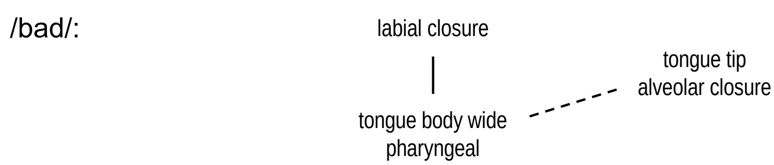



FIGURE 1.3: **Coupling Graph illustrating the phonological structure of the word /bad/**

The phonological structure of the word *pad* differs from *bad* only in that there is an additional glottal abduction gesture coupled to the onset and nucleus gestures (Fig. 1.4).

This simple but powerful model of phonological organization – in which onset gestures are universally coupled in-phase with vocalic nuclei, and coda gestures

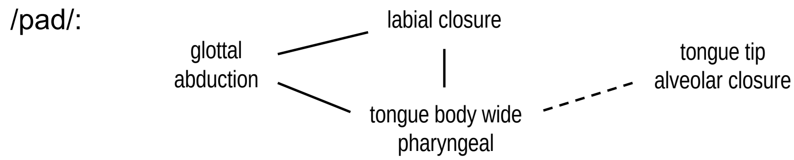



FIGURE 1.4: **Coupling Graph of the word /pad/**

coupled anti-phase to the nucleus – has been used to account for typological preferences in syllable structure (Nam et al. in press), developmental phonological phenomena (Goldstein & Fowler 2003), and asymmetries in clustering (Chitoran et al. 2002). All of these phenomena are especially relevant to liquid consonants, and in Chapter 9 I argue that the most important phonological properties of the class follow from fundamental principles of syllable-level gestural organization, if liquids are modeled as segments comprised of multiple lingual gestures.

### The Gestural Basis of Segmental Structure

In an articulatory view of phonological structure, segments are not considered to be atomic phonological primitives, but correspond to recurrent stable coordinative structures of gestures. Although the set of contrasts which can be created from a finite combinatorial system of gestural primitives is potentially infinite, utterances in any language are constructed from a small set of contrastive gestural combinations. Those subconstellations of gestures which are repeatedly exploited in the phonology of a language may be modeled at a higher level of abstraction as segments or phonemes.[5]

For example, a labial closure is frequently coordinated with a glottalic opening at the beginning of an English word. If the phasing of these gestures is slightly asynchronous – sufficient to create an aspiration burst – we recognize this pattern as a /p/, while a speaker of Hindi would recognize the same coordinative pattern as another type of segment (/$p^h$/). The Hindi speaker would also control an additional phonologically contrastive coordinative structure in which the glottal and labial release gestures were perfectly synchronous – a structure which would correspond to the Hindi segment /p/ (but might be recognized as a /b/ by an English speaker because of the lack of aspiration).

5 Especially for literate speakers, it seems clear that a certain amount of linguistic processing occurs at the level of the segment (e.g. Dehaene-lambertz & Gliga, 2004); however, the case will be made in this dissertation that liquid consonants, like all segments, are essentially epiphenomena which are better modeled as constellations of gestures than bundles of features.

Gestural models of segmental structure have been used to account for lateral allophony in English (Sproat & Fujimura 1993; Browman & Goldstein 1995), and ambisyllabicity in English glides and laterals (Gick 2003). Evidence for the gestural constituency of Spanish and Russian liquids will be presented in Chapters 5 and 8, and in Chapter 9, the case will be made that a gestural model of consonant structure can be extended to account for some cross-linguistic properties of the class of liquids, including the distributional preferences of liquids in syllable structure.

### 1.5.2 Tract Variables

An important characteristic of gestures – one which differentiates them from the static primitives hypothesized in other theories of phonology – is that they are inherently dynamic (Browman & Goldstein 1995). It is the dynamic nature of gestures which allows them to be described using the same formalisms which have been used to describe the behavior of other systems of limbs and articulators. In the task dynamic model of gestural coordination (Saltzman 1986; Saltzman et al. 1987; Saltzman & Munhall 1989), linguistic gestures are modeled in terms of *tract variables*: a discrete set of parameters which describe the configuration of the vocal tract.

Each tract variable corresponds to a single dimension of a linguistically-salient vocal tract constriction which is exploited in phonology. Tract variables provide an important abstraction away from the behavior of individual articulators, because evidence from jaw perturbation (Kelso et al. 1984, Ito et al. 2000) and coarticulation studies (Öhman 1966) suggests that the goals of speech, like any skilled motor activity, are *task-specific* (Saltzman 1986).

For example, the words *bad* and *bid* share an initial labial gesture, however the realization of this gesture can differ considerably between the two words because, due to vocalic context, the jaw will typically be lower during the production of *bad*. The common goal is to achieve complete closure of the lips, but this can be achieved through an infinite number of combinations of movements of the lower lip, upper lip and jaw, which all operate with some degree of independence. Although the individual trajectories of the lips and jaw can be seen to vary between speakers, contexts and utterances (Kelso et al. 1984), the net result – the *task* – is the same in each case: bilabial closure. This behavior is therefore better characterized in terms of a *lip aperture* variable, rather than the activity of the individual articulators which collaborate to achieve the linguistic goal.

A set of eight tract variables has proven sufficient to model much of the phonology of English in an articulatory framework. These tract variables, and the articulators associated with each variable, are enumerated in Table 1.3.

| Tract Variable | | Associated Articulators |
|---|---|---|
| **LP** | lip protrusion | upper lip, lower lip, jaw |
| **LA** | lip aperture | upper lip, lower lip, jaw |
| **TTCL** | tongue tip constriction location | tongue tip, tongue body, jaw |
| **TTCD** | tongue tip constriction degree | tongue tip, tongue body, jaw |
| **TBCL** | tongue body constriction location | tongue body, jaw |
| **TBCD** | tongue body constriction degree | tongue body, jaw |
| **VEL** | velic aperture | velum |
| **GLO** | glottal aperture | glottis |

Table 1.3: **A set of track variables and associated articulators** (Browman & Goldstein 1992)

The utility of the concept of tract variables as a means of describing phonological behavior can be demonstrated by reconsidering the pronunciation of the English word *bad*. As with any utterance, this involves orchestrating the speech articulators in such a way as to reproduce a coordinated system of gestures which corresponds to the mental representation of the word (Fig 1.3). The mapping from the phonological representation to the physical articulation involves a planning process whose output can be modeled as a steady-state solution of a dynamic system of oscillators, each associated with a specific tract variable. A solution to this system will consist of a set of stabilized relative phases between articulators which will dictate the timing and coordination of the gestures involved in the production of the utterance (Nam et al. in press). This resulting organization of tract variable activation can be schematized using a gestural score.

A gestural score depicts the behavior of tract variables (organized vertically) over time (horizontal axis). The gestural score in Table 1.4 indicates that the activation intervals for the labial closure and the tongue body gestures are triggered synchronously, that the vowel gesture lasts longer than that of the onset consonant, and that the tongue-tip closure gesture (whose planning oscillator has converged into an anti-phase relationship with the others) is triggered last.

### Testing Gestural Hypotheses

The task dynamic model of phonological organization makes specific predictions about the dynamic behavior of articulators, which can be compared to real phonetic data. An important component in this methodology is computational simulation. The TADA system (TAsk Dynamic Application; Nam et al. 2004) is a software suite designed for modeling gestural representations of utterances and simulating ar-

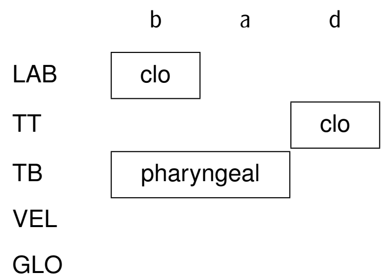



TABLE 1.4: **Gestural score of the word /bad/**, illustrating the temporal organization of the constituent tract variables.

ticulation using the principles summarized in this section. In Chapters 5 and 8, gestural models of Spanish and Russian liquid consonants will be described which have been tested and refined by comparing the output of computational simulations with articulatory data obtained from ultrasound experiments.

### 1.5.3 The Gestural Structure of Liquids

The central hypothesis of this dissertation is that coronal liquids are consonants which prototypically involve the coordination of a consonant-like tongue tip gesture with a vowel-like tongue body gesture. In the phonological representation of a liquid consonant, this intrinsic coordination is modeled as a coupling relationship between tongue body and tongue tip gestures, and constrasts with the single gesture which defines a stop (Fig. 1.5).

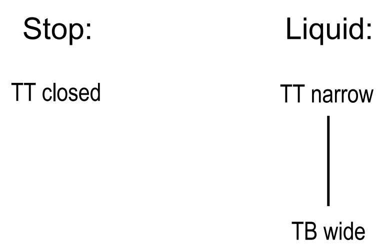



FIGURE 1.5: **Contrasting phonological representations of coronal stops and liquids**.

Articulatory data presented in Chapters 4 and 7 show that the tongue dorsum is largely controlled by context vowels during the articulation of a coronal stop. During the production of a liquid, on the other hand, the tongue dorsum is less susceptible to the effects of vocalic coarticulation, and typically moves toward an independent constriction target. These results are consistent with a model in which the tongue tip gesture of a stop is coupled only to the tongue body gesture of an ambisyllabic vowel, in contrast to the tongue tip gesture of a liquid, which is coupled to its own tongue body gesture as well as that of the vowel. In the gestural scores compared in Figure 1.6, the trajectory of the dorsum during the articulation of a liquid onset is shown to be a function of the competing influence of the gestures associated with both the vowel and the liquid.

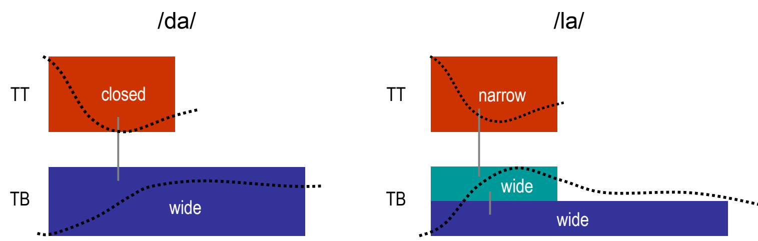



FIGURE 1.6: **Gestural timing and lingual trajectories in coronal stop and liquid onsets**.

Under an articulatory model, there is no distinction between primary and secondary articulations. A liquid consonant is characterized as a constellation of associated gestures, and its phonetic properties are the result of the dynamic interaction of these gestures with others in the syllable. Lateralization in English and Russian [ɫ] , for example, results primarily from the temporal coordination of a retracted dorsal gesture with an alveolar closure gesture, which elongates the tongue: the pharyngeal gesture is intrinsic to this type of lateral, and should not be considered 'secondary' or 'enhancing', as implied by the segmental representations /lˤ/ and /lˠ/. Likewise, Russian and Spanish rhotics are produced with a stabilized mid-oral dorsal gesture coordinated with a tongue blade approximation gesture, which results in tongue tip trilling if the appropriate aerodynamic conditions are met. Both tongue body and tongue tip gestures are critical to trill production, and the segment is result of their coordination.

Despite the wide range of locations and degrees of constriction associated with all of these different gestures, it will be shown that the common factor uniting the diverse set of laterals and rhotics examined in this dissertation is that they are all produced with a relatively open, temporally stable dorsal gesture, coordinated with a more constricted tongue tip gesture of the same, or shorter duration.

## 1.6 Organization of the Dissertation

In Chapter 2, the phonology of liquids is investigated in detail. The nature of the class is examined by reviewing the ways in which rhotics and laterals pattern together in a diverse sample of languages. Some differences in the distribution and behavior of rhotics and laterals are discussed. Based on the results of this survey, the most fundamental phonological properties of liquid consonants are identified.

In the remainder of the dissertation, I examine liquid systems of two languages in detail to consider the relationships between their phonetic and phonological properties.

In Chapter 3, the phonology of Spanish liquids is addressed. The three liquid consonants of Spanish provide an important case study because of their distributional and allophonic behavior. The two rhotics are contrastive only in one environment, and neutralize elsewhere. The Spanish lateral is pronounced as a clear [l] in all environments, and neutralizes with rhotics in coda position in some dialects. In Chapter 4, experimental data examining liquid articulation is presented, and in Chapter 5, articulatory models of Spanish liquids are proposed to reconcile the phonetic and phonological data.

The second language to be studied is Russian – a language of interest because of its unusual consonant clusters, which seem to present a counter-example to the phonotactic characterization of liquids proposed in Chapter 2. The phonotactics of the Russian syllable are examined more closely through corpora analysis in Chapter 6, where contrastive palatalization in Russian consonants is also considered. An experimental study of Russian palatalized and non-palatalized liquid production is presented in Chapter 7. Articulatory data from this study is used to extend the articulatory model of coronal liquid consonants in Chapter 8, and gestural accounts of some synchronic and diachronic phenomena involving Russian liquids are proposed.

In Chapter 9, the broader implications of a gestural phonological model of liquid consonants are considered. The role of gestures in the phonological acquisition of liquid consonants is examined. Theories of syllablic organization are addressed, and a gestural basis for some cross-linguistic phonotactic phenomena is proposed. An account of some allophonic and historical changes changes involving liquids is presented. Finally, some unresolved issues in the gestural representation of liquids are outlined. The dissertation concludes with a summary of the most important experimental findings and a reiteration of the major theoretical claims.

# Chapter 2

# Phonological Characterization of the Class of Liquids

In this chapter, the phonological behavior of liquids will be examined from a cross-linguistic perspective. The groups of rhotics and laterals which function as a class in different languages will be identified, and the different ways in which they pattern together will be described. Based on the results of this survey, three fundamental properties which characterize the class of liquids will be proposed. Finally, some asymmetries in the phonological behavior of rhotics and laterals will be addressed.

## 2.1 Distributional Behavior of Liquids

Rhotics and laterals share many distributional properties, within and across languages, that suggest that they form a phonological class. Some word-level phonotactics involving rhotics and laterals will first be identified, before constraints on the distribution of liquids in the syllable are examined.

### 2.1.1 Distribution within the Word

**Word-Initial Constraints**

In some languages, laterals and rhotics are together subject to word-level distributional restrictions which do not always apply to other approximants. Walsh Dickey (1997) cites eight languages in which there exists a word-initial prohibition on all liquids. Her survey has been augmented with another nine languages and language families in which liquids are (or were) prohibited word-initially (Table 2.1). Although many of these languages are Australian, this phenomenon cannot be simply dismissed as an isolated areal feature, because the same constraint applies also in the Turkic languages, Kuman and Nii (New Guinea), Dizin (Afro-Asiatic) and Tamil (Dravidian).

| LANGUAGE | LIQUID CONSONANTS |
|---|---|
| Nii | /l/ |
| Korean | /l/ |
| Dizin | /l/, /r/ |
| Mongolian | /l/, /r/ |
| Turkic | /l/, /ɾ/ |
| Djabugay | /l/, /r/, /ɹ/ |
| Guugu Yimidhirr | /l/, /r/, /ɻ/ |
| Warrgamay | /l/, /r/, /ɹ/ |
| Yidiɲ | /l/, /r/, /ɹ/ |
| Mbabaram | /l/, /r/, /ɻ/ |
| Kuman | /l/, /ʟ/, /ɾ/ |
| Tiwi | /l/, /r/, /ɹ/, /ɻ/ |
| Mayi | /l/, /ɭ/, /r/, /ɹ/ |
| Tamil | /l/, /ɭ/, /r/, /r̠/, /ɻ/ |
| Diyari | /l/, /l̪/, /ɭ/, /ʎ/, /r/, /ɹ/ |
| Panyjima | /l/, /l̪/, /ɭ/, /ʎ/, /r/, /ɾ/ |
| Pitta-Pitta | /l/, /l̪/, /ɭ/, /ʎ/, /ɽ/, /ɻ/ |

TABLE 2.1: **Constraints on liquid distribution**: *word-initial.

In some cases, the prohibition on word-initial liquids is a historical constraint. Although the lexicon of Modern Turkish, for example, contains hundreds of liquid-initial loan words, these all originate from non-Turkic languages, and are greatly outnumbered by words beginning with other classes of consonants.[1] Likewise, there are no liquid-initial words indigenous to Tamil, but the modern language uses some loan words violate which this constraint: rūpāy [ruːbaːj] *'rupee'*, rācā [raːʃaː] *'long'* (Kuno 1958). No liquid-initial words are attested in Korean (isolate) before the influx of Chinese vocabulary into the language in the 5th Century, and the resistance against initial liquids can be seen in the nativized forms of some of these early borrowings (Cho 2001, Table 2.2).

| CHINESE | KOREAN | GLOSS |
|---|---|---|
| /lok/ | /nok/ | 'green' |
| /lampi/ | /nampi/ | 'pot' |
| /ljuk/ | /nuk/ | 'six' |
| /latjən/ | /nacən/ | 'Latin' |

TABLE 2.2: **Korean Nativization of Liquid-Initial Words**.

Walsh Dickey (1997) observes that Kuman (Trans New-Guinea) uses three liquids – including the rare velar lateral /ʟ/ – none of which may occur word-initially (Pfantz & Pfantz 2005), so this phenomenon cannot be explained cross-linguistically as a constraint on the distribution of coronal segments.

Some languages that prohibit rhotics and laterals word-initially, tolerate word-initial glides, demonstrating that liquids have a distinct status from other approximants in the word-level phonotactics of Mongolian, Pitta-Pitta[2] and Mbabaram. A similar phenomenon can be observed in Yaygir (Pama-Nyungan): words may begin with stops, nasals, glides or vowels, but never rhotics (Table 2.3).

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| /baginaj/ | 'small' | /daːbaj/ | 'dog' | /ɟaːɲaɲ/ | 'ant' | /gaːbi/ | 'wallaby' |
| /maɟa/ | 'boss' | /nagar/ | 'chest' | /ɲaːgi/ | 'see' | /ŋaːbi/ | 'drink' |
| | | /jaːgaj/ | 'shark' | | | /waːgaj/ | 'fire' |
| | | /ina/ | 'foot' | /alina/ | 'wind' | /uːlun/ | 'rain' |
| *#/l/-, *#/r/-, *#/r̥/-, *#/ɽ/- | | | | | | | |

TABLE 2.3: **Constraints on word-initial consonants**: Yaygir (Crowley 1979).

[1] Johanson & Csató (1998) note that prothesis is commonly used as a repair strategy with loan-words to avoid initial liquids in Turkic, e.g. Kazakh: *orïs* 'Russian'.

[2] Blake (1979) cites two clan names which are rhotic-initial: ṛiŋuṛiŋu and raŋwa, but asserts that liquid-initial words are not generally found in Pitta-Pitta.

Along with the three rhotics, Yaygir also uses a lateral /l/ which is distinctive in medial positions, but neutralizes with /d/ in word-initial positions (/duwa/ *'boomerang'* → [duwa] ∼ [luwa]), so Crowley lists no words as underlyingly lateral-initial. Yaygir is another language with a rich inventory of liquids which are subject to constraints which do not apply to the other approximants, suggesting that rhotics and laterals together constitute their own subclass of sonorants within the phonotactic domain.

### Word-Final Constraints

Rhotics and laterals are found word-finally in languages which prohibit other word-final consonants. In most varieties of Modern French, consonants generally delete in word-final position unless undergoing liaison in pre-vocalic environments. Uniquely amongst the French consonants, neither the rhotic /ʀ/ nor lateral /l/ are deleted in word-final non-liaison environments. The examples in Table 2.4 are adapted from Carton (1974).

| | | | |
|---|---|---|---|
| *les camarades* | [le.ka.ma.ʀad] | 'the friends' | (/s/ → ∅ \| _ #) |
| *petit camarades* | [pe.ti.ka.ma.ʀad] | 'small friend' | (/t/ → ∅ \| _ #) |
| *cher camarades* | [ʃeʀ.ka.ma.ʀad] | 'dear friend' | (/ʀ/ → [ʀ] \| _ #) |
| *nul camarades* | [nul.ka.ma.ʀad] | 'no friend' | (/l/ → [l] \| _ #) |

TABLE 2.4: **Preservation of word-final liquids**: French.

In other languages, laterals and rhotics pattern amongst a larger set of segments licensed at the end of words: Literary Tamil disallows word-final consonants except for {/m/-/n/-/ɳ/; /l/-/ɭ/-/r/-/ɻ/; /j/} (Schiffman 1999); Yaygir allows only word-final vowels, nasals, /j/, /l/ and /r/ (Crowley 1979); Fante allows only word-final nasals and [l]∼[r] (Abakah 2005).

In the languages surveyed above, liquids constitute a (sometimes maximal) subset of the segments which distribute word-finally. In other languages, both laterals and rhotics are prohibited from word-final position. In Thai, possible final consonants include all three nasals {/m/,/n/,/ŋ/}, both glides {/j/,/w/}, and a set of stops produced at all places of articulation {/p/,/t/,/k/,/ʔ/}. Missing from this inventory are all fricatives and the two liquids /l/ and /r/ (Iwaski & Ingkaphiron 2005). Similar constraints apply in the Burmese language Shan, which prohibits only the liquids and glottal obstruents from word-final position, while allowing stops and glides (Matisoff 2003).

These examples serve to illustrate that laterals and rhotics can pattern together either by their collective presence or absence from certain environments, often as a subset of larger groups of segments, rather than a uniquely distributed class. Nevertheless, the data illustrate that laterals and rhotics distribute in similar ways across a diverse range of languages, suggesting that a class of liquids has legitimacy in word-level phonology.

### 2.1.2 Distribution within the Syllable

Laterals and rhotics display strong cross-linguistic tendencies to pattern together within the domain of the syllable. In this section, some common patterns of distribution, and constraints upon the syllable-level organization of liquids will be reviewed.

#### Syllabicity of Liquids

In some languages, both laterals and rhotics may act as syllabic consonants; other than nasals, these are commonly the only non-vocoids which may appear in a syllabic nucleus. This is the case in rhotic dialects of English which allow pronunciations such as *bottle* [ˈbʌt.l̩], *butter* [ˈbʌt.r̩], *bottom* [ˈbʌt.m̩], *button* [ˈbʊɾ.n̩]], and in Berlin German, in which the words *Scheitel* 'parting' and *besser* 'better' may be produced as [ˈʃaɪt.l̩] and [ˈbɛs.r̩] (Wiese 2001b).

29 (16%) of 182 languages surveyed by Bell (1978) were found to use at least one syllabic consonant classified as a liquid, while only six languages (3%) use non-liquid, non-nasal syllabic consonants.

Although many languages allow sonorant consonants to become syllabic in reduced syllables or in rapid speech, there is an important distinction to be made between truly syllabic phonemes and 'trapped' consonants, which become syllabified in place of reduced vowels. Scheer (2004) develops a variety of tests, according to which the sonorants in English and German examples do not qualify as true syllabic consonants. Nevertheless, the fact that laterals and rhotics pattern with nasals in their capacity to fill nuclei in these languages indicates that these segments differ from obstruents in some fundamental respect.

In Czech, only /l/ (*vl̠.na* 'wool'), /r/ (*hr̠b.lo* 'throat') and /m/ (*sed.m̲* 'seven') may function as syllabic consonants. Unlike in Germanic languages, Czech liquids (but not the nasal) may function as nuclei of stressed syllables: *prst* 'finger'; *hrb* 'hunch'; *vlk* 'wolf' (Scheer 2004). In Slovak, laterals and rhotics are the only syllabic consonants (excluding trapped consonants). Along with the short lateral /l/ and rhotic

/r/ found in other Slavic languages, Slovak contrasts two additional liquid segments /lː/ and /rː/, all four of which may be syllabic: *dlh* [dl̩h] 'debt', *kĺb* [kl̩ːb] 'joint', *krčma* [kr̩ʃm.a] 'inn', *kŕč* [kr̩ːʃ] 'cramp' (Rubach 1993; Kenstowicz & Rubach 1986).

It appears that laterals and rhotics pattern together in these languages because, unlike obstruents, they share some phonological property with vocoids which allows them to function as syllabic nuclei. The data also suggests that liquids have a different status in many Indoeuropean languages, compared to some Semitic and Athapaskan languages, for example, which allow a greater variety of segments to act as syllabic. In Chapter 9 the role of liquids in syllabification will be examined in further detail, and the case will be made that their potential to act as nuclei derives from the presence in both rhotics and laterals of an intrinsic tongue body gesture.

### Consonantal Organization in Onsets

In languages with consonant clusters, liquids tend to occur closer to the syllable nucleus than other types of consonant. In many cases, there are strict phonotactic constraints on the onset which restrict the distribution of liquids with respect to other segments.

A common type of onset cluster is that found in Boro (Tibeto-Burman), consisting of maximally two consonants, the second of which must be the alveolar trill /r/ or the lateral /l/ (Basumatārī 2005). Onset clusters in Hatam (West Papuan) can consist only of an initial stop or /s/ followed by a liquid: /pri/ 'jump', /bri/ 'clamber', /tri/ 'sell', /kri/ 'tie', /sra/ 'cut along the grain' (Reesink 1998). Onsets in many other languages conform to the same template: /C(L)-/, where C is one of subset of consonants, and L is a lateral or rhotic: Portuguese (Romance), Turkish (Turkic), Kammu (Mon-Khmer), and Tarao (Tibeto-Burman) all follow this pattern, as do Acehnese, Rade, and most other languages in the Chamic (Austronesian) family (Thurgood 1999).

In languages which allow even more complex onsets, the phonotactics often dictate that the cluster is liquid-final. While Dutch allows up to three consonants in an onset cluster /$C_1C_2C_3$-/, $C_3$ may only be the lateral /l/ or rhotic /r/ (Table 2.5).

The same constraints apply to three-consonant onsets in Swedish (Engstrand 2001), Irish (Ní Chiosáin 1999) and Romanian (Chitoran 2002). Onset clusters in Ega (Kwa) can begin with any of the 22 obstruent consonants, but must end with the single phonological liquid – prototypically a lateral /l/, which is realized in free variation with [ɾ] (Connell et al. 2002). Considering the extensive combinatorial possibilities of consonant clustering in each of these languages, it is remarkable that

| | | |
|---|---|---|
| /spr-/ | *spreeuw* | 'starling' |
| /str-/ | *stroom* | 'stream' |
| /skr-/ | *skriba* | 'scribe' |
| /spl-/ | *splinter* | 'splinter' |
| /skl-/ | *sklerose* | 'sclerosis' |
| /sxl-/ | *schreeuw* | 'cry' |

TABLE 2.5: **Dutch three-consonant onset clusters** (Booij 1995).

the set of onsets observed in each language is so small. Of the 6840 three-segment clusters which could potentially be created from the 20 consonants of Dutch, for example, only six combinations (0.09%) are found in onsets. In these languages rhotics and laterals share some special phonological property, distinct from obstruents, which licenses complex onset clusters, and dictates that the liquid must appear as the final element.

Liquids sometimes pattern with a larger set of sonorants as the consonants which are tolerated in cluster-final position. Characteristic of the phonology of Niger-Congo languages such as Dschang (Cameroon) is that onset clusters are either glide-final, or else they conform to the template #(N)OL-, where L represents a liquid (Maddieson 1981). All onsets in Chamorro end with one of the three approximants {/l/,/r/,/w/} (Topping & Bernadita 1973). In other languages, liquids cluster between the obstruents and other approximants: in Eastern Kayah Li (Burma, Sino-Tibetan) onsets may be described by the template #CLG-, where only a liquid may appear in the second slot before a glide (Solnit 1997).

The special status of liquids as cluster-enabling segments can be seen when clusters emerge in languages with a preference for simple onsets. Trask (1989) observes that historically, no complex onsets of any form were permitted in Basque; Hualde (1991) notes that they are still rare and often simplified or repaired in loanword phonology: *luma* < *pluma* 'feather', *liburu* < *libru* 'book'. Despite the strong preference for simple onsets in Basque, a number of clusters have survived in loanwords, all of the form #CL-: *prakak* 'trousers', *andre* 'woman', *fruitu* 'fruit'.

Tamil syllabic structure overwhelmingly conforms to the template (C)V(ː)(C(C)), but Karunakaran (2000) gives examples of five different word-initial clusters which have emerged in some varieties of spoken Tamil (Table 2.6). Other than the single example of an obstruent-glide onset, all of these clusters are facilitated by liquids. The Tamil orthography indicates that each of these words originally began with a CV syllable, which suggests that the clusters arose as the result from vowel deletion: /palaː/ → [plaː], /teɭɭaː/ → [tɭaː], /kiɭaː/ → [kɭaː], /vijaː/ → [vjaː], or metathesis: /paru/ → [praː].

| Onset Cluster | Example | Pronounced | Gloss |
|---|---|---|---|
| /#pl-/ | பலா மரம் | [plaːmarom] | *‘jack tree’* |
| /#pr-/ | பருந்து | [praːntu] | *‘eagle’* |
| /#tɭ-/ | சொள்ளாயிரம் | [tɭaːjrom] | *‘nine hundred’* |
| /#kɭ-/ | இளாக்காய் | [kɭaːkkaːj] | *‘a carissa fruit’* |
| /#vj-/ | வியாழன் | [vjaːɭen] | *‘Thursday’* |

Table 2.6: Tamil word-initial consonant clusters (Karunakaran 2000)

### Consonantal Organization in Codas

Syllable codas too, are often subject to phonotactic constraints which can be formulated more succinctly by appealing to the class of liquids, since rhotics and laterals share similar distributional properties in the rhyme.

Laterals and rhotics are commonly found together amongst a larger set of consonants which are licensed in the rhyme. In Portuguese, the only coda consonants are liquids or /s/ (Azevedo 2005). Syllable codas in Kuman are formed only from {/m/,/n/,/ɾ/,/l/,/ʎ/} (Pfantz & Pfantz 2005). Kanuri (Nilo-Saharan) and Mandarin Chinese (Sino-Tibetan) also restrict their codas to a single nasal or liquid (van Dam 2004), and Diyari (Pama-Nyungan) allows only word-medial codas consisting of a single nasal, rhotic or lateral segment (Austin 1981).

Although liquids and nasals often cooccur in coda position, this cannot be universally explained in terms of sonority (Blevins 2004), because asymmetries in the coda phonotactics of sonorants can also be observed: nasals, but neither /l/ nor /r/ may occur in codas in Manam (Northern New Guinea), while liquids alone ({/l/,/r/}) may follow the nucleus in word-medial codas in Michif (Manitoba).

When languages allow complex codas, laterals and rhotics are frequently found amongst the segments – typically sonorants – licensed in the first post-nucleic slot. All complex codas in Tiwi (Melville Is) are rhotic-intial, e.g. /aɹn.ˈtu.ma/ *‘head ornament’*, /kaɹn.tu.ˈku.ni/ *‘ironwood’* (Osbourne 1974). All root-final two-consonant clusters in Gooniyandi (Western Australia) begin with one of the three segments {/ɾ/,/l/,/ɭ/} (McGregor 1990), and in Warray (Northern Territory), liquids are the only segments which may occur as the first member of a coda cluster (Borowsky & Harvey 1997).

As coda complexity increases, liquids are increasing likely to factor amongst the smaller subset of consonants which can occur closest to the nucleus. Two-consonant codas in Romansch, for example, can begin with one of the consonants {/m/,/n/,/ʃ/,

/l/,/r/}, but only liquid-intial three-consonant codas are attested: /-rms/ and /-lts/ (Montreuil 1999).

Dutch allows complex codas in which only /s/, /l/ and /r/ may precede a final obstruent. Comparing the codas in Table 2.7 with the onsets in Table 2.5, an important phonotactic phenomenon involving liquids can be observed: the asymmetrical organization of complex onsets and codas. In Germanic languages, a liquid will invariably appear closer to the nucleus than any obstruents, resulting in onset clusters of the form #OL- (*pry*, *fly*, *spry*, **rpy*, **lfy*, **rpsy*), and coda clusters with the reverse structure -LO# (*surf*, *kelp*, *carps*,**sufr*,**kepl*,**caspr*). Although this asymmetry does not hold universally (no such constraints apply, for example, in Georgian, Berber or Mongolian), it is a common phonotactic property of clusters that laterals and rhotics are found closer to the nucleus than other consonants.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| /-sp/ | *wesp* | 'wasp' | /-lp/ | *help* | 'help' | /-rp/ | *harp* | 'harp' |
| | | | /-lm/ | *helm* | 'helmet' | /-rm/ | *arm* | 'arm' |
| | | | /-lf/ | *elf* | 'elf' | /-rf/ | *amorf* | 'amorphous' |
| | | | /-lv/ | *elf* | 'eleven' | /-rv/ | *korf* | 'basket' |
| /-st/ | *astma* | 'asthma' | | | | | | |
| | | | | | | /-rn/ | *karn* | 'churn' |
| /-sk/ | *obelisk* | 'obelisk' | /-lk/ | *melk* | 'milk' | /-rk/ | *kerk* | 'church' |
| | | | | | | /-rx/ | *monarch* | 'monarch' |
| | | | /-lɣ/ | *alg* | 'alga' | /-rɣ/ | *erg* | 'very' |

TABLE 2.7: **Dutch two-consonant coda clusters** (Booij 1995).

**Summary**

In this section, the distributional behavior of liquid consonants has been reviewed. It has been shown that laterals and rhotics pattern together in word-level and syllable-level phonologies through shared phonotactic constraints, a mutual ability to act as syllabic consonants, and shared ordering asymmetries in onsets and codas. These cross-linguistic trends suggest the first, and most important characterization of the class of liquids: a set of consonants sharing properties which dictate their position in the organization of the syllable.

## 2.2 Phonological Processes Involving Liquids

Evidence for the class of liquids can be found not only in distributional phenomena, but also in the active phonology of languages. Laterals and rhotics pattern together both as triggers and targets of the same phonological processes. Most importantly, laterals and rhotics often alternate with each other, in historical changes and in allophonic variation. Examples of all of these phenomena – both diachronic and synchronic – are briefly surveyed here.

### 2.2.1 Assimilation

Laterals and rhotics can pattern together in triggering assimilation of adjacent segments. In Latin, for example, the negative prefix /iN-/ place assimilates to a stop-initial stem (Table 2.8b); when the same prefix attaches to liquid-initial stems, the nasal is totally assimilated to the lateral or rhotic Table 2.8c).

| | | | |
|---|---|---|---|
| a. | [in]-V: | *inaequetus* | 'unequal' |
| b. | [im]-[p]: | *imperceptus* | 'unknown' |
| | [in]-[t]: | *intemptatus* | 'untried' |
| | [iŋ]-[k]: | *incultus* | 'uncultivated' |
| c. | [i]-[l]: | *illectus* | 'unread' |
| | [i]-[r]: | *irruptus* | 'unbroken' |

TABLE 2.8: **Total assimilation of nasals**: Latin liquid-initial stems.

A similar process occurs in Hausa (Chadic), where syllable-final nasals generally place-assimilate to a following consonant (Table 2.9a), but totally assimilate to the following lateral or either of the rhotics {/r/,/r̃/} (Table 2.9b; Newman 2000). In Bardi (Pama Nyungan), the extra-action marker /n/ undergoes total progressive assimilation when it appears before any of the consonants {/l/,/ɭ/,/ɽ/,/ŋ/} in the present or immediate perfect tenses (Metcalf 1975). In Oromo (Cushitic), all sonorants regressively assimilate with preceding liquids: *kofol+ne* > [kofolle] 'we have laughed', *dèger+ne* > [ɗègerre] 'we have seen' (Fallon 2002).

In the examples above, liquids behave as a class of consonants which trigger assimilation of an adjacent segment. In other cases, a class of liquids may be defined over a set of segments which pattern together as the target of assimilatory processes. In some varieties of Cuban Spanish, for example, coda laterals and rhotics both undergo total assimilation with a following obstruent. Yoruba (Niger-Congo) liquids

| | | | |
|---|---|---|---|
| a. | *sun bi* | [sumbi] | 'they followed' |
| | *gidansù* | [gidansù] | 'their house' |
| | *gidankù* | [gidaŋkù] | 'our house' |
| | *hanyà* | [haɲ jà] | 'road' |
| b. | *Dan Lādì* | [ɗallādì] | (proper name) |
| | *sôn râi* | [sârrâi] | 'selfishness' |
| | *watàn Ràmàlàn* | [watàr̃r̃àmàlàŋ] | 'the month of Ramadan' |

TABLE 2.9: **Total assimilation of nasals**: Hausa liquid-initial syllables.

pattern with the approximants {/l/,/r/,/w/,/j//} in that they undergo (sometimes total) nasalization before nasal vowels: /lũ/ → [nũ] 'to feed', /rũ/ → [r̃ĩ] 'to walk', /jũ/ → [j̃ĩ] 'to dispense', /wũ/ → [w̃ĩ] 'to lend', and with the nasals in triggering place assimilation of syllabic nasals: /N̩/ → [$\alpha$place] | {+cons $\alpha$place} _ (Akinlabi 2003).

### 2.2.2 Dissimilation

Evidence for a class of liquids may also be found in a variety of dissimilatory phenomena. Segments which dissimilate do not do so randomly – they become differentiated from neighboring segments in some respects, while retaining other characteristics in common – offering useful insights into phonological relationships and class membership.

In Tashlhiyt Berber, for example, labial prefixes de-labialize when combining with a root which also contains a primary labial consonant: [m-xazar] *'scowl'*, but [n̲-f̲ara] *'disentangle'* (Alderete & Frisch 2007). Grassman's law affects classes of aspirated and non-aspirated consonants in Indoeuropean; Thurneyson's Law involves classes of voiced and obstruent consonants in Gothic (Chomsky and Halle 1968); sibilant dissimilation in Iban affects obstruents which share the same values for voicing, oral place and stricture; while dissimilation in Eastern Polynesian affects only the class of labials (Blust 1996). The importance of these examples is to demonstrate that the segments which result from dissimilation typically belong to the same natural class as the segments which were affected. When laterals dissimilate, the result is often a rhotic, and vice versa.

Liquid dissimilation has occurred throughout the history of the Romance languages. In the Latin adjectival suffix [-aːlis], the lateral dissimilated to a rhotic when suffixed to a stem which already contained a lateral (Steriade 1987; Table 2.10). The examples *vulgaris* and *militaris* demonstrate that the dissimilation was not just a local process, but could occur over non-adjacent syllables.[3] Maiden (2000) observes that the sequence [l-l-] is almost completely banned in Italo-Romance clitic morphology. Standard Italian, for example, has *lo dico* 'I say it' and *le parlo* 'I talk to her', but instead of the expected *le lo dico* we find *glielo dico* [ʎelo diːko] 'I say it to her'.

| | | | |
|---|---|---|---|
| *ann-aḻis* | 'yearly' | *singuḻ-aṟis* | 'alone' |
| *capit-aḻis* | 'capital' | *soḻ-aṟis* | 'solar' |
| *nav-aḻis* | 'naval' | *vuḻg-aṟis* | 'common' |
| *infiti-aḻis* | 'negative' | *miḻit-aṟis* | 'soldierly' |

TABLE 2.10: **Dissimilation of laterals**: Latin suffixation.

Dissimilation in the opposite direction from Latin may be seen in Georgian: the rhotic in the suffix /-uri/, denoting nationality, dissimilated to a lateral if the root already contained a rhotic: *asuṟ-uḻi* 'Assyrian', *p'ṟus-uḻi* 'Prussian', *ungṟ-uḻi* 'Hungarian'; but *dan-uṟi* 'Danish', *p'olon-uṟi* 'Polish', *som-uṟi* 'Armenian' (Fallon 1993). In Sundanese (Austronesian), rhotic dissimilation may be observed in the behavior of the infixing plural morpheme: /-ar-/ → [-al-] | _ r#: *k-ar-usut* 'messy', *t-ar-iis* 'cold', but *d-al-ahar* 'eat',*k-al-otor* 'dirty' (Cohn 1992).

Liquid dissimilation is not only triggered by morphological processes such as suffixation and encliticization – it is also found in sound changes affecting uninflected lexical items. Old Javanese /rVr/ sequences became /lVr/ in Modern Javanese (Austronesian): *roro* > *loro* 'two'; *rara* > *lura* 'virgin'; *rereb* > *lereb* 'to rest'; *rurub* > *lurub* 'covering, sheet' (Blust 1996), and again in Romance we find Latin: *aṟboṟ* > Spanish: *àṟboḻ* 'tree'; L: *ṟebuṟ* > Sp: *ṟobḻe* 'oak' (Colantoni & Steele 2005). Diachonic liquid dissimilation is also attested in Yidiny (Pama Nyungan; Crowhurst & Hewitt 1995), Sabaot, and Endo (Nilo-Saharan; Larsen 1991), and dissimilated variations on standard forms occur in many Romance languages, including non-standard Catalan: *aṟmari* → [aḻmari] 'wardrobe' and *juḻiol* → [juṟiol] 'July' (Lloret 1997).

### 2.2.3 Harmonization

Another phenomenon which can affect liquids occurring in proximity is harmonization. Like dissimilation, consonant harmony generally occurs between segments which are members of a natural class: Gafos (1999) illustrates that proximal coronal obstruents are prone to harmonize in Apache (Na-Dene), as are fricatives in Tahltan (Athabskan), Basque (Isolate) and Tzeltal (Mayan).

[3] Many relics of this phenomenon survive in modern Romance languages, and in English, in the liquid alternations in *angular*, *velar*, *polar*, *regular*; cf. *papal*, *total*, *temporal*, *dental*.

Rose & Walker (2004) found that, cross-linguistically, liquid agreement is one of five types of long-distance consonant harmony phenomena commonly observed in languages, along with nasal, laryngeal, and coronal and dorsal agreement. In the Bantu language Bukusu, for example, the lateral in the benefactive morpheme -/ila/ harmonizes when it is suffixed to a stem containing a rhotic (Table 2.11; Odden 1994).

| UNDERLYING LATERAL | | HARMONIC RHOTIC | |
|---|---|---|---|
| /teex-eḻa/ | 'cook for' | /ṟeeb-eṟa/ | 'ask for' |
| /lim-iḻa/ | 'cultivate for' | /kaṟ-iṟa/ | 'twist' |
| /iil-iḻa/ | 'send thing' | /ṟesj-eṟa/ | 'retrieve for' |

TABLE 2.11: **Harmonization of liquids**: Bukusu suffixation.

No word in Toba Batak (Austronesian) contains dissimilar liquids, so in order to maintain liquid harmony, words borrowed into the language have undergone either rhoticization of the lateral: [rijar] < Portuguese/Malay /rijal/, or lateralization of the rhotic: [pulaŋbuli] < /pulaŋburi/ (no glosses given). Some loan words have harmonized in different directions in different dialects, e.g. Menangkabau: /selawal/ > [selawal] (Dairi) > [sarawar] (Sub Toba). Liquid harmonization is a highly productive phonological process in Toba Batak, applying even over adjacent words, whether or not they are compounds: /maḻampis/ + /bibiṟna/ > [maṟampisbibiṟna] 'his lips are thin' (van der Tuuk 1971).

### 2.2.4 Metathesis

Cross-linguistically, metathesis processes often target liquids. Canonical examples of vowel-liquid metathesis can be seen in the development of Southern and Western Slavic languages. In many words which originally contained vowel-liquid sequences, the coda laterals and coda rhotics metathesized with the preceding vowel, resulting in liquid-vowel sequences in the modern languages (Blevins & Garrett 1998; Table 2.12).

In a typological survey of metathesis, Ultan (1978) observes that liquids feature in a disproportionate number of metathesis phenomena, in languages as diverse as Breton (Celtic), Eastern Eskimo (Eskimo-Aleut), Tagalog (Austronesian), Mandaic Aramaic (Semitic), Persian (Indo-Aryan) and Zoque (Mixe-Zoque). He argues that liquids are especially susceptible to metathesis by virtue of their higher sonority, citing evidence from Armenian, in which there appears to have been "a chronological hierarchy in the introduction of metathesis of original clusters of the type con-

| PROTO-SLAVIC | BULGARIAN | POLISH | GLOSS |
|---|---|---|---|
| **olkŭtĭ* | *lákot* | *łokieć* | 'elbow' |
| **orbota* | *rábota* | *robota* | 'work' |
| **gordŭ* | *grad* | *gród* | 'city' |
| **melko* | *mléko* | *mleko* | 'milk' |

TABLE 2.12: **Slavic Liquid Metathesis** (Blevins & Garrett 1998).

sonant + semivowel. The first to metathesize were clusters containing semivowels, followed by the liquids, nasals, spirants, stops and possibly the affricates, in that order." (Ultan 1978: 375).

The majority of the metathesis phenomena observed in these languages involve the simple transposition of a liquid with an adjacent segment, as in the Armenian *elbajr* < **brājr* 'brother' (in which the original rhotic has dissimilated to a lateral during the process of metathesizing) and *erkan* < **kran* 'millstone' (Hayes et al. 2004). van der Tuuk (1971) gives numerous (unglossed) examples of vowel-liquid metathesis in Malayo-Polynesian languages: [arsam] ∼ [ransam] (Menangkabau); [ursa] ∼ [rusa] (Malay); [gaol] ∼ [galu] (Dairi); [alpis] ∼ [lapis] (Toba Batak).

Another type of metathesis which commonly affects both laterals and rhotics, involves the dislocation of a liquid to an adjacent syllable, typically to the syllabic position from which it was displaced. This type of metathesis can be observed in the diachrony of the Bagnéres-de-Luchon words *trende* < **tendro* < Vulgar Latin: *tenuru* 'tender' and *espilingo* < **espingla* < VL: *spinula* 'pin' (Ultan 1978); and in synchronic alternations in Dairi: [limaŋ] ∼ [bilaŋ], and Javanese: [laba] ∼ [bala], [derem] ∼ [redem] (van der Tuuk 1971).

Of special interest is the rarer phenomenon of reciprocal metathesis, which tends to involve members of the same phonological class. In Marathi (Indo-Aryan), for example, the participants in the metathesis [kʰaːmk] < [kaːmkʰ] 'armpit', are both voiceless stops, and in Agde French reciprocal metathesis occurs between sibilant fricatives: [ʃes] < *seche* 'dries' (Ultan 1978). In Chamorro (Austronesian), when a morpheme of the form /-VN-/ is infixed into a word, the nasal can metathesize with a sonorant in the preceding syllable (Klein 2005). The segments which participate in this process are {/m/,/n/,/ŋ/,/r/,/l/} (Table 2.13), suggesting that the two liquids constitute a subset of sonorants in Chamorro.

Diachronic reciprocal metathesis phenomena involving exchange of lateral segments with rhotics are attested in Gayo (Austronesian: *terul* < **telur* 'egg'), Spanish (*milagro* < Old Spanish *miraglo* 'miracle'), Telegu (Dravidian: *rôlu* < Proto-

| BASE | -IN- INFIX | -UM- INFIX | GLOSS |
|---|---|---|---|
| *li'e'* | i) *lini'e'*<br>ii) *nili'e'* | i) *lumi'e'*<br>ii) *muli'e'* | 'to see' |
| *risibi* | i) *rinisibi*<br>ii) *nirisibi* | i) *rumisibi*<br>ii) *murisibi* | 'to receive' |
| *na'i* | *nina'i* | i) *numa'i*<br>ii) *muna'i* | 'to give' |
| *nginge'* | i) *ngininge'*<br>ii) *ninginge'* | i) *nguminge'*<br>ii) *munginge'* | 'to smell' |

TABLE 2.13: **Reciprocal Metathesis of Sonorants**: Chamorro (Klein 2005).

Dravidian **ural* 'mortar'), and Mandaic Aramaic (Semitic: [Salwa:ra] ∼ [Sarwa:la] 'trousers') (Hume 2008).

### 2.2.5 Merger

Evidence for a class of liquids may be found in a number of languages where distinctions between rhotics and laterals have been neutralized as a result of historical mergers. Many cognate forms may be found among Polynesian languages which vary primarily in the identity of the liquid consonants (Table 2.14). If Proto-Polynesian originally used two liquids, then the data suggests a number of historical developments within the class: *l,*r > /r/ (Maori), *l,*r > /l/ (Samoan), and *l > /l/, *r > ∅ (Tongan). In the development of Latin to Campidanian Sardinian (Frigeni 2005), /l/ and /r/ neutralized to /r/ in onset clusters, resulting in a one-liquid system in the modern language (Table 2.15).

| MAORI | TONGAN | SAMOAN | GLOSS |
|---|---|---|---|
| [kere] | [kele] | [ʔele] | *'black'* |
| [kura] | [kula] | [ʔula] | *'red'* |
| [taro] | [talo] | [talo] | *'taro'* |
| [riki] | [iki] | [liʔi] | *'small'* |
| [rama] | [ama] | [lama] | *'torch'* |
| [ŋaru] | [ŋalu] | [ŋalu] | *'wave'* |

TABLE 2.14: **Liquid correlations in Polynesian cognates** (Tregear 1969).

| LATIN | | SARDINIAN | GLOSS |
|---|---|---|---|
| PLUS | > | [ˈprus] | 'more' |
| PRIMUS | > | [ˈprimu] | 'first' |
| FLAMMA | > | [ˈfraða] | 'flame' |
| FRATER | > | [ˈfradi] | 'brother' |

TABLE 2.15: **Liquid neutralization**: Latin > Sardinian.

### 2.2.6 Neutralization

In the examples in Section 2.2.5, the neutralization of contrasts between liquids has ultimately resulted in structural change to the languages' phonologies through merger of originally distinct segments. Liquid neutralization can also be observed in languages which retain the phonological contrast between the segments involved.

In some Carribean and Andalusian dialects of Spanish, the tap-lateral contrast is neutralized in syllable codas: e.g. *verdad* → [bel.da] 'truth', *comprar* → [kom.pral] 'to buy' (Willis 2006).[4] Although the Spanish examples might be viewed as a special case of the very common cross-linguistic phenomenon of neutralization in coda position, liquid neutralization can also be observed in more phonologically prominent environments. The two liquids of Tukang Besi (Austronesian) neutralize in intervocalic environments, where they are realized as either allophone: /r/,/l/ → [r ∼ l] | V_V (Donohue 1999).

### 2.2.7 Alternation

Just as distinctions between liquids can be lost as a result of merger or neutralization, the phonetic realization of liquid segments can change over time. The outcome of this change is often another liquid segment.

#### Historical Liquid Alternation

In the Karnic languages Arabana, Wangkangurru and Wangkayutyuru (Central Australia), the rhotic-initial ergative suffix appears to have evolved from a lateral-initial proto-form: */-la/ > /-ra/ (Bowern 2001). Amongst the languages of the Moru-Madi group (Nilo-Saharan), many cognate forms can be found in which alternations occur between the three liquids /r/-/l/-/ɽ/: 'water rat' [talú] (Logo) ∼ [taɽú]

[4] The details of the neutralization process vary considerably, and are reviewed in Chapter 3.

(Miza); 'knife' [ílí] (Madi) ~ [íɽí] (Miza); 'body' [lúmvú] (Kediru) ~ [rúmvú] (Wadi); [ɔ̀lí] 'wind' (Keliko) ~ [ɔ̀ɽí] (Tucker 1940).

### Rhoticization of Laterals

Rhoticization of coda laterals is attested in a number of Romance varieties: Florentine Italian (Walsh Dickey 1997); Cuban, Canarian and Andalusian Spanish (Quilis 1999); and Caipira Portuguese (Azevedo 1981). In some dialects of Modern Greek, /l/ is rhoticized in preconsonantal positions (Newton 1972). Although speakers of these dialects learn the 'standard' pronunciations [álfa], [délta], these are more commonly realized as [árfa] and [dérta]. In Sphakiá Greek (Crete), laterals are realized as a retroflex rhotic approximant 'like the English itar in tomorrow' when they occur before back vowels (Trudgill 1989).

### Lateralization of Rhotics

Rhotic lateralization affects liquid clusters which form at the boundary between a verb stem and a derivational suffix in Jamsay (Mali, Niger-Congo). This process can be observed in the behavior of the 'reversive' suffix /-rV-/: when added to a (C)VrV verbal stem, the suffixing liquid dissimilates to a lateral, which regressively lateralizes the stem rhotic (Table 2.16; Heath 2008).

| VERB | GLOSS | REVERSIVE | GLOSS |
|---|---|---|---|
| [páʔá-] | 'tie' | [páɣá-rá-] | 'untie' |
| [pɛ́gɛ́-] | 'insert' | [pɛ́gɛ́-rɛ́-] | 'remove' |
| [náŋá-] | 'forget' | [náŋá-rá-] | 'remember' |
| [gòró-] | 'cover' | [gòl-ló-] | 'uncover' |
| [kɔ́rɔ́-] | 'hang up' | [kɔ́l-lɔ́-] | 'take down' |
| [píré-] | 'get stuck' | [píl-lé] | 'become unstuck' |

TABLE 2.16: **Rhotic cluster lateralization**: Jamsay (Heath 2008).

For some speakers of Modern Hebrew, rhotics may be partially lateralized in word-final position, despite the fact that the rhotic and lateral are contrastive in this environment: /til/ [til] 'rocket', /saʁ/ → [saʁˡ] ~ [sal̥] 'minister'. This phenomenon warrants further investigation: since the rhotic is not coronal (for the speakers in which this was observed), it would not seem to be a natural candidate for lateralization.[5]

### 2.2.8 Post-Vocalic Liquids

When liquids appear in the immediately post-vocalic position, they can enter into a variety of phonological process which involve the syllable nucleus. Postvocalic liquids can lengthen or alter the preceding vowel, or disappear all together – phenomena frequently observed across a variety of languages.

In many Commonwealth Englishes, post-vocalic rhotics and laterals have disappeared from many words which contain a low or back vowel (*al.mond*, *palm*, *farm*, *a.larm*). In each case, the originally pre-liquid vowel has been lengthened. For speakers of Australian English, this has resulted in a loss of contrast between many words which once contained post-vocalic liquids (*arms/alms*, *karma/calmer*), as well as the creation of a number of minimal pairs differentiated primarily, or entirely, by vowel length (Table 2.17).

| | | | |
|---|---|---|---|
| *putt* | [pʰɐt] | *part* | [pʰɐːt] |
| *cut* | [kʰɐt] | *cart* | [kʰɐːt] |
| *cuff* | [kʰɐf] | *calf* | [kʰɐːf] |
| *hut* | [hɐt] | *heart* | [hɐːt] |
| *huff* | [hɐf] | *half* | [hɐːf] |
| *pot* | [pʰɑt] | *port* | [pʰɔːt] |
| *cot* | [kʰɑt] | *court* | [kʰɔːt] |
| *pump air* | [pʰɐmpʰɛː] | *palm pair* | [pʰɐmpʰɛː] |
| *his arm and* | [hɪzɐːmənd] | *his almond* | [hɪzɐːmənd] |

TABLE 2.17: **Nucleic lengthening and deletion of post-vocalic liquids**: Australian English.

In Dyirbal (Pama-Nyungan), both the rhotic (Table 2.18a) and the lateral (Table 2.18b) triggered compensatory lengthening after deleting from coda position in the Ngajan dialect – a phenomenon which can be observed by comparing cognates in the related language Mamu (Kavitskaya 2002).

Examples of compensatory lengthening accompanying the loss of post-vocalic liquids may also be found in Komi (Uralic), Onondaga (Iroquoian), Turkish, Uyghur

[5] Laufer (1999) gives the canonical Hebrew rhotic as /r/, but observes that different speakers use an uvular approximant rhotic /ʁ/. As with German, Modern Hebrew presents another interesting case in which the two primary rhotic allophones would appear to be fundamentally disconnected, both articulatorily and acoustically. See Chapter 9 for a further discussion of this dilemma.

| | MAMU | NGAJAN | GLOSS |
|---|---|---|---|
| a. | /marbu/ | /maːbu/ | 'louse' |
| | /ŋamir/ | /ŋamiː/ | 'hungry' |
| | /murŋgal/ | /muːŋgaː/ | 'cockatoo feather' |
| b. | /gulgu/ | /guːgu/ | 'brought together' |
| | /bulal/ | /bulaː/ | 'firefly' |
| | /dʒalgur/ | /dʒaːguː/ | 'meat' |

TABLE 2.18: **Vocalic Lengthening and Deletion of Coda Liquids**: Nganjan.

and Salar (Turkic): /varɣar/ [va(ː)ʁɑ(ː)] '(S)he will go', /gelmiʃ/ [kɛːmɪʃ] '(S)he reportedly came' (Johanson & Csató 1998). Kavitskaya (2002) demonstrates that the phenomenon can provide important insights into the phonological properties of the deleted liquid – rhotic approximants, for example, are more likely to trigger compensatory lengthening than taps or trills. Phonological asymmetries in the behavior of post-vocalic liquids will be addressed in more detail in Chapter 9.

### Vocalization of Liquids

When post-vocalic liquids do not delete completely, they will often vocalize and/or color the preceding vowel. Speakers of both 'rhotic' and 'non-rhotic' dialects of English may realize post vocalic /ɹ/ as something more akin to a schwa, with varying degrees of rhoticization: *burr* [bɜr] ∼ [bɜ˞(ɹ)] ∼ [bɜə˞] ∼ [bɜə] ∼ [bɜː]. In some northern dialects of England, post-vocalic laterals vocalize to a mid back vowel: *milk* [mɪɤk] ∼ [mɪʊk] (Hardcastle & Barry 1989), and in the south west, may be realized as a glide: *Bristol* [bɹɪ.stʊw].

Green (2002) cites post-vocalic liquid vocalization as a common mechanism in African American English, affecting both laterals and rhotics: *bear* [bæə], *bell* [bɜə]; *tore* [to], *cold* [koː], and Hancock (1974) notes that syllabic and postvocalic liquids are vocalized in Liberian English: *little* [lito], *people* [pipo], *care* [keː], *kill* [kiu]. In Lithuanian (Baltic), the combination of a short vowel and a liquid {/l/,/r/} can also function as a diphthong (Levin 2001).

The widespread occurance of these types of liquid vocalization suggests that liquid consonants share some fundamental phonetic similarities to the vowels which they become. In Chapter 9, building on observations by Giles & Moll (1975) , Hardcastle & Barry (1989) and Sproat & Fujimora (1993), the case will be made that vocalization results from the loss of the coronal gesture in segments which are intrinsically composed of coordinated tongue tip and tongue body gestures.

## 2.3 Liquid Allophony

Perhaps the most convincing evidence for the existence of a class of liquids, after their shared phonotactics, is the widespread phenomenon of allophony within the class. A variety of allophonic behaviors involving rhotics and laterals will be surveyed here.

### 2.3.1 Phonologically-Conditioned Liquid Allophony

In languages with a single liquid, this segment may be variously realized either as a rhotic or a lateral, sometimes in free variation, and sometimes in a phonologically conditioned manner.

Toaripi (Trans New Guinea) uses a single liquid, which generally surfaces as a lateral in initial position, and intervocalically as a tap: *lauai* 'eat'; *auri* 'metal' (Brown 1973). The single liquid of Gonja (Niger-Congo) is realized [r̩ʷ] when syllabic, and [l] elsewhere (Zec 1995).

Gbeya (Central African Republic, Niger-Congo) uses two phonological liquids, contrasted in the minimal pair [bolo] 'tree'/[boɾo] 'iron'. The rhotic has four allophones – two oral and two nasal – each of which is phonologically conditioned. Despite the phonemic contrast between the two liquids, two of the allophones of the rhotic are 'lateral flaps', which appear word-initially: /rɔk/ [ɺɔk] 'to be smooth', /rɔ̃k/ [ɺ̃ɔ̃k] 'to be good' (Samarin 1966).

In Korean, the liquid allophony is determined by syllabic phonology, surfacing as a flap in onsets and a lateral in codas (Table 2.19; Iverson & Sohn, 1994).

| | | |
|---|---|---|
| /mʌ.li/ | [mʌ.ɾi] | 'hair' |
| /sa.li/ | [saː.ɾi] | 'side dish' |
| /pal/ | [paʔ] | 'foot' |
| /p'al.kan/ | [p'aɭ.g̊ãn] | 'red' |

TABLE 2.19: **Phonological Conditioning of Liquids**: Korean.

### 2.3.2 Free Variation of Liquids

In other languages which use only a single phonemic liquid, this segment may be realized as any of a variety of rhotics and laterals in free or idiolectal variation.

Reesink (1999) observes that the single phonological liquid of Hatam (West Papuan) "is realized as an alveolar flap or a lateral approximant in free variation … Indonesian *selalu* 'always' can be given as [selaɾu], [seɾaɾu], [selalu]". Sentani (Cowan 1966) is typical of many Papuan languages, in which the realization of the single liquid varies freely between taps, trills and laterals (Foley 1986).

In some languages, the identity of the liquid is specified in some environments, but not in others. Jita (Tanzania, Niger-Congo) is a single-liquid language in which, morpheme-initially, only the coronal lateral [l] is found. Elsewhere the same phoneme surfaces in free variation, either as the lateral or as an apical tap [ɾ] (Downing 2001).

More remarkably, free variation is also found in languages with multiple liquid phonemes. Kikongo Kituba (Congo, Bantu) uses two phonological liquids {/l/-/r/} which neutralize in many environments. In these cases, both phones are used in free variation so that *bilo* is realized [biro] ∼ [bilo] (Mufwene 2001). Hausa has a three-liquid inventory /l/-/r/-/r̃/, all contrastive in initial and medial positions. In final position the two rhotics are variously realized as the lateral. In some dialects all allophones appear in free variation in syllable final position; for others the rhotics are interchangeable in this environment (Newman 2000).

Both free variation and phonologically-conditioned allophony can be observed amongst rhotics and laterals in languages with even richer liquid inventories. Only one of the three liquids of Lardil may occur in word initial position, where it can also be realized as either of the other two phones: /ɽ/ → [ɽ] ∼ [r] ∼ [l] | # _ (Round, p.c.)

The fact that rhotic-lateral allophony is observed so frequently, across such a variety of languages, seems to provide some of the best phonological evidence for a the existence of a class of liquids in these languages. Futhermore, these data suggest that the liquid consonants which pattern together in these languages are sufficiently closely united by some phonetic property that allophony of this type is possible. In Chapter 9, it will be argued that this common phonetic factor is the common presence of a dorsal gesture amongst laterals and rhotics.

## 2.4 Asymmetries in the Behavior of Liquids

Laterals and rhotics do not always pattern together in the ways surveyed so far in this chapter. In this section, some important asymmetries in the distribution and behavior of laterals and rhotics will be discussed – differences which must be taken into account when considering the extent to which they constitute a class.

An illustrative example may be found in the phonology of Koyra Chiini, a Nilo-Saharan language spoken in Timbuktu, Mali. In most respects, the lateral /l/ and rhotic /r/ of Koyra Chiini behave as a prototypical class of liquids. They pattern together in the phonotactics of the syllable: both are restricted to coda position. Both segments can geminate. The lateral and rhotic participate in many of the same phonological processes as a subclass of sonorants: blocking morpheme-final nasalization of vowels, and providing an environment in which the voiced velar stop is deleted (*farga > [faraa] 'tired'). Both diachronic (*malqaa 'meeting place' > [maraa] 'assemble') and synchronic (kul > [kur] 'all'; hal > [har] 'until') alternations are attested between laterals and rhotics (Heath 1999).

In one important phonological process, however, there is a significant asymmetry between the liquids in Koyra Chiini. The rhotic undergoes total progressive assimilation to a following alveolar stop (Table 2.20), but no such process affects the lateral, which can appear freely before alveolars (except for the rhotic, to which it is assimilated).

| | | |
|---|---|---|
| /a gar-ni/ | > [agan:i] | 's/he found you(sg)' |
| /njeer-di/ | > [ndʒeːdːi] | 'the antelope' |
| /yer-ta/ | > [jetːa] | 'we' |
| /yer-si bey/ | > [jesːibej] | 'we don't know' |

TABLE 2.20: **Total Assimilation of Rhotics**: Koyra Chiini (Heath 1999).

The situation in Koyra Chiini is typical of that found in many languages – rhotics and laterals will pattern together in many significant ways, which collectively indicate that they form a class, but they will also demonstrate asymmetries in distributional or active phonology, which suggests that the class of liquids is not monolithic. By examining some of these differences in more detail, we can gain further insights into the phonological characterization of liquids.

### 2.4.1 Word-Level Distributional Asymmetries

It is not always the case that laterals and rhotics occur in the same phonotactic environments. In Section 2.1.1, it was shown that in some languages, laterals and rhotics are subject to distinct distributional constraints at the word level. In other languages, such constraints apply only to a subset of liquids.

In Humburi Senni Songhay, for example, a two-liquid language of Mali (Nilo-Saharan), the lateral occurs in word-initial and word-final position, but the rhotic does not occur in either of these positions, other than in a few loan words (Heath

2007). Bolognesi (1998) describes a similar constraint in the Sestu dialect of Campidanian Sardinian, which prohibits word-initial rhotic and glide onsets, but tolerates laterals word-initially. The data in Table 2.21 demonstrates that Sestu has systematically resorted to vowel epenthesis to avoid initial rhotics, while lateral-initial words have been inherited relatively unaltered from Latin.

| SESTU | LATIN | GLOSS | SESTU | LATIN | GLOSS |
|---|---|---|---|---|---|
| [arɔːza] | < *rose* | 'rose' | [luʒi] | < *lucis* | 'light' |
| [arːana] | < *rana* | 'frog' | [ledʒu] | < | 'ugly' |
| [arːiu] | < *rivus* | 'river' | [latːi] | < *lactis* | 'milk' |
| [arːɔda] | < *rota* | 'wheel' | [luðu] | < *lutum* | 'mud' |

TABLE 2.21: ***Rhotic-Inital: Sestu Campidanian Sardinian**.

Smith (2003) argues that these types of asymmetries are reflective of the higher sonority of rhotics compared to laterals, and motivates the preference for word-initial laterals as an example of a broader cross-linguistic preference for low-sonority onsets. The issues of sonority and phonotactic ordering or liquids with respect to other segments will be addressed at length in Chapter 9.

### 2.4.2 Clustering Asymmetries

Further insights into the differential characteristics of liquids may be gained by looking at organization within the syllable. At this level, there are asymmetries in the ways in which laterals and rhotics may combine in clusters, and in the types of liquids that can fill syllable nuclei.

It was shown in Section 2.1.2 that obstruent-liquid clusters are commonly found in onsets; however, rhotics tend to combine with obstruents more freely than laterals in this environment. Gaps in attested onset cluster combinations, for which corresponding obstruent-rhotic clusters exist, reveal this to be the case in English (*/tl-/, */dl-/, */θl-/, */ʃl-/), Spanish (*/tl-/, */dl-/), Dutch (*/tl-/, */dl-/), and French (*/tl-/, */dl-/). The same trend is observed in more complex onsets: in Camsá (Colombia, isolate), three-consonant onset clusters may end with a rhotic or a nasal, but not a lateral (Howard 1967). The same asymmetry can be observed in some languages with greater combinatorial freedom in consonant clusters: the only types of morpheme-internal coda clusters commonly found in native Lezgi (North Caucasian) words are /-rC/ and /-lC/, with the rhotic-obstruent coda being much more common than the lateral-obstruent (Haspelmath 1993).

Evidence from Romance suggests that when obstruent-lateral clusters are permitted, they may be less stable than obstruent-rhotic clusters. The direction of neutralization of liquids in Campidanian clusters, for example, was lateral > rhotic (Table 2.21). Colatoni & Steele (2005) argue that obstruent-rhotic clusters are more diachronically robust: clusters containing rhotics in Latin were more likely to survive unchanged into modern Romance languages; clusters containing laterals, on the other hand, have devolved through a variety of processes, including assimilation, palatalization and vocalization (Table 2.22).

| LATIN | SPANISH | FRENCH | ITALIAN | PORTUGUESE | GLOSS |
|---|---|---|---|---|---|
| pratu | prado | prarie | prato | prado | 'meadow' |
| plorare | [ʎ]orar | pleurer | [pj]angere | [ʃ]orar | 'to cry' |
| credere | creer | croire | credere | crer | 'to believe' |
| clavis | [ʎ]ave | clef | [ki]ave | [ʃ]ave | 'key' |
| barba | barba | barbe | barba | barba | 'beard' |
| alba | alba | a[ub]e | a[ub]ora | a[wr]ora | 'dawn' |
| firmus | firmo | firme | fermo | firme | 'firm' |
| pulmone | pulmón | po[um]on | polmone | pulmão | 'lung' |

TABLE 2.22: **Diachronic Instability of Romance Obstruent-Lateral Clusters**.

In liquid-liquid coda clusters, rhotics are commonly found closer to the nucleus than the lateral. This is the case in Romansch /ʃtiərl/ *'calf'* but */-lr/# (Montreuil 1999), English: *pearl* but */-lr/#, and generally throughout the Germanic languages.

### 2.4.3 Asymmetries in Syllabification

Further evidence for differences in the stability of obstruent-liquid clusters may be found by examining patterns of syllabification in medial clusters. van de Torre (2003) observes that although all types of obstruent-liquid clusters are found in both word-initial and stressed word-medial positions in Dutch (Table 2.23a), medial obstruent-lateral clusters are prone to break across syllables, while obstruent-rhotic clusters tend to remain heterosyllabic at unstressed syllable boundaries (Table 2.23b).

A similar phenomenon can be observed in Icelandic, where the prosodic need for a stressed first syllable causes vowel-lengthening in open syllables, creating an in-built diagnostic for syllabification boundaries (van de Torre 2003). The long vowels in *etru* 'sober' and *ekra* 'field', for example, indicate that the medial obstruent-rhotic clusters are tautosyllabic (['ɛː.tru], ['ɛː.kra]), while the lateral clusters in *sigla* 'sail' and *ekla* 'lack' follow short initial vowels, and so must be heterosyllabic (['sɪk.la],

| | | | | | | |
|---|---|---|---|---|---|---|
| a. | *praat* | [prat] | ‘talk’ | *reprise* | [rə.ˈpri.zə] | ‘reprise’ |
| | *draak* | [drak] | ‘dragon’ | *adres* | [a.ˈdrɛs] | ‘address’ |
| | *krant* | [krɑnt] | ‘newspaper’ | *acryl* | [a.ˈkril] | ‘acryl’ |
| | *plaats* | [plats] | ‘place’ | *repliek* | [rə.ˈplik] | ‘reply’ |
| | *klant* | [klɑnt] | ‘customer’ | *eclips* | [e.ˈklɪps] | ‘eclipse’ |
| b. | *cobra* | [ˈko.bra] | ‘cobra’ | *Popla* | [ˈpɔp.la] | ‘Popla’ |
| | *metro* | [ˈme.tro] | ‘metro’ | *Revlon* | [ˈrɛp.lɔn] | ‘Revlon’ |
| | *okra* | [ˈo.kra] | ‘okra’ | *Teflon* | [ˈtɛf.lɔn] | ‘Teflon’ |

TABLE 2.23: **Instability of Medial Obstruent-Lateral Clusters**: Dutch.

[ˈɛk.la]). The relative instability of the obstruent-lateral clusters allows Icelandic to override the maximum onset principle, while obstruent-rhotic combinations appear to be sufficiently robust consonantal clusters that they force Icelandic to use another strategy to satisfy its prosodic demands.

### 2.4.4 Interactions with Syllable Nuclei

Pursuing the idea that rhotics are more ‘vocalic’ than laterals, another interesting asymmetry may be observed in Eastern Kayah Li (Tibeto-Burman), in which many syllables take the form /CLV/. Although any set of consonants and liquids can combine to create an onset within this template, aspiration on the initial consonant is entirely predictable from the identity of the following liquid: voiceless stops will only aspirate before the rhotic, never the lateral: [pʰr-], *[pʰl-]; [pl-], *[pʰl-] (Solnit 1997). This suggests that the rhotic has a greater affinity for the syllable nucleus, patterning more like a glide by allowing the initial consonant to aspirate, while the lateral remains part of a complex cluster in the onset, blocking aspiration of the preceding consonant because it is no longer adjacent to a sufficiently vocalic segment.

This phenomenon suggests that there might be a greater asymmetry – in terms of their affinity for the nucleus – between the liquids in Eastern Kayah Li than there is in a language like English, where both liquids typically block aspiration in onset clusters (*[spʰr-], *[spʰl-]). More research is required to see how voiceless stops aspirate when followed by liquids in onset clusters in other languages, as this could provide interesting insights into language-specific characteristics and asymmetries of liquid consonants.

### 2.4.5 Asymmetries in Liquid Syllabicity

In Section 2.1.2, the shared capacity of rhotics and laterals to act as syllabic nuclei was considered as evidence for a class of liquids in some languages (Czech, Slovak). In other languages (Croatian, Serbian, Macedonian) the rhotic, but not the lateral, may be syllabic. Dihovo Macedonian, for example, uses nucleic rhotics in words such as [vr̩f] 'top' and [r̩ʃ] 'rye', but unlike Czech, has no words with syllabic /l̩/ (Crosswhite 2001).

The rhotic of Hakka Chinese patterns with the (non-dorsal) nasals in that it can fill a syllabic nucleus: /m̩˩/ *'not'*, /n̩˩/ *'fish'*, /sɹ̩˧/ *'teacher'* (Lee & Zee 2009). Unlike the nasals, the rhotic cannot occur in syllable-intial position: /ma˧/ *'mother'*, /na˧/ *'to take'*, */ɹa/. The lateral, on the other hand, patterns with the obstruents in that its distribution is restricted to syllable-initial position: /la˧/ *'to pull'*; */l̩/. These data are consistent with the cross-linguistic trend that laterals pattern more closely with other consonants than rhotics.

The asymmetry in syllabicity between liquids is clearly demonstrated in the allophonic behavior of the Gonja liquid (Section 2.3.1), which appears to be underlyingly lateral, but surfaces as a rhotic when the liquid becomes syllabic (Zec 1995). Diachronic evidence also points to the inferiority of the lateral as a syllabic consonant: the two syllabic liquids reconstructed for Proto-Indo-European merged into a single syllabic rhotic in Vedic Sanskrit: */l̩/, */r̩/ > */r̩/ (Watkins 1992).

### 2.4.6 Summary: Asymmetries between Liquids

In this section, some differences in the behavior of laterals and rhotics have been identified. Evidence from gaps in cluster inventories, the comparative diachronic stability of obstruent-liquid clusters, capacity to act as syllabic nuclei and other asymmetries in syllabification, all demonstrate that laterals can differ from rhotics in some important respects. Cross linguistically, when these asymmetries are observed between liquids, laterals tend to pattern more closely with obstruents, while rhotics behave more similarly to voicoids. It remains to be seen whether there might be a phonetic basis to these differences, and if so, how it might be modeled in an articulatory framework.

## 2.5 Summary: Phonological Characterization of the Class of Liquids

The data presented in this chapter constitutes a significant body of evidence suggesting that laterals and rhotics together constitute a phonological class within many languages. Some of the properties shared by liquids – such as distribution within the syllable – are commonly observed across a wide variety of languages. Yet, compared to other families of segments which pattern together phonologically (nasals, stops, vowels), the evidence for a universal class of liquids is less compelling. Some of the phenomena described here are restricted to a small number of languages, and none would appear to apply as universally as phonological processes such as devoicing or nasalization, which suggest the existence of more generic classes. Nor do the phonotactic constraints on liquids appear to be as universal as those which apply to broader classifications of segments, which in most languages, allow the classes of consonants and vowels to be defined with respect to their organization in the syllable.

Nevertheless, the data show that the consonants which function as liquids repeatedly exhibit similar behaviors across languages – behaviors which are broadly characterized by three important properties:

i. *liquids are cluster-enabling consonants*: complex onsets and codas typically involve, and often require, liquids to combine with obstruents to facilitate clustering
ii. *liquids exhibit an affinity for the nucleus*:[6] the ordering of consonants in onset and coda clusters is typically asymmetrical, locating liquids closer to the nucleus; liquids often function as syllabic consonants
iii. *liquids exhibit a high degree of interchangability within the class*, observed in rhotic-lateral allophony, as well as phonological processes including merger, neutralization, alternation, dissimilation, assimilation and harmonization

Some asymmetries in the phonology of liquids have been identified which suggest that laterals tend to be more consonantal in their behavior, and rhotics more vocalic. Having surveyed the ways in which rhotics and laterals pattern together (and differ) cross-linguistically, we will now examine the phonological and phonetic behavior of liquids in two languages in detail: Spanish and Russian. The goal of these case studies it to test the hypothesis that liquids in these languages are

[6] The phrase is attributed to Sproat & Fujimura (1993: 291), who proposed that English lateral approximants have a vocalic gesture which shows "a strong affinity for the nucleus of the syllable."

articulated as multi-gestural segments, and to examine some ways in which their phonological properties might follow from such a characterization.

# Chapter 3

# The Phonology of Spanish Liquids

Spanish is a language of interest in this study because it uses a system of three liquid consonants which display some interesting distributional and allophonic behavior. The two rhotics – a trill and a tap – are contrastive in some environments and neutralize in others. The Spanish lateral is pronounced as a clear [l] in all environments, and neutralizes with rhotics in coda position in some dialects. An understanding of the articulatory nature of these three consonants, how they contrast and how they pattern together, is important when considering the phonetic and phonological properties of the class of liquids.

Spanish also provides an ideal test case for the central hypothesis being examined in this dissertation: that liquid consonants are characterized by a more global set of articulatory gestures than obstruents. Evidence from earlier studies was reviewed in Chapter 2 indicating that both of the liquids of English are produced with dorsal gestures. Yet because English uses a dark [ɫ] and an approximant rhotic, it is not surprising to find that these consonants are articulated with a dorsal component. It remains to be seen whether the clear lateral and the trill and tap of Spanish are also produced with a dorsal gesture.

In this chapter, an overview of the sound structure of Spanish will first be presented. The phonological behavior of the Spanish liquids will be compared to the behavior of other consonants, and the role of liquids in the phonological organization of the Spanish syllable will be considered. Building on the findings of previous studies, the goals of a new phonetic study of Spanish liquids will be set out, before these experiments are presented in Chapter 4.

## 3.1 Spanish Consonantal Phonology

Most varieties of Spanish distinguish 16 consonants and five vowels. Stress can be phonologically contrastive, but unstressed vowels are not significantly reduced. The phonemic inventory used by most standard varieties of American Spanish is illustrated in Table 3.1. Castilian Spanish uses an additional fricative /θ/ which contrasts with the alveolar fricative /s/ in pairs such as *cima* [ˈθi.ma] ‘summit’ / *sima* [ˈsi.ma] ‘abyss’. [1]

| | LAB | LD | DEN | ALV | PA | PAL | VEL | |
|---|---|---|---|---|---|---|---|---|
| Stop | p | | t̪ | | | | k | |
| | b | | d̪ | | | | g | |
| Nasal | m | | n̪ | | | ɲ | | |
| Affricate | | | | | tʃ | | | |
| Fricative | | f | | s̺ | | | x | |
| | | | | | | (ʝ) | | |
| Rhotic | | | | r | | | | |
| | | | | ɾ | | | | |
| Lateral | | | l̪ | | | | | |
| Vowel | | | | | | i | | u |
| | | | | | | e | | o |
| | | | | | | | a | |

TABLE 3.1: **Phonemic inventory of standard Latin American Spanish** (adapted from Hualde 2005).

The phonemic status of /ʝ/ is controversial, but in general, all non-nasal palatal consonants which occur in unstressed prevocalic and syllable-initial positions – [j], [ʝ], [ʒ], [ɟ] – can be treated as allophones of the high front vowel /i̯/ (Hualde 2005).[2] Similarly, the high back glide (/w/ according to Harris 1969), found in words such as *dueño* [ˈdu̯e.ɲo] ‘owner’, can be treated as a vocoid /u̯/ because there are no minimal pairs which constrast the high back vowel with a labio-velar approximant. The major implication of this analysis is that the liquids are the only non-obstruent oral consonants in Spanish.

1 These phonemes have merged into a single dental fricative in *ceceo* dialects of southern Andalusia (/θ/,/s/ → [θ]), and into a single alveolar fricative in the *seseo* varieties spoken in Cordoba, the Canary Islands, and most parts of Latin America (/θ/,/s/ → [s]).

2 In some varieties (Buenos Aires), there is a distinct palatal consonant which contrasts with the high-front vowel: *yerba* [ˈʒer.βa] ‘mate leaves’ / *hierba* [ˈi̯er.βa] ‘grass’; however, for most Spanish speakers, these words would be homophonous ([ˈjer.βa]).

### 3.1.1 Liquid Inventory

Most Spanish speakers distinguish three liquid consonants: two apical rhotics /r/ and /ɾ/, and the lateral /l/. *Lleísta* dialects (Paraguay and some Andean Spanishes) distinguish a second lateral (*polo* [ˈpo.lo] 'polo' / *pollo* [ˈpo.ʎo] 'chicken'). In these varities, the palatal lateral contrasts also with a palatal approximant (*poyo* [ˈpo.jo] 'stone bench') and the lateral-vowel sequence /li/ (*polio* [ˈpo.li̯o] 'polio'). In most areas, however, the palatal lateral has merged with the palatal approximant – typically through the process of *yeísmo* (/ʎ/,/j/ → [j]) – but *žeísmo* (/ʎ/,/j/ → [ʒ]) and *šeísmo* (/ʎ/,/j/ → [ʃ]) mergers are also found in Argentina. As a result of these changes, most modern varieties of Spanish use only a single lateral consonant (Hualde 2005).

Martínez-Celdrán et al. (2003) assert that Castilian Spanish distinguishes two lateral phonemes (*luz* [luθ] 'light' / *alli* [aʎi] 'there') as well as a palatal affricate (*yate* [ɟ͡ʝate] 'yacht'), which supposes a four-liquid system. However, because they give no minimal pairs which contrast the palatal approximant and the two laterals in the same phonological environment, we can conclude that the Spanish variety which they are describing is not a *lleísta* dialect, but rather a *yeísta* variety in which either the merged palatal approximant is lateralized or the alveolar lateral is palatalized before high front vowels.

Spanish /l/ is produced as a clear lateral in all environments – no [ɫ] allophone appears in coda position, or as a result of back vowel coloring: *lata* [ˈla.ta] 'can' cf. *tal* [tal] 'such'. Hualde (2005) claims that the place of coronal articulation of the lateral assimilates to a following non-labial consonant: *alto* [ˈal̪.t̪o] 'tall', *colcha* [ˈkolʲ.tʃa] 'bedspread', cf. *balsa* [ˈbal.sa] 'raft'. There is no restriction on the distribution of /l/, which appears in onsets, codas, word-initially, and word-finally. In *lleísta* dialects, the palatal lateral merges with the alveolar lateral in word-final position: *élla* [eʎa] 'she' but *él* [el] 'he' (Harris 1969).[3]

### 3.1.2 Distribution of Rhotics

Spanish rhotics have a limited distribution: the trill and the tap are contrastive only in intervocalic contexts: *coro* [ˈko.ɾo] 'choir' / *corro* [ˈko.ro] 'circle'; *quería* [ke.ˈɾi.a] 'I wanted' / *querría* [ke.ˈri.a] 'I would want'. In phonological environments other than intervocalic, the trill and tap do not contrast, and different rhotic allophones are used depending on dialect, speaker and register.

Most commonly, the trill is found word-initially (*rata* [ˈra.ta] 'rat') and in medial

[3] Palatal nasals are also prohibited word-finally in all Spanish varieties.

onsets following consonantal codas (*honra* [ˈon.ra] 'honour'). Martínez-Celdrán et al. (2003) claim that in Castillian Spanish, the trill appears in medial onsets only after [l], [n] and [s].[4]

The tap is the prototypical rhotic found in onset clusters (*broma* [ˈbɾo.ma] 'joke', *abre* [ˈa.bɾe] 'he opens'), and in medial pre-consonantal codas (*carta* [ˈkaɾ.ta] 'letter'). Importantly, the tap also appears in word-final codas before another vowel – a position in which the rhotic would be resyllabified as an onset in *andante* and *presto* speech (*mar ancho* [ˈma.ɾan.tʃo] 'wide sea'). Hualde (2005) observes that the tap is the only consonant in the phonology which is contrastive word-medially, but excluded from word-intial position.

The distribution of Spanish rhotics is summarized in Table 3.2. It is important to note that these are the allophones which prototypically appear in the environments indicated in most standard varieties of Spanish. According to Harris (1969), the type of rhotic which occurs in *all* environments can vary stylistically and idiolectally.

| RHOTIC | ENVIRONMENT | EXAMPLE |
|---|---|---|
| Trill: | # _ | [ˈro.ka] |
| | C [$_\sigma$ _ | [ˈen.re.do] |
| Tap: | [$_\sigma$C _ V | [ˈgɾa.mo] |
| | V _ #V | [ˈse.ɾa.mi.gos] |
| Contrastive: | V _ V | [ˈka.ɾo] / [ˈka.ro] |
| Variable: | V _ ]$_\sigma$C | [ˈpaɾ.te] ∼ [ˈpar.te] |
| | V _ #C | [ˈseɾ.po.ˈe.ta] ∼ [ˈser.po.ˈe.ta] |
| | V _ ## | [ˈseɾ o ˈno ˈseɾ] ∼ [ˈser o ˈno ˈser] |

TABLE 3.2: **Distribution of Spanish rhotics** (adapted from Hualde 2005).

Because the trill and the tap occur in complementary distribution in all but one context, numerous analyses have been proposed under which these consonants are analysed as allophones of a single rhotic phoneme (Harris 1969, 1983; Mascaró 1976; Wheeler 1979). Under these approaches, the trill is typically treated as the surface realization of a geminate tap: /ɾɾ/ → [r] (Bonet & Mascaró 1997, Lloret 1997). This analysis is consistent with a *diachronic* account of Spanish trills, which developed from geminate rhotics in Latin (Penny 2002). The geminate origin of Spanish trills also explains their limited distribution in intervocalic position.

Nevertheless, as Hualde (2005) observes, the way in which trills syllabify in mod-

[4] *La Real Academia Española* prescribes the use of the trill after these consonants alone.

ern Spanish argues against their synchronic analysis as underlying geminates. Unlike in Italian, where long intervocalic rhotics syllabify across both coda and onset ([kar.ro] *'cart'* cf. [ka.ro] *'dear'*), Spanish intervocalic trills are syllabified in the same manner as taps – entirely in the onset: [ka.rro] *'cart'* cf. [ka.ro] *'expensive'*. Furthermore, if trilled rhotics were underlyingly geminates in modern Spanish then we would expect to find taps word-initially; instead we find trills in this environment, which Hualde (ibid.) suggests is the result of word-initial fortition of the rhotic.

In conclusion, the distributional behavior of Spanish rhotics suggests that there are two underlying phonemes which contrast in medial non-resyllabified onsets, and neutralize elsewhere. A fundamental goal of the phonetic study will therefore be to characterize the production of these two sounds in intervocalic environments, and to compare their production in other environments where they neutralize.

## 3.2 The Phonology of Spanish Liquids

Evidence for a class of liquids may be found in a variety of distributional phenemona, allophony, and other phonological processes in Spanish. The most important phonological characteristics of the Spanish liquids will briefly be reviewed in this section.

### 3.2.1 Spanish Syllable Phonotactics

Spanish syllable structure conforms to the template $(C_1(C_2))V(C_3(C_4))$, but shows a strong preference for open syllables with simple onsets (Table 3.3). Only vowels can fill a syllabic nucleus; there are no syllabic consonants.[5] Liquids play a special role in the phonotactics of the Spanish syllable as they are essential in the formation of onset clusters, and because they feature in a disproportionate number of codas.

#### Onset Structure

Spanish syllable onsets can be filled by a single consonant or one of a restricted set of clusters. Onset clusters are limited to a two-consonant sequence /$C_1C_2$-/ in which $C_1$ can only be the fricative /f/ or a stop, and $C_2$ either of the liquids /l/ or

[5] See discussion in Section 3.1 on the phonemic status of glides and the structure of the nucleus.

| SYLLABLE TYPE | FREQUENCY |
|---|---|
| CV | 55.81% |
| CVC | 21.61% |
| V | 9.91% |
| VC | 8.39% |
| CCV | 3.14% |
| CCVC | 0.98% |
| VCC | 0.13% |
| CVCC | 0.02% |
| CCVCC | 0.01% |

TABLE 3.3: **Frequencies of occurance of Spanish syllable types** (Guerra 1983).

/ɾ/. Examples of each of these clusters are given in Table 3.4. The distribution and felicity of coronal-lateral clusters varies between dialects.[6]

| RHOTIC-FINAL | | LATERAL-FINAL | |
|---|---|---|---|
| /prado/ | *'field'* | /plaka/ | *'sheet'* |
| /brava/ | *'fierce'* | /blanka/ | *'white'* |
| /trampa/ | *'trick'* | (/atlas/) | *'atlas'* |
| /drama/ | *'drama'* | — | |
| /krasa/ | *'crass'* | /klara/ | *'egg white'* |
| /gramo/ | *'gram'* | /glasea/ | *'he glazes'* |
| /franka/ | *'sincere'* | /flaka/ | *'skinny'* |

TABLE 3.4: Examples of possible **Spanish onset clusters**.

### Coda Structure

Complex codas are rare in Spanish (Table 3.3).[7] Although most consonants are licensed in coda position, few post-nuclear consonants commonly occur in Spanish

[6] Word-initial /tl-/ onsets are found in words of Nahuatl origin in Mexican Spanish: *tlapalería* 'paint store', *tlecuil* 'hearth'. Word internal /-tl-/ sequences which are broken across syllables in most varieties of Peninsular Spanish are syllabified as onsets in all Latin American varieties: [a.tlas] *'altlas'*, [a.ˈtlan.ti.co] *'atlantic'* (Hualde 2005).

[7] All coda clusters in native words take the form /-Cs/, where C is one of a limited set of consonants, e.g. *biceps*, *ads.cri.bir*, *trans.por.te*. In Peninsular Spanish, some family names end with the cluster /-nθ/: *Sanz*, *Sainz* (Hualde 2005). Other types of clusters are found only in loan words, eg. *Nueva York*, *thorax*. All complex codas are prone to simplification through deletion: eg. [to.ras], [tras.por.te], [nu̯e.va.jor] (Colina 2006).

syllables. Colina (2006) and Hualde (2005) observe that simple codas most frequently consist of one of the coronals {/d/,/s/,/n/,/ɾ/,/l/}, as well as the fricative /θ/ in Peninsular Spanish, yet they do not support the claim with any lexicostatistical data.

In order to examine the structure of Spanish codas more thoroughly, an electronic corpus was automatically syllabified and searched to provide an estimate of the distribution and frequency of coda consonants. The corpus consisted of a dictionary of 68,415 of the most common roots of Mexican Spanish (Free Software Foundation 1994). Of the 250,213 syllables occurring in the corpus, 177,176 (71%) were found to be coda-less. The most commonly occurring coda consonants were /-n/ (33%), /-ɾ/ (29%), /-s/ (18%) and /-l/ (6%). Less than 3% of all syllables ended other than with a nasal, liquid, /-s/ or no coda (Table 3.5).[8]

| CODA | COUNT | % SYLLABLES | % CODAS |
|---|---|---|---|
| No coda | 177,176 | 70.8% | |
| Nasal | 27,435 | 11.0% | 37.6% |
| Liquid | 25,597 | 10.2% | 35.0% |
| /-s/ | 12,866 | 5.1% | 17.6% |
| Other | 7,139 | 2.9% | 9.8% |
| Total | 250,213 | 100.0% | 100.0% |

TABLE 3.5: **Representative frequencies of Spanish coda consonants**.

These data are consistent with those of Guerra (1983), who estimated 68.9% of Spanish syllables to be coda-less (Table 3.3). While the data in Table 3.5 do not support the claim that /d/ ranks amongst the most frequent coda consonants (/-d/ accounts for only 0.6% of codas in this corpus), it does demonstrate that the great majority of Spanish coda consonants are coronals (86%), sonorants (73%) or both (68%). 35% of all codas in the corpus were liquids.

Harris-Northall (1990: 40) suggests that liquids appear in a disproportionate number of codas in (Castillian) Spanish because they "have always shown themselves to be more resistant to erosion than other consonantal segments". He demonstrates that throughout the history of the language, coda obstruents and nasals have often been deleted or moved out of post-nuclear postions through the application of metathesis or epenthesis; liquids, on the other hand, have proven to be more diachronically stable in syllable-final and word-final positions.

8 Because the data source is a dictionary of base wordforms, some consonants which commonly occur in inflectional suffixing codas, especially /s/ and /n/ will be under-represented in this frequency analysis. It is also likely that the liquid /ɾ/ will be over-represented because of the disproportionate number of infinitive verb forms in the corpus.

For example, a major force in the development of Old Spanish, was [-e] apocope. At the peak of the application of this process in the 12th and 13th Centuries, word-final consonants of all types were found in Spanish words (Table 3.6). Most of the word-final consonants attested in Old Spanish are no longer found in absolute word-final position in Modern Spanish – as the data in Table 3.6 illustrates, [-e] epenthesis has generally been used to repair dispreferred word-final closed syllables. However, liquids, as well as /s/ and /n/, were tolerated in word-final position in many words, and have survived into the modern language.

| LATIN | OLD SPANISH | MODERN SPANISH | GLOSS |
|---|---|---|---|
| PRINCIPE | princip | principe | 'prince' |
| PONTE | puent | puente | 'bridge' |
| NOCTE | noch | noche | 'night' |
| NOVE | nuef | nueve | 'nine' |
| DICIT | diz | dice | 'say'-3SG.PRES |
| CRUDELE | cruel | cruel | 'cruel' |
| MARE | mar | mar | 'sea' |

TABLE 3.6: **Diachronic stability of Spanish word-final liquids** (Harris-Northall 1990).

**Coda Preferences in Loanword Phonology**

Is is not only in ancestral forms that coda liquids have proven to be more diachonically stable than other types of consonant. Harris-Northall (1990) notes that final liquids were also maintained in many Arabic loanwords, yet he provides only two examples, and does not describe the sound changes which affected other consonants in the transfer from Arabic.[9] Versteegh (1997) estimates that Modern Spanish uses more than 4000 words of Arabic origin. Because both the Classical and Hispaño-Arabic from which these words were sourced were languages with rich sets of coda consonants, examination of the phonological changes which have shaped Arabic loanwords in Spanish can offer further insights into the role of liquids in the phonotactics of the Spanish syllable.

To better consider the diachronic stability of coda consonants in Spanish, a corpus of 1,250 Arabic loanwords was examined (wordlist obtained from Batzarov 2004; etymons taken from Real Academia Española 2009). The survey reveals that words which were originally consonant-final in Arabic have typically undergone

[9] One of the examples of final lateral 'preservation' cited by Harris-Northall (1990) has a unclear etymology, but appears to be the result of the lateralization of a final stop in the Hispaño-Arabic (originally Persian) loanword: *azúl* < [laːzaward] 'blue' (Real Academia Española 2009).

paragoge so as to conform with the prefered open syllable structure of Spanish: *aladroque* < [alħatˤruk] 'anchovy'; *alcrebite* < [kibriːt] 'sulphur'; *jarabe* < [ʃaraːb] 'syrup'. Only 6.7% of Arabic loanwords listed by Batzarov (2004), for example, were found to be obstruent-final, while 18.9% ended with an obstruent-vowel sequence.

Lateral- and rhotic-final words of Arabic origin, on the other hand, abound in Modern Spanish: *alcázar* < [qasˤr] 'fortress'; *azúcar* < [sukkar] 'sugar'; *mandil* < [mandiːl] 'apron'; *zagal* < [zuggluːl] 'lad', *alcohol* < [kuħl] 'alcohol'; *abismal* < [mismaːr] 'abysmal'. Some words which originally ended with a liquid-vowel sequence in Arabic are liquid-final in Modern Spanish, e.g. *albur* < [buːriː] 'word game'. 13.2% of the Arabic loanwords listed by Batzarov were found to be liquid-final – twice as many as were obstruent-final, despite the greater frequency of obstruent consonants.

It is not only final obstruents which have been affected in the phonological transfer: although some words of Arabic origin have maintained their final nasal (*algodón* < [qutˤn] 'cotton'; *almacén* < [maxzan] 'warehouse'), many other nasal-final words have also been altered through epenthesis of a final vowel (*aduana* < [diːwaːn] 'customs'; *mezquino* < [miskiːn] 'mean, stingy'; *fulano* < [fulaːn] 'so-and-so'), which suggests that liquids might be more felicitous absolute final coda consonants in Spanish than the other sonorants. A more rigourous examination of the historical development of Arabic loanwords would be necessary to justify such claims; however, it is apparent from even a small survey of such wordforms that liquids have a special status as coda consonants in Modern Spanish.

### 3.2.2 Phonological Processes Involving Liquids

As well as their shared phonotactic distribution, Spanish rhotics and laterals pattern together in a range of phonological processes which suggest that they form a class.

#### Liquid Dissimilation

Liquids have dissimilated in many Spanish words which originally contained two similar liquids in Latin: ARBOR > *arbol* 'tree'; REBUR > *roble* 'oak'. Colantoni & Steele (2005) observe that this change occurred only in those Romance varieties in which the rhotic was realized as a tap.

Synchronic liquid dissimilation is also observed in both Peninsula and Caribbean Spanish dialects, in words such as *peregrino* → [pelegrino] 'wanderer', *glándula* →

['grandula] 'gland', *delantales* → [delantares] 'aprons' (Lloret 1997; Hualde 2005). Lloret (1997) identifies a wide range of sonorant dissimilation phenomena in Iberian languages, but notes that dissimilation within the class of liquids is more common than changes between nasals and liquids.

### Metathesis

As in other languages, liquids feature in a high proportion of the metathesis phenomena which are attested in Spanish. Mutual metathesis of liquids has occurred in the development of some words from their Latin etymons: PERICULUM > *peligro* 'danger'; MIRACULUM > *milagro* 'miracle', as well as synchronically in variants such as *fraile* → [flaire] 'monk' (Quilis 1999).

More common than mutual metathesis is CV metathesis, which is attested in many varieties of Spanish, and most commonly involves liquids and nasals. The most common pattern in examples cited by Russell Webb & Bradley (2009) involves the metathesis of coda rhotics into complex onsets: *garbanzo* → [grabanzo] 'chickpea', *permiso* → [premiso] 'permission', *porfiar* → [profiar] 'to insist'. Quilis (1999) cites an example demonstrating the opposite pattern for a lateral, which is metathesized out of an onset and into coda position: *clueca* → [kuleka] 'broody'. Liquid metatheses which result in the same patterns of resyllabification – laterals moving into codas, and rhotics into onsets – are ubiquitous in Judeo Spanish, e.g. *dadlo* → [daldo] 'give it'; *tarde* → [tadre] 'late'; *sordo* → [sodro] 'deaf' (examples from Bradley 2006).

### Coda Liquid Neutralization

In Andalusian, Extremaduran and Caribbean Spanish varieties in particular, the tap/lateral contrast tends to be neutralized in coda position. As a result of this process, pairs such as *mar* 'sea'/*mal* 'evil' and *harto* 'full'/*alto* 'tall' have become homophonous for some speakers in the Dominican Republic and Cuba (Lipski 1994).

Neutralization results from a number of different processes which affect liquids in coda position. In Puerto Rican Spanish, for example, the neutralized consonant can be realized either as a type of a lateralized rhotic: *puerta* → ['pue$^{r}$l.ta] 'door'; *por favor* → [po$^{r}$l.fa.'βol] 'please' (Hualde 2005); while in Cuban Spanish, pre-consonantal liquids tend to assimilate to varying degrees to the following consonant, sometimes resulting in an intervocalic geminate (Quilis 1999): *el golpe* → [eg.'gob.pe] 'the blow'; *el verde* → [eb.'bed.de] 'the green one'; *pulga* 'flea', *purga* 'purgative' > ['pug.ga] (Hualde 2005).

Many other phonological processes which affect coda liquids have been reported in both Peninsular and American Spanish varieties, some of which result in liquid neutralization, and some of which only affect the rhotic or lateral. The most important of these processes are summarized below.

**Rhotacism and Lambdacism**

Rhoticization of final laterals is a feature of the Spanish spoken in the Bahía Honda, Havana and Cárdenas regions of Cuba, e.g. *delantal* → [delantar] 'apron'; *multa* → [murta] 'fine'; *pulso* → [purso] 'I press' (Quilis 1999). Coda laterals are also described as partially or completely rhotized in some varieties in Venezuela (D'Introno et al. 1979), Andalusia (Quilis-Sanz 1998) and the Canary Islands (Marrero 1988).

Rhoticization is not limited to laterals in coda position, but also occurs in tautosyllabic onset clusters in Leónese and Murcian Spanish, e.g. *planta* → [pranta] 'plant'; *flor* → [fror] 'flower'; *iglesia* → [igresia] 'church'; *clavel* → [kraβel] 'carnation' (Quilis 1999).

Lateralization of coda rhotics is reported in regions of Cuba, Panama and Puerto Rico (López-Morales 1983). Willis (2006) illustrates the phenomenon in Dominican Spanish: *ver̲dad* → [bel̲.da] 'truth', *comprar̲* → [kom.pral̲] 'to buy', and Quilis (1999) gives numerous examples from the Cuban Spanish spoken in Santigo de Cuba: *abrir* → [abril] 'open'; *tambor* → [tambol] 'drum'; *secarse* → [secalse] 'dry oneself'. [10]

**Liquid Vocalization**

In some Spanish varieties spoken in Colombia, Andalusia, the Canary Islands, and most famously in the Cibao region of the Dominican Republic, coda liquids are prone to vocalization pre-consonantally, and word-finally in words with final stress (Hualde 2005). For both laterals and rhotics, the segment which results from this process is a high front vowel or a palatal glide: *algo* [ˈai̯.ɣo] 'something', *cuerpo* [ˈkwei̯.po] 'body', *mujer* [mu.ˈhei̯] 'woman', *baul* [ba.ˈui̯] 'trunk' (Jiménez Sabater 1975). Quilis (1999) observes that liquids can also vocalise to a schwa in unstressed codas.

[10] Quilis (1999) notes that lateralization rarely affects coda rhotics which appear before nasals.

**Spirantization and Nasalization of Liquids**

Other phonological processes which affect both coda laterals and rhotics in some Spanish varieties include spirantization (Guane, Cuba): *alpargata* → [ahpaɾ'gata] 'espadrille', *perla* → ['peh.la] 'pearl'; and nasalization (Cuba and the Dominican Republic): *piel* → [pjen] 'skin', *calamar* → [kala'mãn] 'squid' (Quilis 1999).

### 3.2.3 Phonological Acquisition of Spanish Liquids

Studies of phonological development show that the lateral and rhotics are acquired later than other consonants by Spanish speaking children (Stoel 1973, Jimenez 1987, Vihman 1996), despite their high frequency (Section 3.2). Before mastery, alternations are observed between all the liquids and /d/ (Stoel 1973). The data points to an earlier development of the lateral over the rhotics, however, once /l/ is established it provides a substitute for both rhotics until they have been mastered (Yavaş 2004, Barlow 2005).

Liquids are also acquired late, and often imperfectly, by second language learners of Spanish (Berkowitz 1986; Elliot 1997; Zuengler 1988). Non-native productions of all three liquids serve as a strong sociolinguistic marker of second language speakers (Face & Menke 2008), who often substitute their native rhotic for both target rhotics (Face 2006; Major 1986), and fail to acquire a clear lateral in coda postition (Segalowitz et al. 2004).

### 3.2.4 Summary – The Class of Liquids in Spanish

In this section, a wide range of phonological phenomena involving liquid consonants in Spanish have been identified. The trill and the tap neutralize in most phonological environments, where they are realized as different types of rhotics by different speakers. Phonotactically, both laterals and rhotics appear in a disproportionate number of codas, and the liquids are the unique class of sounds which facilitate complex onsets in Spanish.

Diachronically, synchronically, and during acquisition, laterals and rhotics participate in a variety of mutual and shared phonological processes, including substitution, dissimilation, metathesis with each other and with adjacent vowels, neutralization and vocalization. Spanish liquids have been shown to be especially susceptible to phonological processes in coda environments, where they tend to neutralize with each other.

Collectively, this represents a convincing body of evidence that the consonants {/l/,/ɾ/,/r/} constitute a phonological class. We can gain some insights into the properties of this class by considering some of these phenomena more closely. The fact that liquids are acquired later than other consonsants suggests that they are more phonetically complex in some respect, which is consistent with the hypothesis that liquid production involves a greater degree of global lingual coordination than obstruents.

The widespread occurance of phonological processes in Spanish which involve substitution of one liquid for the other (dissimilation, rhoticism, lambdacism), or neutralization of different liquids into a common realization, suggests that the liquids might share some common phonetic properties. It is also noteworthy that the liquids tend to pattern more with each other than with the other the other sonorants in all of these phenomena, as this indicates that the common property which liquids share might be more specific than merely sonority. Likewise, although the liquids pattern with the other coronals in some aspects of Spanish phonology (distribution in codas), in general the other coronals neither share the same distributional properties (cluster phonotactics) nor participate in the same processes as the liquids (dissimilation, vocalization, etc.), which suggests that the liquids might be characterized by some shared phonetic properties which distinguishes them from the other coronals.

The goal of the experimental component of this part of the dissertation will be to investigate potential phonetic bases for some of this class-like behavior. Before outlining the specific aims of these experiments, the phonetic literature on Spanish liquids will briefly be reviewed to consider what is already known about the production of rhotics and laterals.

## 3.3 Phonetic Characterization of Spanish Liquids

Phonetic studies of the Spanish liquids have primarily focused on the acoustic properties of these sounds (e.g. Massone & Gurlekian 1981, Quilis 1999, Simonet et al. 2008). Articulatory data on these consonants are limited, and often address only coronal activity. Partly due to the difficulty of obtaining data, and partly due to a lack of appreciation of the importance of studying the whole vocal tract, the dynamics of articulation of Spanish liquids have not been studied extensively, and are not well understood.

Liquid production has been more thoroughly examined in Catalan than in Spanish (Barnils 1933; Recasens 1986, 1991, 2007; Solé 2004, etc.). Because of the phonological similarities between the languages, the results of these studies are of interest;

however, the first goal of the present study is to address this deficit by examining the phonetics of the Spanish liquids in much greater detail, using modern experimental techniques.

### 3.3.1 Phonetic Properties of Spanish Laterals

The primary goals of production of the Spanish lateral /l/ are described by Ladefoged & Maddieson (1996): an apical coronal closure is formed in the dental-alveolar region while the body of the tongue is elongated, allowing airflow around the sides of the tongue, rather than through a central channel. Comparison of data from palatographic studies (Navarro Tomás 1970, Recasens 2004, Ladefoged & Maddieson 1996) reveals considerable variation in the place of articulation and extent of contact of the coronal constriction; unsurprisingly, less variation in the coronal articulation of [l] is observed in *lleísta* varieties which contrast a palatal lateral.

The behavior of the tongue dorsum during the production of Spanish laterals is less well understood. Articulatory studies of Spanish and Catalan laterals have either used palatography (Recasens et al. 1995, 1996, Martínez-Celdrán & Fernández-Planas 2007) – which provides no information about regions of the tongue which do not come into contact with the roof of the mouth – or else have inferred details about dorsal articulation from the acoustic analysis of coarticulation (Recasens 1987). Some static articulatory data is available from X-ray studies of single speakers of Castilian Spanish (Quilis 1963, Straka 1965, Martínez Celdrán 1984). Midsagittal X-rays captured during mid-consonantal production in these studies show that the back of the tongue assumes a lower posture than that observed during lateral production in English and Russian.

Acoustically, Spanish [l] is characterized by a relatively high second formant frequency. Cross-linguistically, it has been observed that the frequencies of the first two formants – especially F2 – are correlated with the degree of velarization or pharyngealization of /l/: laterals with F2 > 1200Hz generally being perceived as clear, and those with F2 < 1200Hz perceived as dark (Fant 1960, Recasens 2005). Acoustic studies of laterals produced by male speakers of a variety of different Spanish varieties report second formant frequencies above 1800Hz in the context [ala], and greater than 1400Hz in the context [ulu] (Chafcouloff 1972, Quilis et al. 1979, Hualde 2005). These values are consistent with the lower/more advanced dorsal postures observed in the X-ray studies cited earlier, and the characterization of Spanish [l] as a clear lateral.[11]

[11] An important difference between Spanish and Catalan is that Catalan uses a dark lateral, which is also observed in the Spanish spoken in Cataluña. Recasens et al. (1995) charaterize Castilian and Argentinian Spanish laterals as clearer than French, but darker than German [l].

### 3.3.2 Phonetic Properties of Spanish Rhotics

The production of the Spanish tap (*vibrante simple*),[12] is described as involving the rapid vertical movement of the tongue tip, resulting in a single contact in the post-dental region (Ladefoged & Maddieson 1996), while the trill (*vibrante múltiple*) typically involves two or three contacts in the same region (Hualde 2005). Spectrograms provided by Martínez-Celdrán (1984) show trills produced with four coronal contacts, however the consonant /r/ is often produced by Spanish speakers with a single contact, which raises the question of how a short trill differs from a tap.

The fundamental phonetic distinction between the two rhotics is the mechanism by which the tongue tip is moved: the tap being articulated by lingual muscular activity – the same as a coronal stop – while the coronal articulation in a trill results primarily from aerodynamic factors (once the tongue tip and blade have been actively approximated to the passive articulators). Studies of trill production in Catalan and other languages (Catford 1977, McGowan 1992, Solé 2002) have identified the complex set of articulatory and aerodynamic conditions which are necessary to initiate tongue-tip trilling: positioning and relaxation of the tongue tip, contraction of the tongue body to achieve the right shape and elasticity requirements, creation of a sufficiently narrow aperture to create a Bernoulli effect, and the maintenance of sufficient pressure difference across the lingual constriction. However; once trilling is initiated, tongue-tip vibration is maintained as a self-sustaining vibratory system.

Although the *mechanics* of trill production have been described in detail, the broader phonetic characterization of trilled rhotics, and the way in which the trill is differentiated from the tap in Spanish is less well understood. Recasens (1991) has investigated the rhotic contrast in Catalan,[13] and concluded that "the tongue body is subject to a higher degree of constraint during the production of the trill than the tap", based on their differing degrees of resistance to coarticulation from adjacent vowels. These results built on an earlier study of VCV sequences in Catalan and Spanish, in which Recasens (1987) concluded that the trill and the Catalan dark lateral [ɫ] were more resistant to coarticulation because these consonants involve "a velarization gesture", unlike the tap and the clear [l].

12 Harris (1969), Ladefoged (1975) and others use the terms *tap* and *flap* interchangably. As Ladefoged (2005) later observes, it is useful to distinguish between a rhotic articulated primarily through lingual movement perpendicular to the passive articulator (*tap*), and one in which tongue tip movement is first away from and then towards the passive place of articulation (*flap*). This distinction is important when characterising the liquid systems of some Dravidian and Australian languages. It will be shown in Chap. 4 that Spanish rhotics are prototypically articulated as taps, rather than flaps.

13 Catalan, like Spanish, also uses a trill and a tap, contrastive only in intervocalic enviroments.

If trills are characterized phonetically by the use of a dorsal gesture which is not present in the production of a tap, this raises the question of whether the taps differ phonetically from the coronal obstruents, which presumably only involve a specification for a coronal gesture. Likewise, if the 'clear' laterals of Spanish are inherently different from laterals in English, Russian and Catalan, in that they also lack a dorsal gesture, they might also be expected to display similar phonetic properties to the coronal obstruents which are not observed in the production of the trill.

Evidence from previous phonetic studies suggests that taps differ from coronal obstruents in at least two respects. Monnot & Freeman (1992) found that the Spanish tap differs from flapped allophones of American English /t/ and /d/ in that it does not involve any anticipatory articulation. In a study of Castilian coronal consonant clusters, Romero (1996) concluded that [ɾd] clusters consisted of two different segments, which is consistent with the hypothesis that the tap involves a different type of articulation from alveolar obstruents. While these results are suggestive, in neither study was the full set of Spanish liquids examined and compared with the stops. It remains to be seen exactly how the production of coronal consonants in each class might be characterized with respect to lingual control, and whether they differ in terms of dorsal articulation.

The conclusion to be drawn from a survey of the phonetic literature is that much more (and more specific) data is required to fully understand the articulatory nature of the Spanish rhotics and the way that they differ; however there is evidence that both rhotics seem to require a type and precision of lingual control which differs from that involved in the coronal stops.

### Svarabhakti in Spanish Rhotics

It has long been observed that medial rhotic-initial clusters appear to be pronounced differently to other heterosyllabic clusters in some Spanish varieties (Lenz 1892, Gili Gaya 1921). Navarro Tomás (1918) has hypothesized that this effect results from epenthesis of a vowel fragment ("el elemento esvarabático") between the coda tap and the following consonant.[14] Malmberg (1965) illustrates the phenomenon in his transcription of the (Southern) Peninsular Spanish pronunciation of four words containing medial rhotic clusters (Table 3.7).

[14] The original reference to *svarabhakti* in Spanish rhotics is attributed to Lenz (1892): "he oído a españoles y peruanos ... pronunciarla (la *r*) con sonoridad muy completa, como en *arte*, *trabajar*, *cuerpo*, donde entre el golpe de lengua de la *r* y las consonantes vecinas puede percibirse un perfecto sonido glótico (*svarabhakti*)." (Quilis 1999: 338). In the Romance phonetics literature, the term has come to refer specifically to the "short, vowel-like fragments found between a tap /ɾ/ and its adjacent consonant" (Schmeiser 2009).

| | | |
|---|---|---|
| árboles | [arᵊ.βo.les] | *'trees'* |
| verdes | [verᵊ.ð̞es] | *'green'* |
| cargar | [karᵊ.ɣar] | *'to load'* |
| fuerzes | [fu̯erᵊ.ses] | *'force'* |

TABLE 3.7: **Rhotic svarabhakti** in Peninsular Spanish - ɾC- clusters (Malmberg 1965).

Quilis (1999) observes that svarabhakti also occur in tautosyllabic rhotic-final onset clusters. In the spectra in Figure 3.1, a resonant fragment is evident between the stop interval and the tap closure in the obstruent-rhotic clusters which begin each word. Quilis transcribes this fragment as *e*, noting its "considerable duration": *prado* [perado] 'field', *trece* [terese] 'thirteen', *fresa* [feresa] 'strawberry', *droga* [deroga] 'drug'.

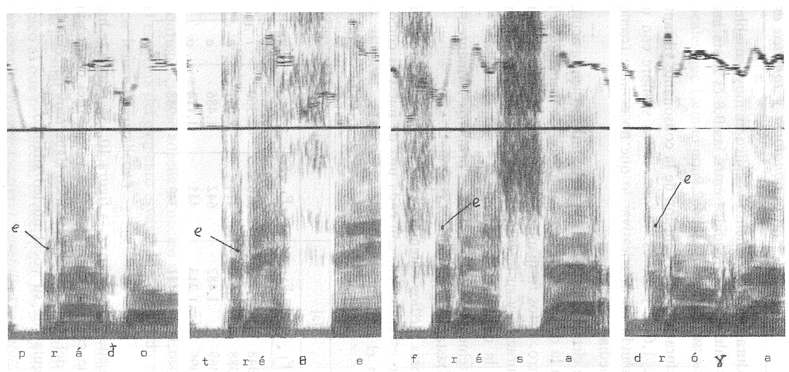



FIGURE 3.1: Spectra of **cluster-initial Spanish words showing svarabhakti** (Quilis 1999: 339).

Observations of svarabhakti – all based exclusively on acoustic data – have been made in many other other descriptions of Spanish rhotic clusters (Massone 1988; Almeida & Dorta 1994; Blecua 1996, etc.). The intermediary fragment is not always realized as a resonant element: in an acoustic study of five speakers of Highland Equadoran Spanish, Bradley (2004) found that coda rhotics are separated from following consonant either by a short vowel or a fricative burst resulting from assibilation. Martínez Celdrán (2007) describes the element which precedes the final syllable in the word *neutro* as having schwa-like formant qualities, and transcribes this pronunciation accordingly: [neutᵊro].

The common assumption in all of these descriptions is that the resonant fragment is intrusive: an epenthetic element which is introduced between a rhotic and its adjacent consonant to break up the cluster. Considering the overwhelming preference for open syllables and simple onsets in Spanish syllable structure (Section 3.2.1), the interpretation of Spanish cluster svarabhakti as epenthetic vowels is understandable, as similar processes occur in many languages, including Lenakel (Kager 1999), Italian (Maiden & Parry 1997), and Morocan Colloquial Arabic (Gafos 2002), as well as in loanword phonology in Japanese and many other languages.

Under an Optimality Theoretic approach (Prince & Smolensky 1993), for example, the presence of svarabhakti in both onset (Table 3.8) and coda clusters (Table 3.9) could be explained by a common constraint hierarchy in which a prohibition on complex onsets outranks both a coda prohibition and input faithfulness constraints: *COMPLEX ≫ NO-CODA ≫ LIN-IO ≫ DEP-IO.

| /prado/ | *COMPLEX | NO-CODA | LIN-IO | DEP-IO |
|---|---|---|---|---|
| pra.do | *! | | | |
| par.do | | *! | * | |
| ☞ pə.ra.do | | | | * |

TABLE 3.8: **Svarabhakti in Spanish rhotic onset clusters**: an OT account.

| /arboles/ | *COMPLEX | NO-CODA | LIN-IO | DEP-IO |
|---|---|---|---|---|
| ar.bol.es | | ***! | | |
| ar.bo.les | | **! | | |
| a.rbo.les | *! | | | |
| raboles | | * | *! | |
| ☞ a.rə.bo.les | | * | | * |

TABLE 3.9: **Svarabhakti in Spanish rhotic medial clusters**: an OT account.

An alternative explanation offered by Bradley (2004) is that that the resonant fragments which appear in rhotic clusters are the result of timing differences in the accompanying coronal segments. Under this account, coda svarabhakti are not epenthetic, but appear when gaps arise between the otherwise contiguous tongue tip gestures of the coda rhotic and the following onset consonant (Fig. 3.2).

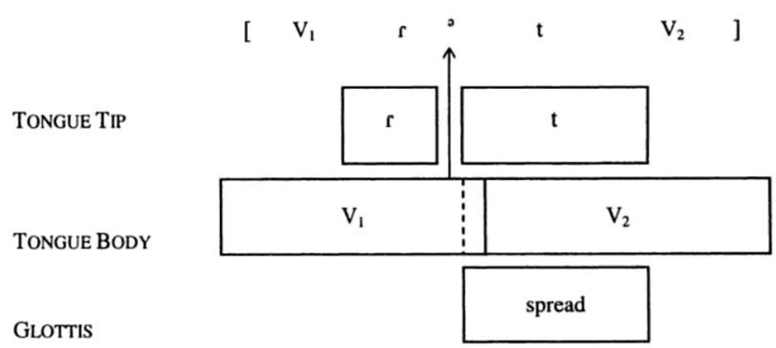



FIGURE 3.2: A gestural account of intrusive **svarabhakti vowels** in Spanish medial rhotic-final clusters (taken from Bradley 2004: 206).

If Bradley's account is correct, then we should expect the svarabhakti which appear in Spanish medial rhotic-initial clusters to have the same properties as the vowels which precede them. On the other hand, if svarabhakti are essentially epenthetic, as Quilis, Martínez Celdrán and Malmberg's descriptions suggest, then these resonant fragments might be expected to have the phonetic properties of a schwa. Acoustic data on the formant properties of svarabhakti (Quilis 1970) is inconclusive: when plotted in an F1-F2 plane, these vowel fragments cluster around schwa, but distribute in the directions of the acoustic targets of the adjacent context vowel.

Another possibility, which has not been properly explored in the literature, is that the svarabhakti observed in Spanish clusters are neither epenthetic nor reflexes of adjacent vowels, but an intrinsic part of the rhotic. If taps share with trills the property of having a controlled dorsum, then we would expect to see some phonetic reflexes of this dorsal articulation in the acoustic signal. Martínez Celdrán (2007) has alluded to this commonality: based on her comparisons of svarabhakti in intervocalic and coda rhotics, she has proposed that there might be a "vocalic element" common to all Spanish rhotics, which is sometimes masked by a following vowel.

Svarabhakti phenomena in Spanish rhotic clusters remain poorly understood. Studies have largely relied on acoustic data alone; the few articulatory studies which have examined rhotic production in cluster environments have generally used EPG data (e.g. Martínez Celdrán 2007) which offers limited insights into dorsal articulation. A broader phonetic study, including articulatory and acoustic data of rhotics produced in both coda and non-coda environments, will be necessary to come to a more complete understanding of the nature of svarabhakti, and the extent to which they might arise from an articulatory component intrinsic to the rhotic.

## 3.4 Summary

In this chapter, the phonological properties of the Spanish liquid consonants have been examined. Their behavior as a class has been demonstrated in their phonotactic, allophonic and other shared phonological properties. The tendency for Spanish liquids to alternate and neutralize suggests that they might share some common phonetic properties. Their unique distribution in onset clusters demonstrates that Spanish liquids are characterized by an affinity for the nucleus in the organization of the syllable.

A survey of the phonetic literature has revealed a lack of adequate articulatory data on Spanish liquids. In Chapter 4, an experiment designed to shed more light on the phonetic characterization of the class of Spanish liquids will be described. Specifically, the goals of this study are to:

i. examine the *dynamic* articulation of the three Spanish liquids

ii. compare the production of the liquids with the production of coronal obstruents, focusing in particular on the differences in dorsal articulation

iii. characterize the articulation of the tap, and how it differs from the trill and the coronal stop

iv. examine the articulation of rhotics in medial clusters in order to come to a better understanding of the origins of svarabhakti

# Chapter 4

# Experimental Investigation of Spanish Liquid Production

In this chapter, an ultrasound study of Spanish liquid consonants will be described. The aim of this study is to come to a better understanding of the goals of production of Spanish liquids using dynamic articulatory and acoustic data.

In Chapter 3 it was shown that the three liquids of Spanish consitute a phonological class by virtue of their interchangeability, their shared distributional properties in the syllable and their common participation in a variety of phonological processes. We will now consider the extent to which these common properties might be grounded in the phonetic domain.

Evidence reviewed in Chapter 2 indicates that the liquids which pattern together in English and some other languages share the property that are produced with a dorsal gesture. While this appears to be a phonetic characteristic common to dark laterals and some types of rhotic approximants, it raises the question of whether a shared dorsal gesture might be also found amongst liquids in languages with clear laterals and trilled/tapped rhotics, or whether these consonants are articulated as purely coronal segments, like stops. The hypothesis to be examined is that Spanish liquids are united by the presence of a dorsal articulatory component.

The structure of this chapter is as follows. The methodology employed in all of the experiments in this dissertation – exploiting intrinsic coarticulation to investigate the phonetic properties of consonants – will first be explained. The use of ultrasound to examine lingual articulation will be described. The phonetics of Spanish liquids in intervocalic environments will be examined, before considering coronal consonant production in other phonological environments where some liquid contrasts are lost. Finally, the production of medial coda liquids will be examined to consider the origin of svarabhakti elements in rhotic clusters.

## 4.1 Investigating the Goals of Consonant Production using Coarticulation

It has long been observed that the phonetic properties of consonants are influenced by the surrounding vowels (Menzerath & de Lacerda 1933; Liberman et al. 1954). This phenomenon of vocalic coarticulation can be exploited experimentally to provide insights into the phonetic characterization of consonants.

Although consonantal production varies between different contexts, the most fundamental phonetic properties of a consonant – those which can be considered to characterize its production – are affected less by vocalic coarticulation than the properties which are unspecified for that sound. Although the acoustic properties of consonants are *intrinsically* dependent on their vocalic context (Öhman 1966; Liberman et al. 1967), articulatorily, the vocal tract constrictions which are most salient and fundamental to the production of the consonant should exhibit less coarticulatory variance across phonological environments.

For example, the production of a dental stop primarily involves the creation of a complete constriction between the tongue tip and the region behind the upper teeth. Because the tongue dorsum is not actively recruited in this gesture, it is free to adopt a variety of postures, and it will tend to retain the articulation imposed by the previous vowel or to anticipate the dorsal gesture required of the following vowel. Coarticulatory effects of this nature have been demonstrated repeatedly in the production of stops (Farnetani 1990; Recasens 2002) and fricatives (Engwall & Badin 2000; Shadle et al. 2008), across a variety of languages. Coarticulatory effects are so pervasive during intervocalic coronal consonant production that coronals have been characterized as independent gestures superimposed on the underlying diphthong formed by the two vowels in the VCV sequence (Öhman 1966; Gafos 2002).

If, however, the tongue dorsum is involved in production of a consonant, it is not entirely free to be recruited in the production of the adjacent vowels, and we should expect to see fewer effects of vocalic coarticulation. In an MRI study of European Portuguese consonants, for example, Martins et al. (2008) found that stops were generally less resistant to coarticulatory effects than fricatives, which require control of the dorsum in order to manage the airstream necessary for frication. Similar differences have been reported amongst Swedish (Lindböm 1985) and Catalan obstruents (Recasens & Pallarès 2001).

Crucially, coarticulation is a highly asymmetrical phenomenon: although it proceeds in both directions, the influence of vowels on neighbouring consonants greatly exceeds the effect which consonants have on vowels. Zharkova & Hewlett (2009) estimated the coarticulatory influence of context vowels on the lingual articulation British English /t/, for example, to be three times greater than the influence of consonants (/t/ vs. /k/) on the low vowel /ɑ/.

Because of this asymmetry, we can exploit the intrinsically coarticulatory nature of consonant production to examine the phonetic properties of liquids. By eliciting consonants in a variety of phonological environments, and identifying regions of articulatory stability, we are able to seek patterns which characterize their production. This technique will be employed in all of the languages under consideration, by comparing the dynamics of production of liquids with obstruents.

The essential hypothesis which will be examined in these experiments is the following: if liquid consonants, like coronal obstruents, are fundamentally characterized primarily by their tongue tip gestures, we should expect to see the same degree of variation in their dorsal articulations across different environments as we observe in amongst the stops. If, however, the goal of production for a liquid consonant includes an intrinsic dorsal gesture, we would predict that this consonant should exhibit a higher degree of resistance to vocalic coarticulation than a coronal obstruent elicited in the same environment.

## 4.2 Method

A high-speed ultrasound study was conducted to compare liquid and stop consonant production by five speakers of Latin American Spanish.

### 4.2.1 Subjects

Five native speakers of Spanish – four female and one male – participated in the experiment. Speakers of different Spanish varieties were recruited so that a range of dialectal variation in the rhotics could be examined (Table 4.1). Although four subjects had lived most of their lives in the United States and classify themselves as bilingual speakers of Spanish and American English, all subjects were raised in Spanish-speaking domestic environments and associate regularly with Spanish-speaking communities. Subjects were paid for their participation, and naïve as to the purpose of the experiment.

| SUBJ | AGE | HOMETOWN | VARIETY | OTHER LANGUAGES | TIME IN US |
|---|---|---|---|---|---|
| M1 | 25 | Managua | Nicaraguan | US English, French | 15 years |
| W1 | 21 | Guaynabo | Puerto Rican | US English, Portuguese | 3.5 years |
| W2 | 20 | Quito | Ecuadoran | US English | 19 years |
| W3 | 20 | Miami, USA | Cuban | US English | 20 years |
| W4 | 19 | Santo Domingo | Dominican | US English, French | 15 years |

TABLE 4.1: **Participants in the Spanish liquids study.**

### 4.2.2 Lingual Imaging

The Haskins Optically-Corrected Ultrasound System (HOCUS) was used to image the tongue in the midsagittal plane at at framerate of 127Hz and correct the lingual images for head movement (Fig 4.1). A detailed description of the ultrasound system, its integration with the Northern Digital OptoTrak system, and the experimental protocol may be found in Whalen et al. (2005).

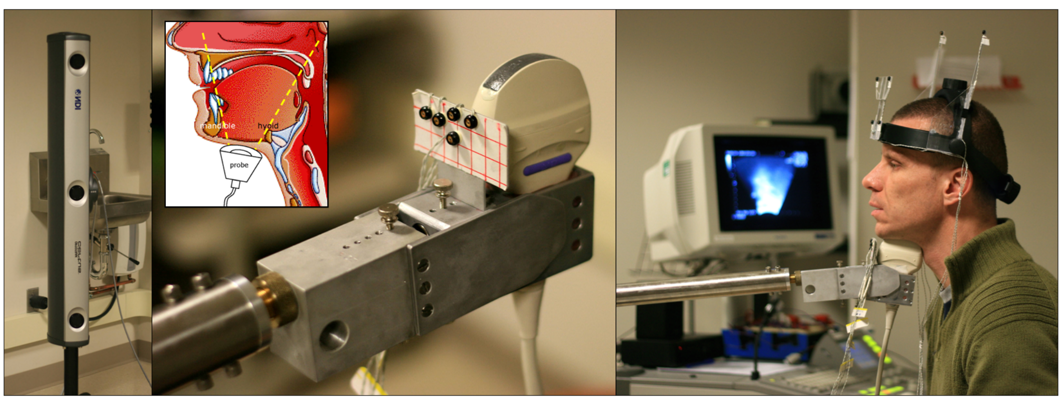



FIGURE 4.1: **Dynamic imaging of midsagittal lingual articulation using HOCUS**. Left: OptoTrak camera; Center: pivoting ultrasound probe holder; Inset: typical field of view of ultrasound probe, from alveolar ridge to tongue root. Right: Subject positioned on probe, wearing optically-tracked tiara used to correct for head movement;

For most subjects, a clear image extending from the mandible shadow to the hyoid shadow was obtained, providing a dynamic profile of the midsagittal tongue edge from the alveolar ridge to the mid oropharynx. In some cases, because of the anatomy of the subject or their positioning on the probe, only part of the tongue was clearly resolvable.

### 4.2.3 Audio Acquisition

Acoustic recordings were made using a headset-mounted Sennheiser microphone positioned 5cm from the subjects' lips, laterally offset to avoid the direct airstream. The audio signal was low-pass filtered at 10500Hz and digitized at a 22000Hz sampling rate with 16 bit quantization using a Northern Digital Equipment Optotrak Data Aquisition Unit II. The section of the audio signal corresponding to the period of ultrasound recording was identified by detecting synchronization pulses marking the beginning and ending of the recording. The superfluous parts of the audio signal were truncated, and the nine second segments of synchronized audio were saved as WAV files.

### 4.2.4 Articulatory Analysis

Image sequences were extracted from the ultrasound DICOM recordings, synchronized with the corresponding audio files, and saved as uncompressed AVI video files. The synchronized audio and video data for each token was analyzed using a graphical interface written in Matlab (Mathworks 2007), facilitating simultaneous review of acoustic and articulatory events, measurement of consonantal duration, extraction of formants, quantification of distances on different regions of the tongue, and comparison of lingual distances across experimental trials (Fig 4.2).

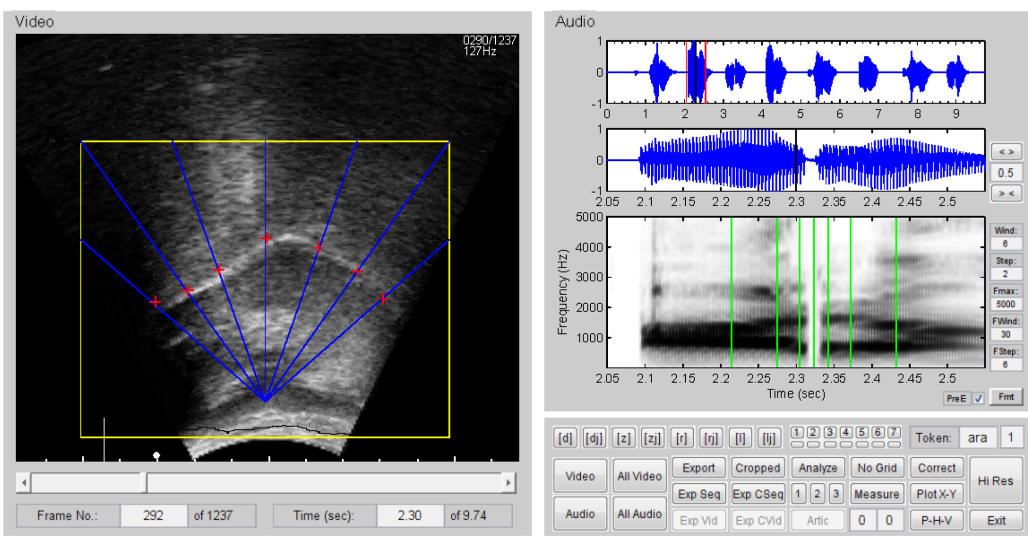



FIGURE 4.2: Matlab GUI used to review synchronized ultrasound and audio data

Speech segments were delineated for articulatory anaylsis by selecting acoustic landmarks in the audio signal and spectrogram. The corresponding sequences of ultrasound frames were identified in the video signal, cropped, and corrected for head movement. Every third frame within each interval was exported as a JPEG image file, resulting in a sequence of video frames representing tongue motion throughout the token with an effective sampling rate of 42.3 fps.

Tongue edges were automatically identified within each ultrasound frame using EdgeTrak software (Li et al. 2005) and manually corrected where necessary. Curves defining tongue edges were exported as sets of cartesian coordinates representing locations in the midsagittal plane, and all subsequent processing and analysis of lingual activity was performed in Matlab.

### 4.2.5 Acoustic Analysis

Acoustic analysis of the audio recordings was conducted in Praat (Boersma & Weenink 2007) and Matlab. Spectrograms were generated using 512-point DFFTs calculated over 10 msec (80% overlapped) Hamming-windowed time slices of audio segments pre-conditioned with a +3db treble emphasis high-pass filter. Formants F1 to F4 were automatically identified in each spectrogram using an LPC-based tracking algorithm operating over the same windowing parameters.

## 4.3 Phonetic Characterization of Intervocalic Liquids

The Spanish liquid consonants were first examined in intervocalic environments, where the rhotics are contrastive, with the goal of characterizing the fundamental phonetic properties of the three consonants. Voiced coronal stops were elicited in the same environments to provide a voiced obstruent to contrast with the liquids. The acoustic properties of each of the four intervocalic consonants are discussed in Section 4.3.3 before intervocalic articulation is examined in Section 4.3.5.

### 4.3.1 Stimuli

Intervocalic consonants were elicited using the Spanish words listed in Table B.2. Where possible, words were chosen such that in each set, stress occurred in the same position in the word with respect to the syllable containing the target consonant. Each consonant was elicited in five different vocalic contexts, although not all of these tokens were analyzed for each speaker.

The corpus was presented as five lists of five words which the subjects were asked to read in the order listed. Each list was repeated three times by each subject, and the two utterances which imaged most clearly were selected for analysis.[1]

### 4.3.2 Results: Acoustics of Intervocalic Coronal Consonants

#### Acoustic Characterization of Intervocalic Stops

Voiced intervocalic coronal stops were produced with a great amount of variation amongst the subjects in this study. Prototypical dental stops – characterized by clearly defined intervals of near-zero energy – were produced in most cases by subjects W1 and W2. The spectra of these tokens (shown in a front vowel context in Fig. 4.3) are characterized by stable formant structures in the context vowels, varying amounts of formant movement in the transitions into and out of the stop closure, and a near or complete absence of formant structure during the period of coronal closure.[2]

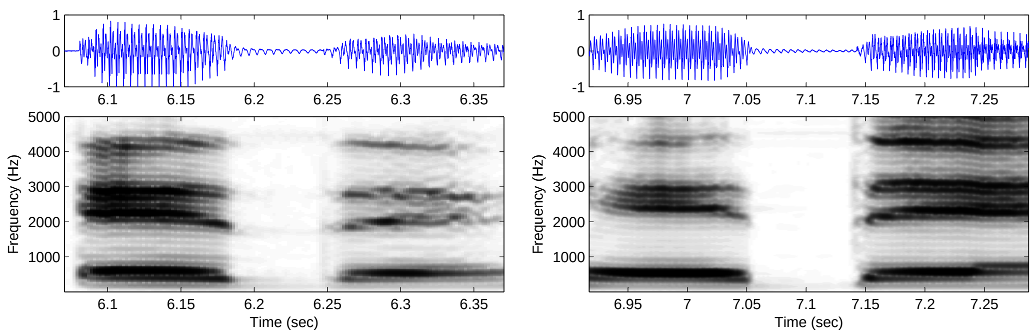



FIGURE 4.3: Acoustic waveforms and spectra of **Spanish intervocalic stop [ede]** showing distinct acoustic stop intervals. Left: subject W1; right: subject W2.

Stop duration was reasonably consistent across tokens and subjects. The mean duration of the acoustic stop interval was 74 msec ($\sigma$= 5 msec); duration of the VCV sequence measured between the acoustic centers of pre- and post-consonantal vowels was 226 msec ($\sigma$= 40 msec) (Table 4.2).

Subjects W3, W4 and M1 all typically produced intervocalic stops with a large amount of spirantization, as shown in the [eðe] tokens in Fig. 4.4. Stops produced

[1] A feature of many Spanish dialects and idiolects is that voiced intervocalic stops are spirantized. For speakers of these varieties, the pronunciation of the elicitation items targeting the coronal stop in Table B.2 would be [iˈðilio], [ˈeðe], [kaˈpaða], [ˈpoðo] and [vuˈðu]. While it is important to note this difference, the structure of the experimental corpus is not affected: each of these words still contains a phonemic obstruent which can be compared to a voiced liquid consonant produced at the same (coronal) place of articulation.

[2] Spectra were calculated over the full frequency range ($f_s/2$ = 11 kHz), but are plotted only to 5 kHz for readability.

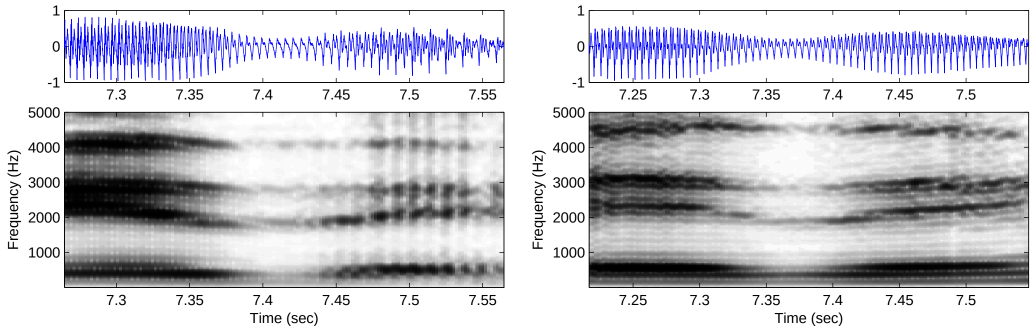



FIGURE 4.4: **Sprirantized intervocalic stop [eðe]** – subjects W3 (left) and W4 (right).

by other subjects varied in degree of spirantization, sometimes quite radically, as can be seen in the comparison of two utterances of the same token /ada/ in Fig. 4.5.

In all spirantized stop spectra, as well as in many other stops, distinct formants are clearly visible throughout the stop interval; in these sequences, formant trajectories in all vowel contexts typically show little movement. In many tokens produced by subject M1, the formant structure of the context vowels persists unperturbed throughout the entire interval of stop 'closure' (Fig. 4.6). In other cases, acoustic properties vary across repetitions of the same utterance: while the mid-consonantal resonances F2 and F3 are equivalent in the two spectra in Fig. 4.5, there is a large difference in the trajectory of the first formant, suggesting that the [aða] token was produced with a lower dorsum (F1 = 688 Hz) than in the [ada] token (F1 = 378 Hz).

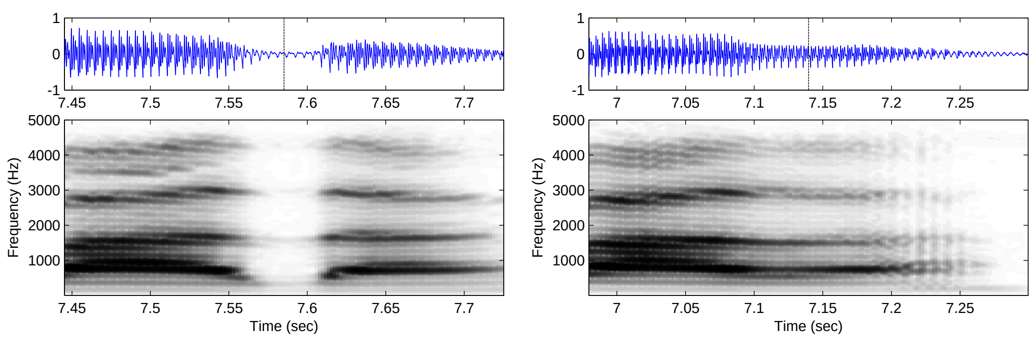



FIGURE 4.5: **Varying degrees of sprirantization in intervocalic stop production**: two utterances of token /ada/ – subject W1.

In summary, these data show that the Spanish intervocalic voiced coronal stop is produced with a wide range of dialectal and idiolectal variation in the degree of spirantization and the extent of attenuation of the acoustic signal during the stop closure. Considerable acoustic variation was also observed between different repetitions by the same subject of the same VCV sequence. The spectral data indicate that the stop is characterized by a high degree of susceptibility to vocalic coarticulation: when formant structures can be observed during the consonantal interval,

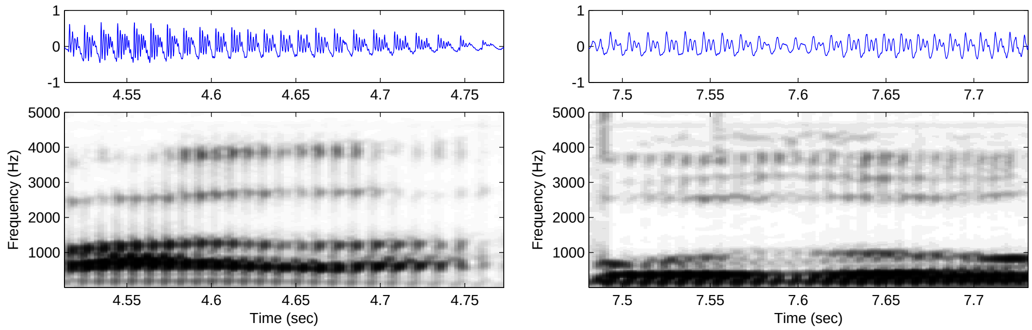



FIGURE 4.6: **Heavily sprirantized intervocalic stops** showing little or no movement in formant trajectories – subject M1. Tokens [aða] (left) and [uðu] (right).

they are strongly or completely shaped by the context vowels, and they persist largely unperturbed throughout the realization of the stop.

### Acoustic Characterization of Intervocalic Laterals

Unlike the stops, lateral tokens produced by all subjects in the study were characterized by distinct formant structures which were highly stable throughout the consonantal interval. Much less acoustic variation across repetitions and subjects was observed in the production of the lateral, compared to the stops.

Intervocalic lateral production was typically characterized by an attenuated periodic signal of constant amplitude, a sharply rising first formant in low vowel contexts, a rising F2 in back vowel contexts, and a stationary or falling F2 in front vowel contexts. Typical lateral waveforms and spectra are illustrated for two subjects in Fig. 4.7.

### Acoustic Characterization of Intervocalic Taps

The taps were the shortest of the Spanish intervocalic consonants examined in this study. The mean duration of the acoustic tap interval was just 34 msec ($\sigma$= 16 msec) – half the duration of the stops and laterals, and one third the length of the trills. Although the interval of coronal closure was much shorter than the other consonants, the total period over which the tap was articulated – as measured by the interval between the acoustic centers of the pre- and post-consonantal vowels – was not significantly shorter than the other consonants: 220 msec ($\sigma$= 49 msec), compared to the mean duration of 235 msec ($\sigma$= 48 msec) for all intervocalic consonants elicted in the study. The ratio of consonantal to intervocalic duration for the tap was 16%, compared to 33% for the stops, and a mean duration ratio of 29% for all consonants

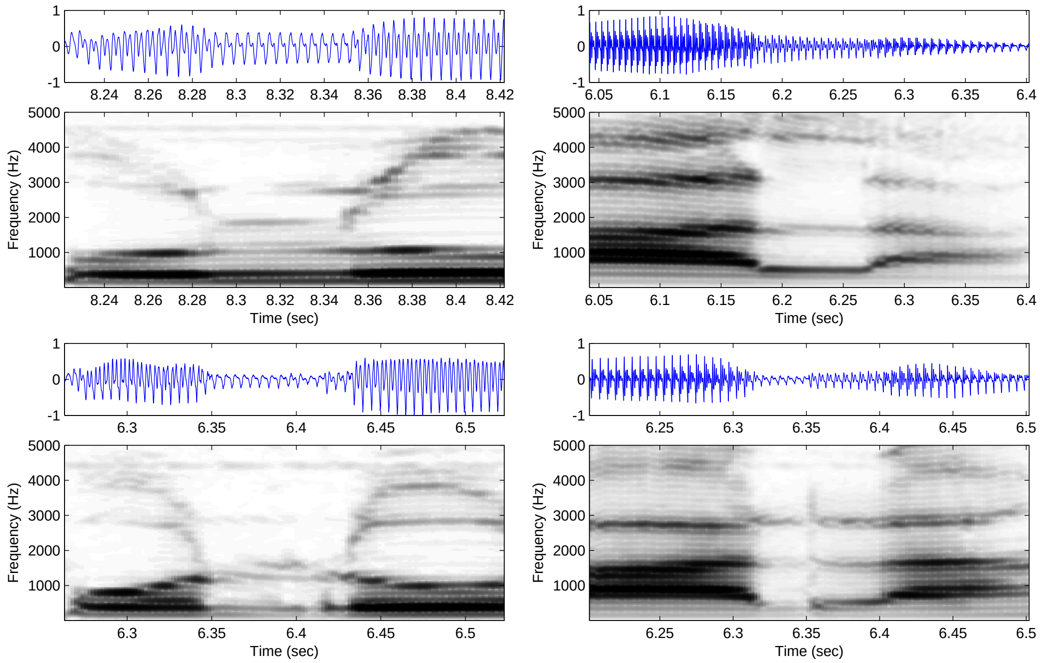



FIGURE 4.7: Acoustic waveforms and spectra of **Spanish intervocalic laterals**: left column: [ulu]; right column: [ala]. Top row: subject W3; bottom row: subject W4. Second formant trajectories in all utterances convergent on range 1450 Hz < F2 < 1900 Hz.

(Table 4.2).

| | /d/ | /ɾ/ | /r/ | /l/ | MEAN |
|---|---|---|---|---|---|
| mean $t_{VCV}$ | 0.226 | 0.220 | 0.258 | 0.235 | 0.235 |
| standard deviation | 0.050 | 0.049 | 0.047 | 0.046 | 0.048 |
| mean $t_C$ | 0.074 | 0.034 | 0.090 | 0.080 | 0.069 |
| standard deviation | 0.017 | 0.016 | 0.022 | 0.024 | 0.020 |
| $t_C$ / $t_{VCV}$ | 32.7% | 15.5% | 34.9% | 34.0% | 29.4% |

TABLE 4.2: **Mean durations of Spanish intervocalic consonants**. All values in seconds, averaged over all utterances in Table C.6. First row: mean difference between acoustic centers of pre- and post-consonantal vowels. Second row: standard deviations of VCV durations. Third row: mean duration of consonantal acoustic interval. Fourth row: standard deviations of consonantal interval durations. Fifth row: ratio of consonantal to intervocalic durations.

This result is of interest because it indicates that the production of the tap extends over a much greater interval of time than the period of signal attenuation corresponding to the coronal closure. The difference in duration ratios also suggests that the proportion of time spent articulating parts of the tongue other than the tip and blade are greater for taps than for stops.

This effect can be observed in the spectra of intervocalic taps, where changes in formant structure often begin much earlier in relation to the closure interval than in the stops produced in the same vowel contexts. Considering the spectra of the /uɾu/ tokens in Fig. 4.8, for example, second formant transitions in particular can be seen to commence earlier in the pre-consonantal vowel, and continue longer into the post-consonantal vowel than in the /udu/ tokens, where F2 transitions into the closure interval are more abrupt. The other major difference between the stops and taps which can be observed in Fig. 4.8 is that the higher formants (most noticably F4) are largely unaffected by the stop closure, but lower abruptly during the tap closure.

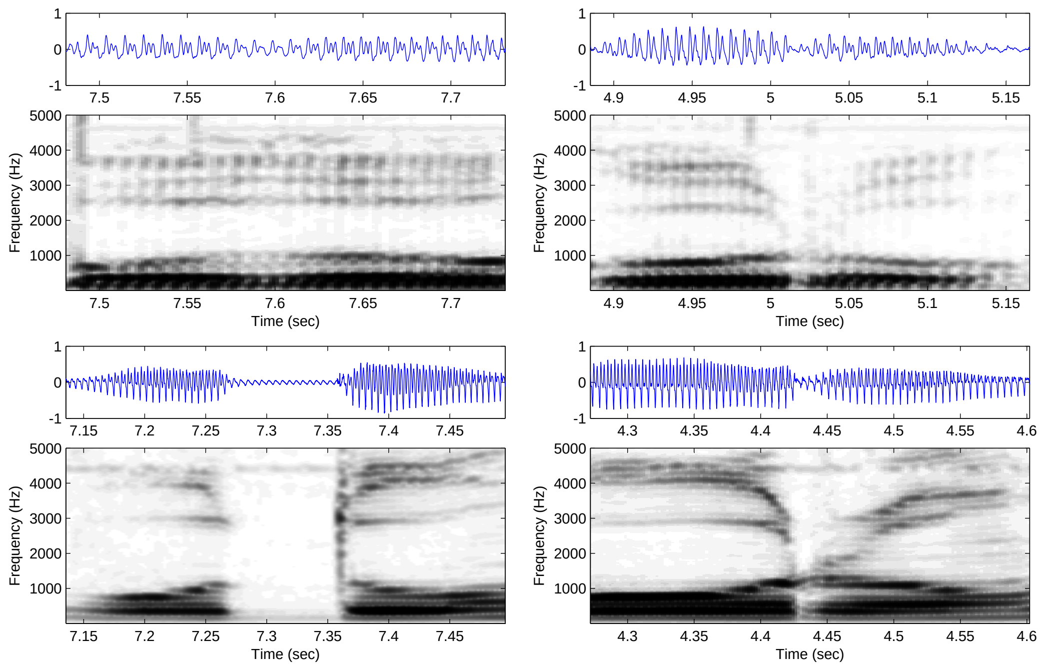



FIGURE 4.8: Comparison of **Spanish intervocalic coronal stops and taps**. Left column: [udu]; right column: [uɾu]. Top row: subject M1; Bottom row: subject W4.

### Acoustic Characterization of Intervocalic Trills

Of the four consonants being examined in this experiment, the Spanish trills exhibit the most phonetic variation. The most obvious difference between trills was the number of closures, which ranged from one to four.[3] Subjects W1, W4 consistantly produced more closures per trill (at least two; typically three) than subject W2,

[3] The term 'tap' is often used to denote the apical closure gesture in a trill, but will not be used for this purpose here to avoid confusion with references to the second Spanish rhotic. The term 'contact' must also be qualified: coronal approximation in a trill does not always result in a com-

who typically produced only one closure per trill. The median number of closure intervals across all trills elicited in the study was two. Trills produced by the same subject in different vowel contexts sometimes showed differences in the number of contacts (Fig. 4.9).

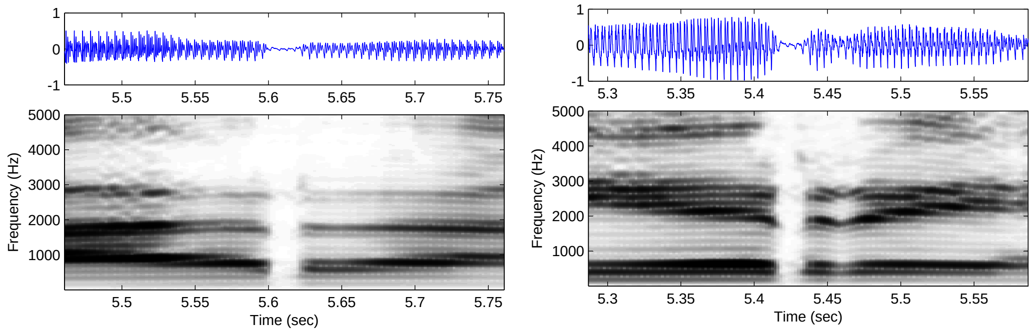



FIGURE 4.9: Spanish intervocalic trill production: **variation in number of closure intervals** – subject W2. Left: single closure ([ara]); right: double closure ([ere]).

Another type of variation observed amongst the trills in this study was the degree of spirantization. While subject W1 produced all of her intervocalic trills without any noticeable frication, most other subjects spirantized some of their intervocalic trills to some degree; all trills produced in this environment by subject W4 were heavily spirantized. Spectra of spirantized intervocalic trills typically reveal a concentratation of frication energy in a band lying between 3 and 4 kHz, which is often associated with, or impinges on F3 (Fig. 4.10).

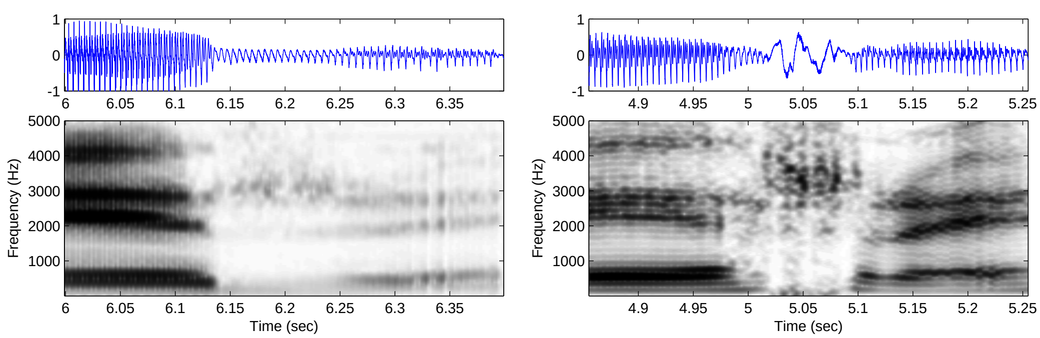



FIGURE 4.10: **Spirantization in Spanish trills** in a mid-front intervocalic context: [ere]. Left: subject W3; right: W4.

plete closure of the oral tract, nor in a clearly-defined interval of silence in the acoustic signal. For this reason, the number of coronal approximations in each trill is estimated by the number of attenuated intervals between periods of greater resonance in the speech signal.

### Acoustic Characterization of Spanish Rhotics

An acoustic property which has been associated with many types of rhotics in many languages is a lowered third formant. It has been proposed that a lowered F3 might represent the unifying characteristic of rhotics in general (Ladefoged 1975, Lindau 1978), or the unifying property amongst allophones in languages with a high degree of rhotic variation, such as English (Nieto-Castanon et al. 2005).

Although a falling F3 was observed in many of the taps and trills produced by the Spanish speakers in this study, this was not a universal property of all the rhotics elicited. In none of the taps and trills whose spectra are shown in Fig. 4.11, for example, does F3 lower significantly during rhotic production.

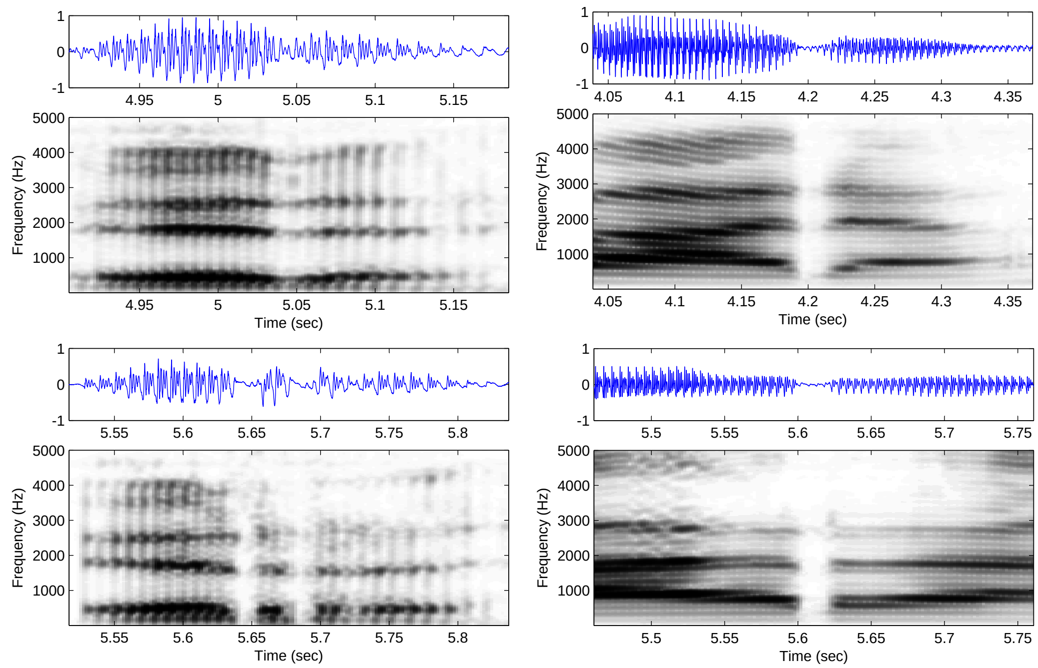



FIGURE 4.11: **Non-lowered third formants** in Spanish intervocalic rhotics. Top left: [ere] (subject M1); top right: [ara] (W1). Bottom left: [ere] (M1); bottom right: [ara] (W2).

While no phonetic description as simple as 'a lowered F3' can account for all of the Spanish intervocalic rhotics elicited in this study, for both trills and taps, the trajectories of the lower three formants can be shown to be functions of vowel context, for any given speaker. Furthermore, some of the same patterns which characterize the formant dynamics of the rhotics are also observed during lateral production. These patterns will be described in Section 4.3.3, before the relationship between the acoustics and articulation of Spanish liquids is examined further in Section 4.3.5.

### 4.3.3 Formant Analysis of Intervocalic Liquids

#### Method

For each intervocalic liquid under analysis, the interval of speech corresponding to the VCV sequence was identified, and the frequencies of the first four formants were extracted automatically from the spectrogram at five points in time: (i) the acoustic center of the pre-consonantal vowel, (ii) the beginning of the consonantal interval, (iii) the acoustic center of the consonant, (iv) the end of consonantal interval, and (v) the acoustic center of the post-consonantal vowel (Fig. 4.12).

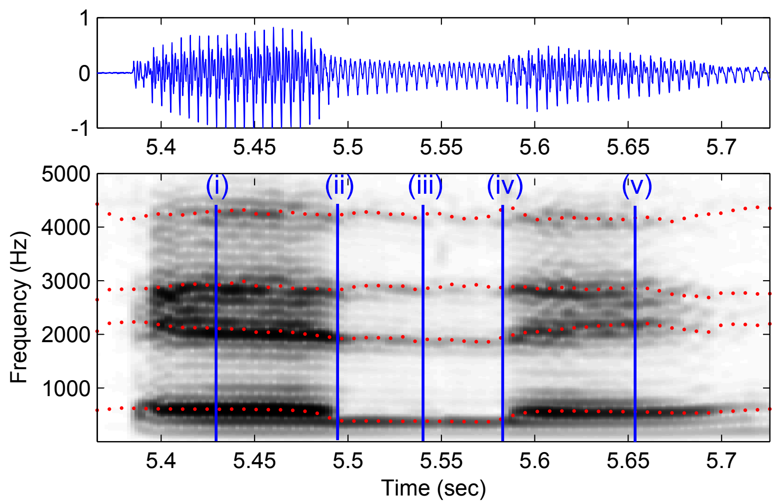



FIGURE 4.12: **Acoustic landmarks used for analysis of intervocalic consonants**: (i) pre-consonantal vowel; (ii) beginning of consonantal interval; (iii) center of consonant; (iv) end of consonantal interval; (v) center of post-consonantal vowel. (Sequence illustrated: [ele], subject W1).

In each eCe, aCa and uCu token, formant values were extracted at each acoustic landmark. Two repetitions of each token by each speaker were analyzed, and formant values averaged across both tokens. Mean F1-F2 trajectories for each of the liquids were calculated to provide an estimate of the acoustic transitions from pre-consonantal vowel into the consonant, and the transitions from the consonant into the post-consonantal vowel. Formant values for speaker W1 (Table C.1) are plotted in Fig. 4.13.

The trajectories in Fig. 4.13 reveal the vowel-liquid-vowel sequences to be acoustically dynamic entities with distinct targets. The beginning and ending points corresponding to the pre-consonantal and post-consonantal vowels are closely located in regions corresponding to the acoustic targets of the context vowels. The distribution of the three intermediate points – corresponding to the vowel-consonant transition, the mid-point of the liquid and the consonant-vowel transition respectively

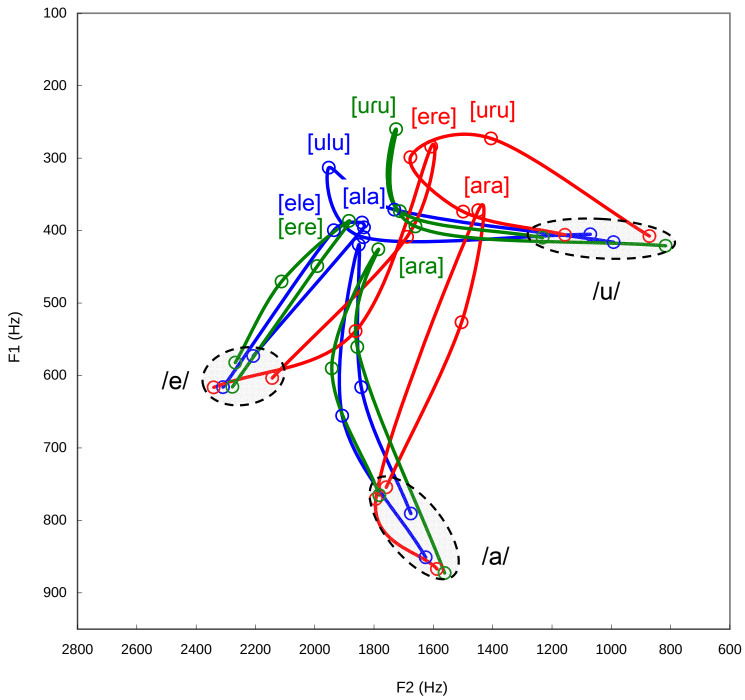



FIGURE 4.13: **Formant trajectories of Spanish intervocalic liquids – subject W1**. Horizontal axis: first formant frequency (Hz); Vertical axis: second formant frequency (Hz). Circled: landmarks on acoustic trajectories of each intervocalic liquid VLV, calculated at points indicated in Fig. 4.12.

– varies according to the liquid. In the case of the laterals, these points are generally located close together, reflecting the stability of the intervocalic formant structures. The formant trajectories suggest that the rhotics are more dynamic consonants: the transitional formant values are located further from the mid-consonantal acoustic target than in the laterals. Asymmetries can be observed between the rhotic formation and release trajectories: F1 is lower during the formation of the trill by subject W1 in the high-back vowel context [uru], for example, than it is during release.

A clearer understanding of the acoustic targets of the liquids can be gained by considering only those formant values corresponding to the acoustic center of each consonant (Fig. 4.12: landmark (iii)). In Fig. 4.14, an elipse has been drawn around the formant values at the center of the acoustic trajectory of each liquid produced by speaker W1.

Figure 4.14 shows that although individual acoustic targets are pulled towards the values of the context vowels, each of the three liquids converges onto a relatively small region in F1-F2 space. For subject W1, the three liquids are collectively characterized by having a lower F1 target than any of these three context vowels. The individual liquids are differentiated by their mean second formant frequencies: the

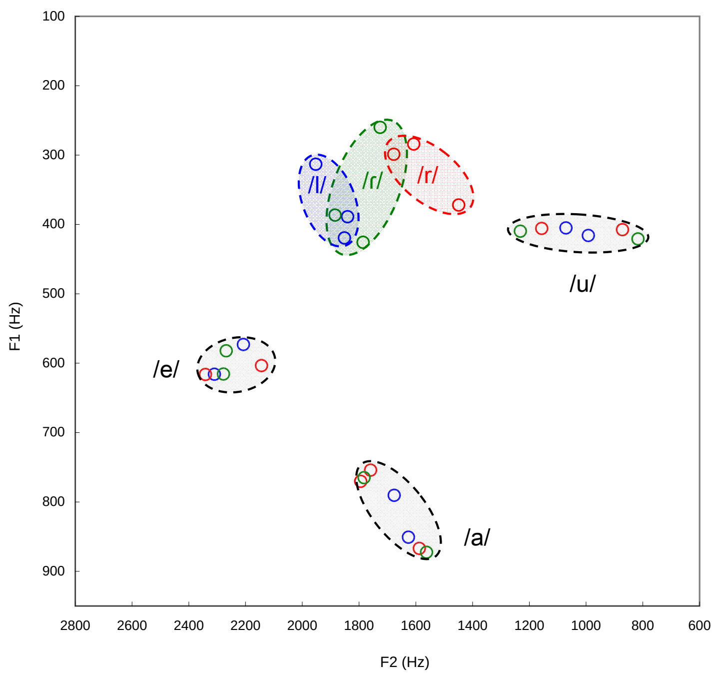



FIGURE 4.14: **Acoustic targets of Spanish intervocalic liquids: subject W1**. Horizontal axis: first formant frequency (Hz); Veritical axis: second formant frequency (Hz). Ellipses enclose acoustic center frequencies of liquids produced in all vowel contexts.

lateral characterized by a higher mean F2 than the rhotics.

A number of differences can be observed in the acoustic trajectories of the Spanish liquids produced by the other four subjects in this study, shown in Figs. 4.15 and 4.16 (formant values are listed in Tables C.1 to C.5), yet in each case the trajectories of individual liquids produced in different vowel contexts can be seen to be convergent on an acoustic target located forward of the high back vowel /u/ and above the low vowel /a/. Acoustic target regions in F1-F2 space for liquids produced by subjects W2 to M1 have been indicated with ellipses in Figures 4.17 and 4.18.

The data reveal that acoustic targets of the liquids vary considerably amongst individual speakers. The elliptical regions bounding the target formant frequencies of the three intervocalic liquids produced by speaker W3, for example, are all concentric, suggesting similar acoustic targets for all three liquids. Furthermore, for this speaker, the relative sizes of the ellipses suggest differences in the degree of coarticulatory susceptance: the acoustic target of the lateral appearing to be less influenced by vocalic context than the rhotics. Another notable difference amongst these subjects is the location of the acoustic target of the trill in F1-F2 space: for speaker W2, for example, the trill is produced with higher mean first formant fre-

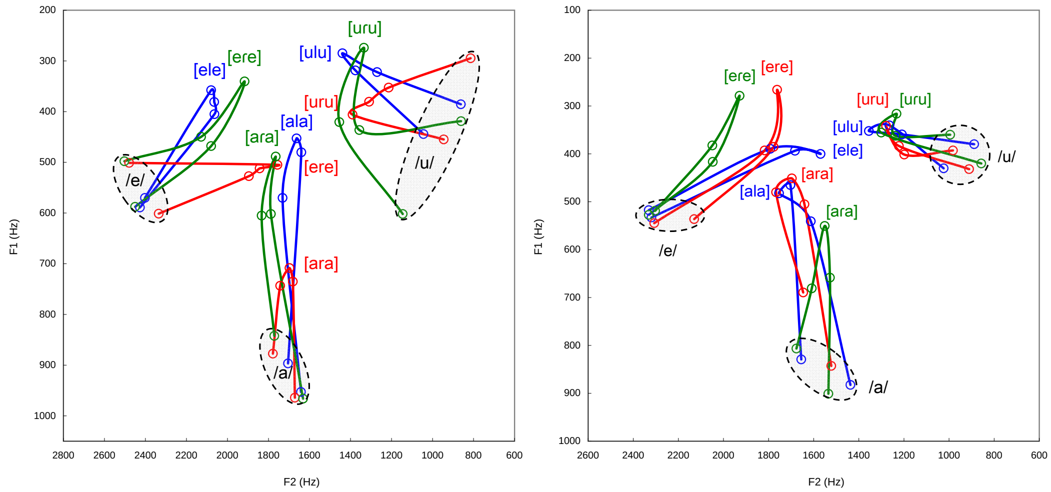



FIGURE 4.15: **Formant trajectories of Spanish intervocalic liquids**: subjects W2 (left); W3 (right).

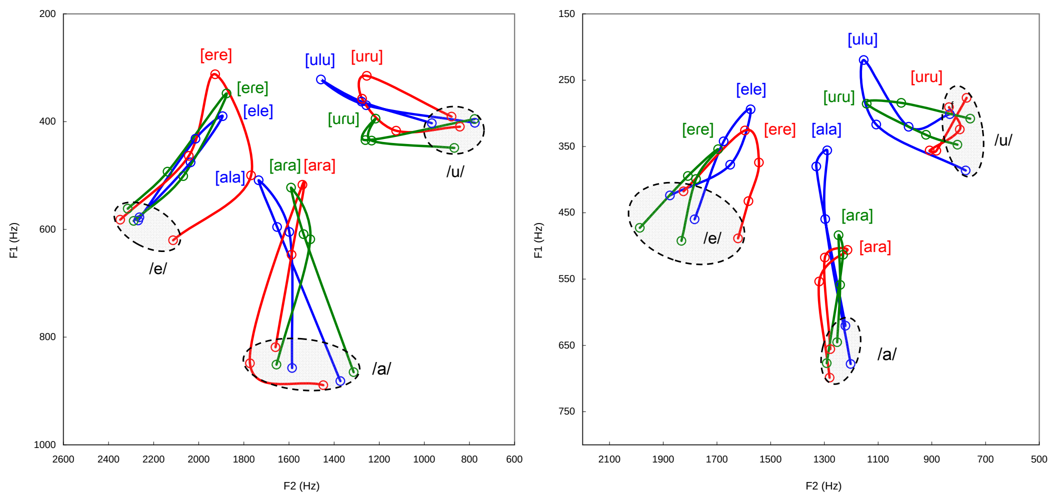



FIGURE 4.16: **Formant trajectories of Spanish intervocalic liquids**: subjects W4 (left); M1 (right).

quencies across all vowel contexts than for the other subjects.

### 4.3.4 Summary: Acoustic Properties of Spanish Intervocalic Liquids

In this section, the acoustics of the three Spanish liquids have been examined in intervocalic environments, where they have been compared to the voiced coronal stop. Considerable variation amongst speakers and repetitions was observed for all consonants, most noticeably in the degree of spirantization. The stop was found to be the consonant which displayed the most variability between utterances; the lateral was the most acoustically stable. The trill was found to be the consonant which exhibited the most variability in realization between different speakers: numbers

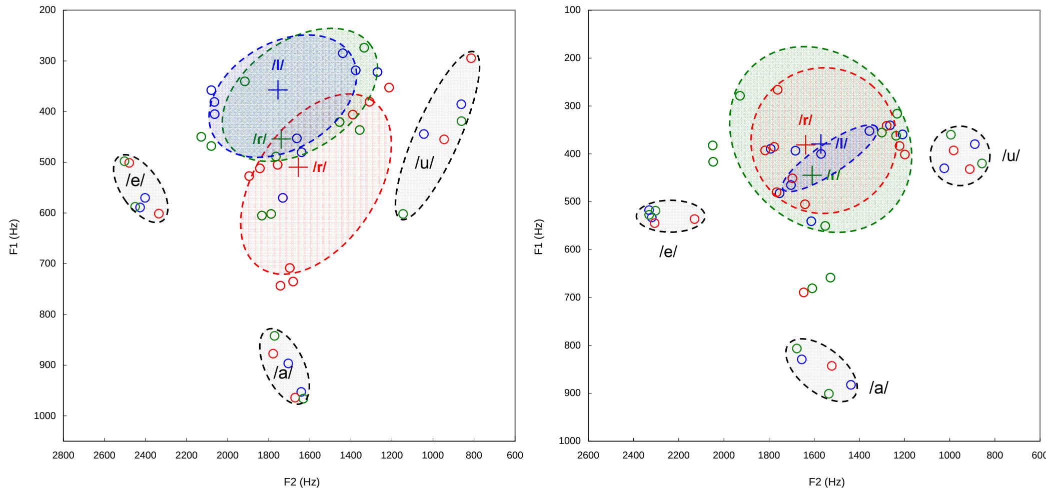



FIGURE 4.17: **Acoustic targets of Spanish intervocalic liquids**: subjects W2 (left) and W3 (right).

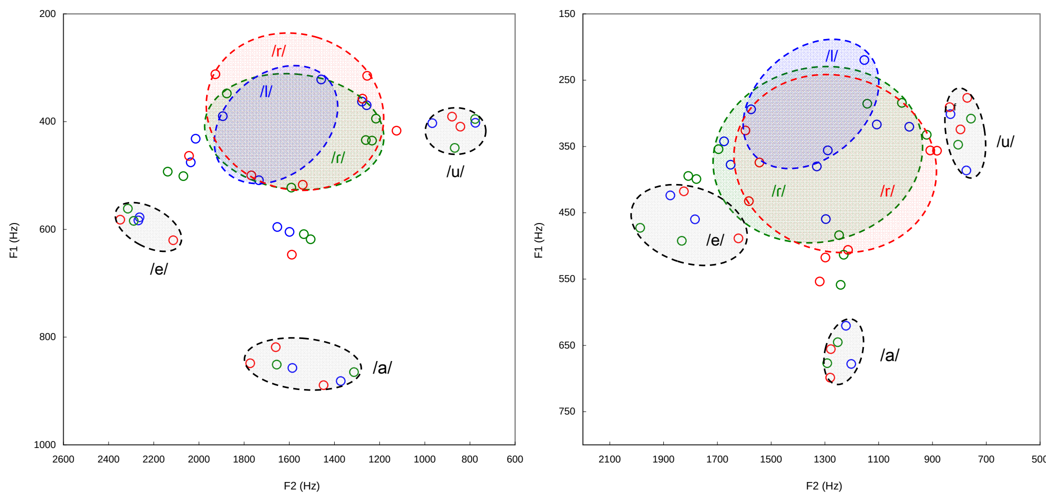



FIGURE 4.18: **Acoustic targets of Spanish intervocalic liquids**: subjects W4 (left) and M1 (right).

of contacts and degree of spirantization were the main sources of variability.

Differences in the abruptness of formant transitions into the consonantal closure intervals suggest that the stops are more susceptible to vocalic coarticulation than the liquids. Analysis of the trajectories of the lower two formants suggests that each of the liquids has an acoustic target in F1-F2 space. It has long been observed that the frequencies of the lower two formants are strongly and inversely correlated with height and horizontal displacement of the tongue body (Fant 1960, Bondarko 1977, etc.), a relationship which has been exploited to examine dorsal articulation using the acoustic signal alone (e.g. Recasens & Pallarès 1997, Padgett 2001, Fant 2004, Carter & Local 2007; Iskarous & Kavitskaya submitted).

The results of the formant analysis conducted here suggest that the tongue dorsum plays an active role in Spanish liquid articulation, that the dorsal target of the lateral resembles that of the rhotics, and that although different subjects employ different dorsal gestures in the production of liquids, these gestures resemble those of central vowels. At the same time, the data illustrates the limitations of a purely acoustic analysis of consonant production: although we can identify broad trends in articulation by their influence on formant trajectories, we are not able to make strong claims about the details of liquid production from acoustic data alone. To better assess the goals of the dorsal articulation in Spanish liquid production, we next examine the articulatory data which was acquired from these speakers at the same time as the acoustic recordings were made.

### 4.3.5 Results: Dynamic Analysis of Midsagittal Lingual Articulation

#### Articulation of Spanish Coronal Consonants in a Low Vowel Context

**Articulation of Stops.** The change in lingual articulation during the production of the token [ada] by subject W1 is illustrated in Fig. 4.19. The first half of the sequence – four frames beginning at the midpoint of the pre-consonantal vowel (blue curve) and ending at the midpoint of consonantal closure (red curve) – is illustrated in the left panel (-71 to 0 ms). The second half of the sequence – six frames commencing at the point of stop release (red curve) and ending at the midpoint of articulation of the post-consonantal vowel (blue curve) – is shown in the figure on the right (0 to 118 ms).[4]

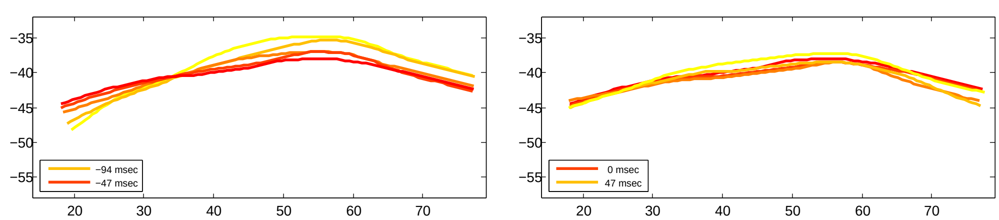



FIGURE 4.19: Dynamic midsagittal lingual **articulation of Spanish intervocalic coronal stop [ada]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

The plots in Fig. 4.19 show that there is little movement during the production of the stop, other than some raising of the tongue blade to achive the coronal closure.

4 In all figures showing midsagittal articulatory data, the left of the figure corresponds to the front of the vocal tract (towards the alveolar ridge), and the right of the figure corresponds to the back of the vocal tract (back of the tongue and upper pharynx). All values indicate displacement in millimeters from an arbitrary origin defined for each experimental session. Position coordinates are therefore comparable across all tokens produced by the same subject, but cannot be compared across subjects.

Throughout the entire VCV sequence, the tongue dorsum remains lowered and retracted, in a position corresponding to the pharyngeal articulation of the context vowel.

**Articulation of Liquids.** In contrast to the stops, the production of Spanish liquids was revealed to involve dorsal activity which is often counter to – and therefore independent of – vocalic coarticulation.

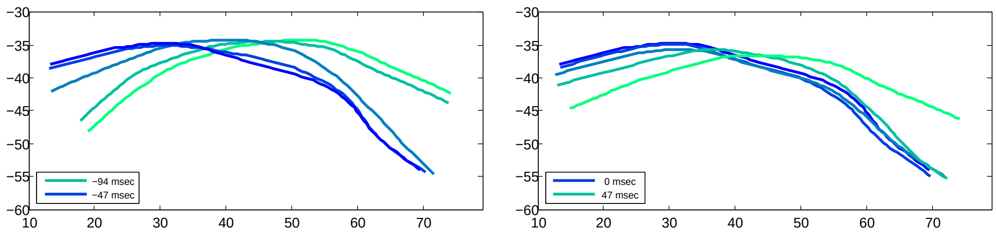



FIGURE 4.20: Midsagittal lingual **articulation of Spanish intervocalic lateral [ala]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

The articulation of the token [ala] by subject W1 is shown in Fig. 4.20. At the same time that the tongue blade is raised to form the coronal constriction, the tongue body is advanced, moving it away from the target constriction location of the pharyngeal vowel. During the consonantal release, the tongue body remains in an advanced position until rapidly returning to the starting position 118 msec after the midpoint of consonantal production.

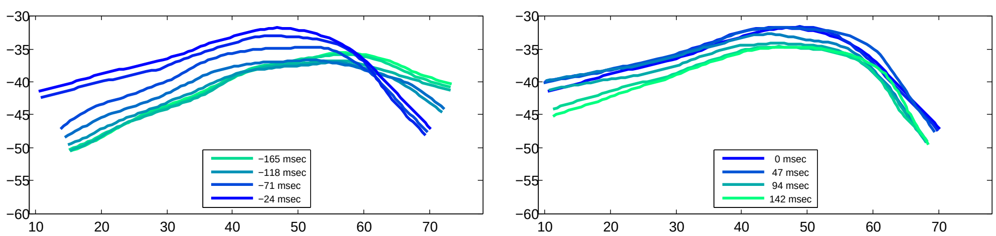



FIGURE 4.21: Midsagittal lingual **articulation of Spanish intervocalic trill [arra]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

A similar pattern can be observed during the production of the Spanish intervocalic trill (Fig. 4.21) which, like the lateral, involves articulation of a dorsal gesture with a different target to the context vowel. For subject W1, trill formation involves advancement and raising of the tongue body from the pharyngeal starting position. Lingual articulation of the trill is also asymmetrical: the consonantal release does not involve any recovery of the back of the tongue towards the position from which it started; rather, the back of the tongue dorsum continues to advance away from the vocalic constriction target throughout the second half of the production of the token [ɑɾɑ].

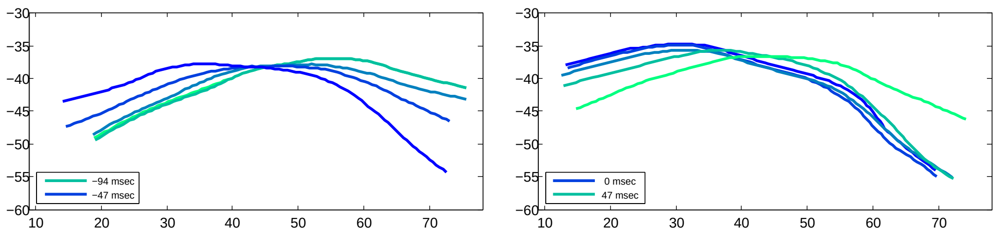



FIGURE 4.22: Midsagittal lingual **articulation of Spanish intervocalic tap [ɑɾɑ]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

Lingual activity during the production of the other Spanish rhotic – an intervocalic tap – is shown in Fig. 4.22. As with the trill and the lateral, but unlike the coronal stop, articulation of the tap can be seen to involve dorsal advancement which accompanies the coronal closure, and which continues after the midpoint of production of the consonant.

**Comparison of Stop and Liquid Articulation** The same broad patterns of tongue movement during the production of coronal consonants in a low vowel context – described above for subject W1 – were observed for the other four subjects in the study. Dorsal activity during the articulation of stops was generally consistent with the coarticulatory requirements of the pharyngeal vowel; the production of all three liquids, on the other hand, was characterized by dorsal advancement which was counter to the coarticulatory requirements of the context vowel and therefore must be attributed to the consonant. Side by side comparison of the articulation by subject M1 of a stop and a trill illustrates this difference most clearly (Fig. 4.23).

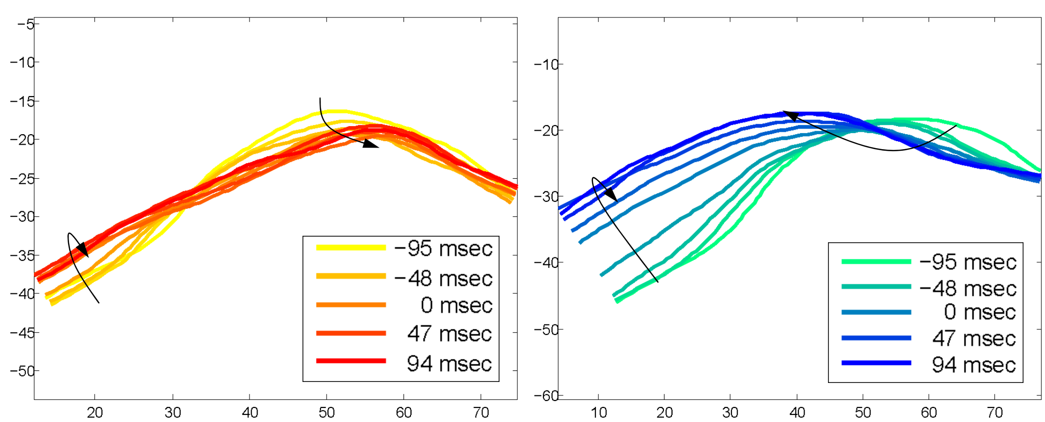



FIGURE 4.23: **Comparison of articulation of Spanish stop and trill** in low intervocalic context – subject M1. Left panel: token [ɑdɑ]; Right panel: token [ɑrɑ].

The similarity of the dynamic activity of the tongue during the production of the three liquids can clearly be seen in a side by side comparison of a lateral, tap and trill produced by subject M1 in a low vowel context (Fig. 4.24).

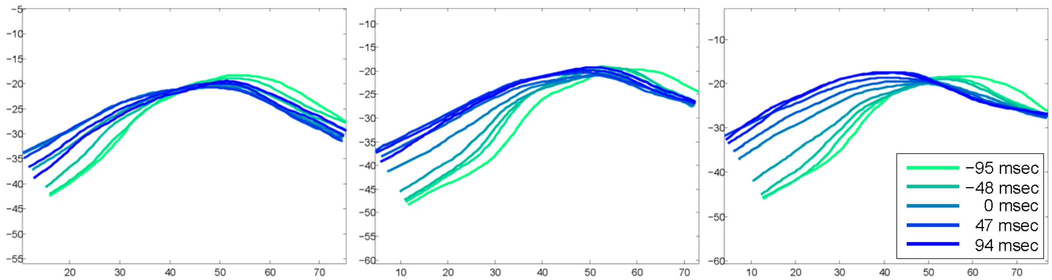



FIGURE 4.24: **Comparison of articulation of the three Spanish liquids** in a low intervocalic context – subject M1. Left: [ala]; Center: [aɾa]; Right: [ara].

### Articulation of Spanish Coronal Consonants in a Front Vowel Context

We can gain more insights into the articulatory goals of production of stops and liquids in Spanish by analyzing their production in vowel contexts other than [a_a] and comparing the patterns of dorsal activity. Although the high front vowel context [i_i] would provide the greatest contrast with the pharyngeal vowel, the consonants elicited between palatal vowels were sometimes imaged poorly by the ultrasound, making it difficult to segment the tongue reliably in all tokens across all subjects. For this reason, the mid-front vowel context [e_e] was used for this part of the experimental analysis.

**Articulation of Stops.** The articulation of the token [ede] by subjects W1 and M1 is illustrated in Fig. 4.25. Throughout the production of both stops, the back of the tongue remains more advanced than was observed in the [a_a] contexts for these subjects. The dorsum begins and ends in a posture corresponding to the front vocalic target constriction, but lowers mid-production as the tongue elongates to achieve coronal closure. Similar patterns of tongue movement were observed for the other three subjects not shown here.

Articulation of the Spanish liquids by subject W1 in a mid-front context is shown in Fig. 4.26; the production of the same tokens by subject M1 is shown in Fig. 4.27. Unlike the stops, no tongue body lowering can be observed during the production of any of the liquids. The lateral and the tap are both characterized by a remarkable amount of stability of the back of the tongue and the entire dorsum during their production in the [e_e] context. Alone amongst the consonants in this vowel context, the articulation of the trill involves dorsal retraction and raising – activity

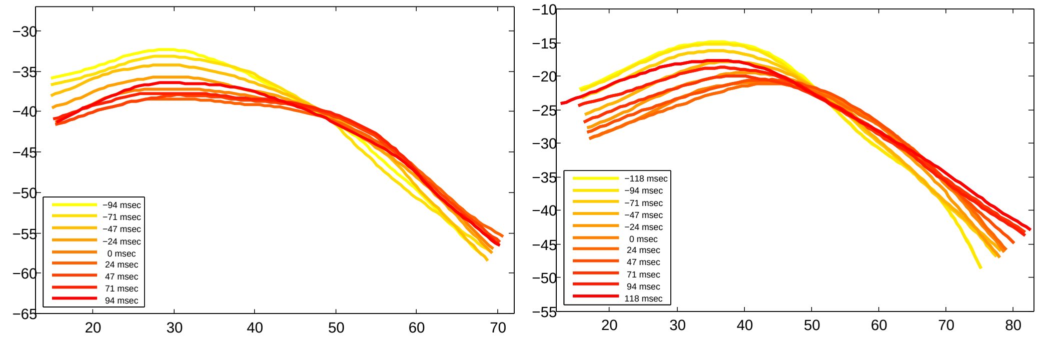



FIGURE 4.25: Dynamic midsagittal lingual **articulation of Spanish coronal stops in a front intervocalic context**. Left panel: [ede] (subject W1); Right panel: [ede] (subject M1).

which differs from that observed during stop production because the movement is away from the vocalic constriction target (mid-front). The dorsal movement is also counter to that which would be expected if the tongue body was *uncontrolled* during the trill production (lowering as a result of coronal extension, as observed in the stops).

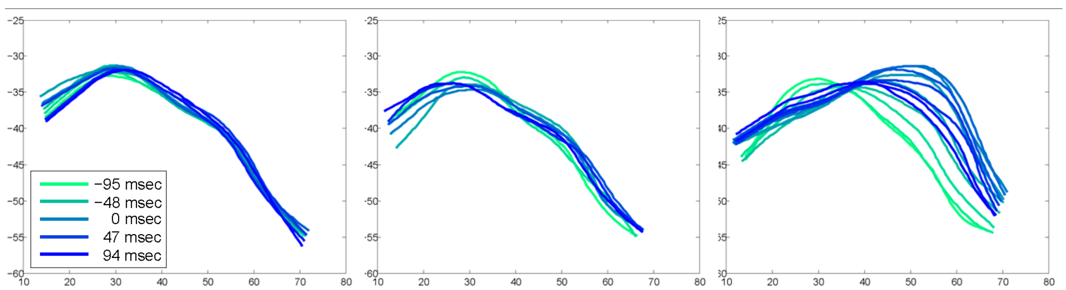



FIGURE 4.26: Midsagittal lingual **articulation of Spanish liquids in a front intervocalic context** – subject W1. Left: [ele]; Center: [ere]; Right: [ere].

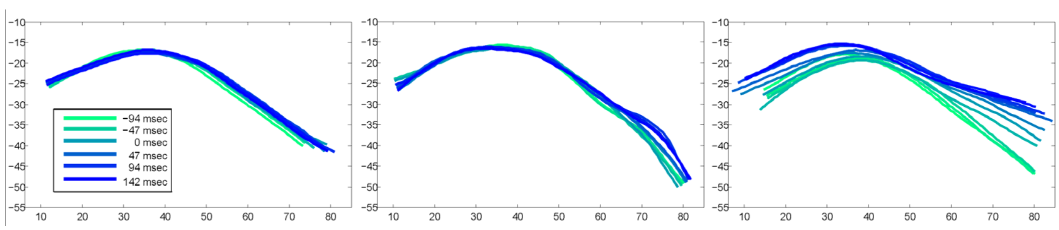



FIGURE 4.27: Midsagittal lingual **articulation of Spanish liquids in a front intervocalic context** – subject M1. Left: [ele]; Center: [ere]; Right: [ere].

### 4.3.6 Comparison of Mid-consonantal Dorsal Articulation

The dynamic analysis of the ultrasound data presented in Section 4.3.5 provides important insights into qualitative differences between stops and liquids; however, it is difficult to identify and locate specific consonantal gestures using this approach, because consonant production is so strongly influenced by vowel context. In order to better examine the goals of articulation of different types of consonant, tongue shapes of consonants produced in different vocalic contexts were compared directly.

For each VCV token, the midsagittal lingual profile was captured at three points in time (Fig. 4.28):

i. the end of the pre-consonantal vowel (the last frame at which the vowel formants were stable before the transition into the consonant)
ii. the midpoint of the consonant (the middle frame in the intervocalic acoustic interval)
iii. the beginning of the post-consonantal vowel (the first frame after the vowel formants had stablized after the transition out of the consonant)

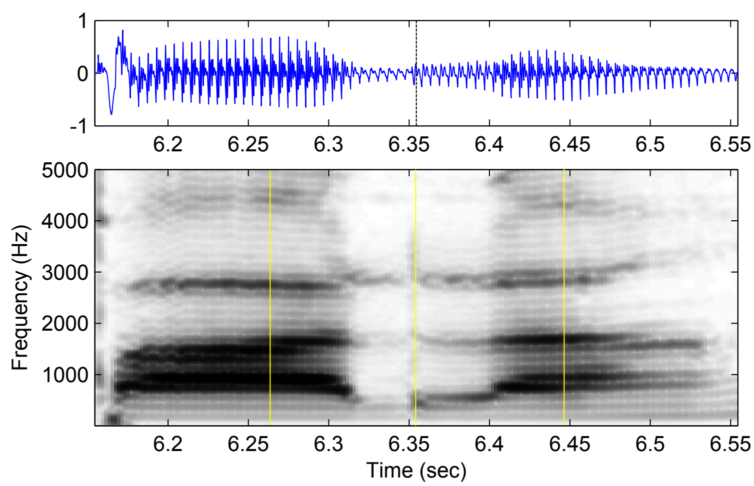



FIGURE 4.28: **Analysis landmarks for Spanish intervocalic consonants**: (i) pre-consonantal vowel; (ii) mid consonant; (iii) post-consonantal vowel. (Token illustrated: [para], subject W1).

Tongue edges were extracted at each of these points in time from three different tokens – one for each vowel context: [e_e], [a_a] and [u_u] – and superimposed on the same plot. The midsagittal lingual articulation by subject W1 of the coronal stop and the three liquids are shown in Fig. 4.29.

### Quantification of Vowel-Consonant Coarticulation

For each frame of analysis, the location of the tongue dorsum was estimated by finding the apex (maximum vertical displacement) of the curve defining the tongue

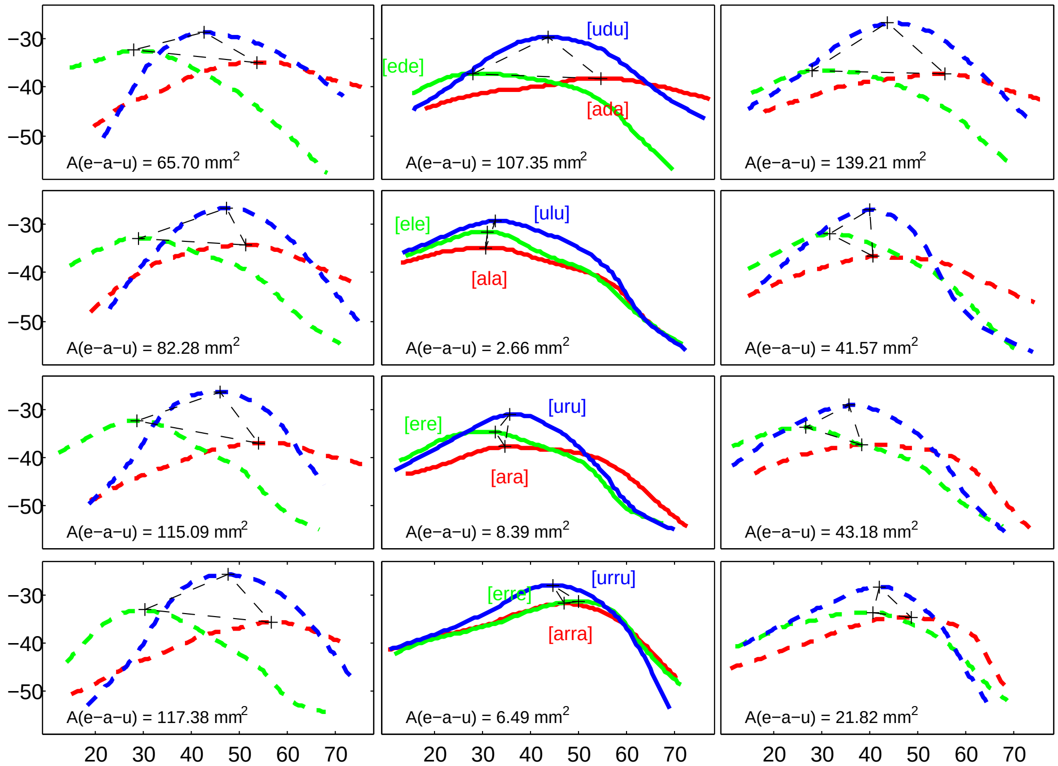



FIGURE 4.29: **Midsagittal lingual articulation of Spanish coronal consonants in three intervocalic contexts** – subject W1. Top row: stop; 2nd row: lateral; 3rd row: tap; 4th row: trill; Left column: pre-consonantal vowel; Center column: mid consonant; Right column: post-consonantal vowel.

edge. Three such points were identified for each frame, corresponding to dorsal locations in the [e_e] context, [a_a] context and [u_u] context. A triangle was constructed between the three points, and the area of the triangle was calculated (Eq. 4.1) as a means of quantifying gross dorsal positional differences between vocalic contexts for each consonant, at each point of time.

$$A_{e-a-u} = \frac{1}{2} \mid x_e.y_u - x_e.y_a + x_a.y_e - x_a.y_u + x_u.y_a - x_u.y_e \mid \qquad (4.1)$$

For example, in Fig. 4.29, the small area of the central triangle in the bottom row ($A_{VrrV}$ = 6.49 mm$^2$) demonstrates that the trill is produced with a more consistently controlled dorsum which is less susceptible to coarticulatory effects. In contrast, the much larger area of the middle triangle in the top row ($A_{VdV}$ = 107.35 mm$^2$) indicates that the coronal stop is produced with a greater variety of dorsal postures, depending on the context vowel.

Differential dorsal displacements of the Spanish coronal stop and liquids, calculated using this method for all five subjects, are given in Fig. 4.30.

| f1 | V | C | V |
|---|---|---|---|
| d | 65.7 | 107.3 | 139.2 |
| l | 82.3 | 2.7 | 41.6 |
| r | 115.1 | 8.4 | 43.2 |
| rr | 117.4 | 6.5 | 21.8 |
| Stop | 65.7 | 107.3 | 139.2 |
| Liquid | 104.9 | 5.8 | 35.5 |

| f2 | V | C | V |
|---|---|---|---|
| d | 52.0 | 52.5 | 66.3 |
| l | 48.3 | 35.2 | 70.7 |
| r | 59.7 | 22.6 | 39.0 |
| rr | 27.8 | 6.7 | 19.2 |
| Stop | 52.0 | 52.5 | 66.3 |
| Liquid | 45.3 | 21.5 | 43.0 |

| f3 | V | C | V |
|---|---|---|---|
| d | 79.1 | 96.9 | 76.2 |
| l | 78.7 | 25.0 | 79.5 |
| r | 82.7 | 37.1 | 56.9 |
| rr | 45.9 | 2.7 | 29.2 |
| Stop | 79.1 | 96.9 | 76.2 |
| Liquid | 69.1 | 21.6 | 55.2 |

| f4 | V | C | V |
|---|---|---|---|
| d | 108.1 | 51.1 | 53.7 |
| l | 108.8 | 33.0 | 64.3 |
| r | 80.7 | 40.9 | 68.5 |
| rr | 94.6 | 2.9 | 35.0 |
| Stop | 108.1 | 51.1 | 53.7 |
| Liquid | 94.7 | 25.6 | 55.9 |

| m1 | V | C | V |
|---|---|---|---|
| d | 76.2 | 55.4 | 91.6 |
| l | 94.7 | 40.1 | 36.9 |
| r | 99.1 | 70.8 | 81.8 |
| rr | 119.3 | 76.3 | 31.3 |
| Stop | 76.2 | 55.4 | 91.6 |
| Liquid | 104.4 | 62.4 | 50.0 |

FIGURE 4.30: **Consonantal susceptance to vocalic coarticulation**, as measured by total dorsal displacement ($mm^2$) across three vowel contexts [e_e]-[a_a]-[u_u] – all subjects.

In order to be able to compare susceptance to vocalic coarticulation across subjects, the data in Fig. 4.30 were normalized by dividing by the maximum dorsal displacement for each subject; mean dorsal displacements were then calculated for each consonant across the experimental population, and are plotted in Fig. 4.31.

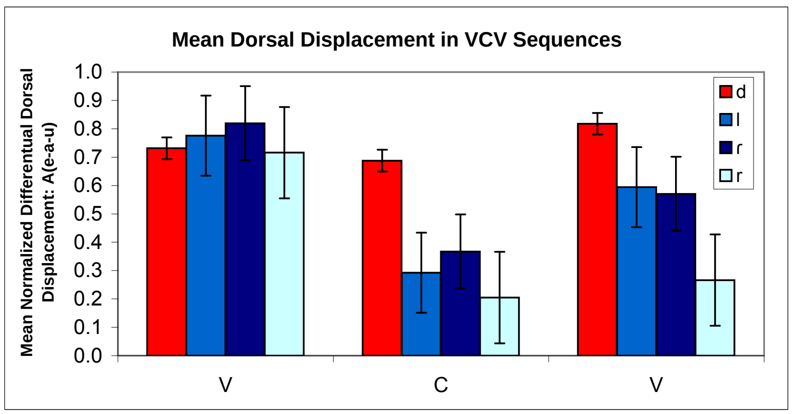



FIGURE 4.31: **Mean normalized differential dorsal displacement** for Spanish coronal consonants – all subjects.

Two main effects can be observed in the data represented in Fig. 4.31:

i. the effect of vocalic coarticulation (as measured by differential dorsal displacement in the consonant) is greater during the production of stops than liquids

ii. the effect of consonantal coarticulation on the post-consonantal vowel (as measured by differential dorsal displacement) is greater for liquids than stops

To examine these observations more closely, two tests were conducted:

i. a *one-way analysis of variance test* of the null hypothesis that dorsal coarticulatory effects (as measured by the differential dorsal displacement data) are the same for Spanish coronal stops and liquids

ii. a *two-sided Wilcoxon rank sum test* of the null hypothesis that the differential dorsal displacement data for stops and liquids are independent samples from identical continuous distributions with equal medians, against the alternative that they do not have equal medians

The results of these tests are shown in Table 7.2. Both tests reject the null hypothesis (at a 0.01 significance level) that coarticulatory differences in dorsal articulation do not differ for stops and liquids during mid- and post-consonant production (second and third columns). Importantly, the same tests also *accept* the null hypothesis that coarticulation does not differ between stops and liquids during the production of the pre-consonantal vowel (first column) – a result which would not be expected if the syllabification of the experimental tokens was other than V.CV, or if there was extensive anticipatory coarticulation of the consonants in either class.

| TEST | V1-STOP = V1-LIQ | C-STOP = C-LIQ | V2-STOP = V2-LIQ |
|---|---|---|---|
| ANOVA | 0 (p=0.5929) | 1 (p = 0.0022) | 1 (p = 0.0073) |
| Rank Sum | 0 (p=0.3827) | 1 (p = 0.0068) | 1 (p = 0.0291) |

TABLE 4.3: **Hypothesis testing of Spanish differential dorsal displacement by class** – Stops vs. Liquids. 1st column: dorsal displacement amongst pre-consonantal vowels; 2nd column: mid-consonantal dorsal displacement; 3rd column: dorsal displacement amongst post-consonantal vowels.

The most important conclusions to be drawn from this analysis are that there is a categorical difference in the susceptance to vocalic coarticulation between the Spanish coronal stop and the liquids, and that this difference persists into the post-consonantal vowel.

### Location of Liquid Dorsal Gestures

We can attempt to quantify the relative locations of the gestural targets for Spanish liquids by calculating dorsal displacement from a nominal point chosen in the center of the lingual articulatory space (approximately corresponding to schwa). F Fig. 4.32. Tongue edges were extracted at the same three points in time, and dorsal triangles constructed in the same way as for the consonantal comparisons in Figure 4.29. For each triangle connecting lingual apicies, a center of gravity was calculated. Because these centers of gravity are calculated from lingual profiles perturbed in antagonistic directions by the effects of vocalic coarticulation (eCe-aCa-uCu), they can be used to provide an estimate of the mean dorsal target for each of the liquids. For subject W1, for example, the dorsal target of the lateral (x = 31.4, y = -31.8 mm) is located approximately 15.8 mm anterior to (15.7 mm forward of, and 1.3 mm below) that of the trill (47.1, -30.4).

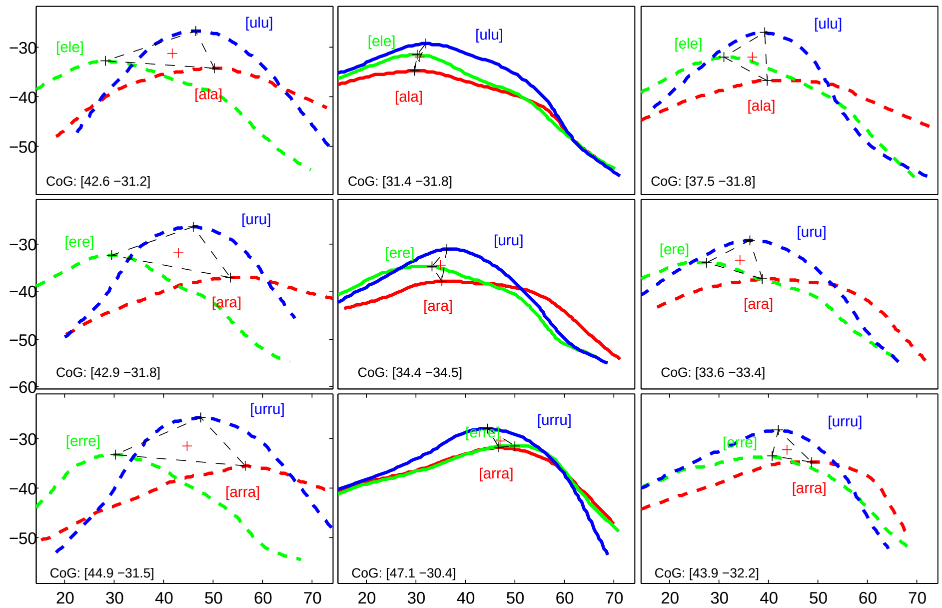



FIGURE 4.32: **Location of Spanish liquid dorsal gestures**, estimated using centers of gravity of dorsal apexes across three vowel contexts [e_e]-[a_a]-[u_u] – subject W1.

Because the reference system is uniquely calibrated for each experimental session, the cartesian coordinates of these centers of gravity are not directly comparable between subjects; as a result, a system of relative displacements is required to compare gestural targets. Assuming that the lingual profiles of the pre-consonantal vowels are relatively consistant across trials, we can also calculate their centers of gravity, (which will roughly correspond to the location of a schwa gesture), and then calculate the displacements to the centers of gravity calculated at the center of production of each liquid. Mean lingual displacements from pre-consonantal vowels for each liquid and each subject are given in Table 4.4.

| | **dx** | | | **dy** | | |
|---|---|---|---|---|---|---|
| | /l/ | /ɾ/ | /r/ | /l/ | /ɾ/ | /r/ |
| W1 | 11.11 | 8.49 | -2.29 | 0.60 | 2.63 | -1.11 |
| W2 | 7.38 | 2.61 | 1.31 | 0.70 | 1.46 | -0.24 |
| W3 | 4.72 | 0.01 | -1.08 | -0.16 | 0.74 | 1.79 |
| W4 | 2.91 | -1.24 | -3.78 | 1.24 | 0.55 | -0.41 |
| M1 | 3.27 | 2.14 | 0.48 | 2.47 | 1.44 | 0.52 |
| Mean | 5.88 | 2.40 | -1.07 | 0.97 | 1.37 | 0.11 |

TABLE 4.4: **Mean displacements (mm) of dorsal targets from pre-consonantal vocalic center**: Spanish intervocalic liquids – all subjects.

Displacements for each subject, and mean displacements of intervocalic liquid dorsal targets from the vocalic center are plotted in Fig. 4.33. The data confirm the observations made in Section 4.3.5 that the dorsal target of the Spanish lateral is anterior to that of the trill, and that the tap patterns most closely with the lateral.

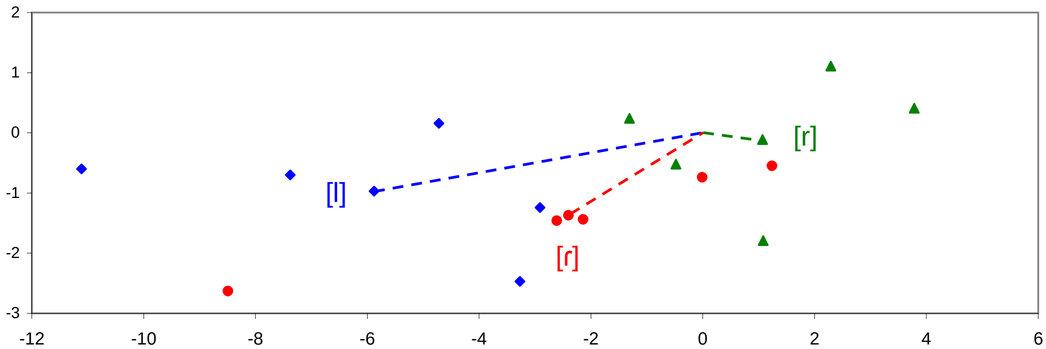



FIGURE 4.33: **Mean locations of Spanish liquid dorsal targets with respect to 'schwa'.** Blue: intervocalic laterals; Red: intervocalic taps; Green: intervocalic trills. Dashed lines indicate mean dorsal displacement from pre-consonantal vocalic center.

### 4.3.7 Summary of Results – Spanish Intervocalic Consonants

Analysis of the Spanish consonants [d], [l], [ɾ] and [r] produced in intervocalic position by the five speakers in this study has revealed the following:

i. the trill, lateral and rhotic are all produced with significantly less variation in dorsal articulation than the stop
ii. the trill, lateral and rhotic all have a significantly greater coarticulatory effect on the post-consonantal vowel than the stop
iii. the dorsal target of the lateral is anterior to that of the trill, and resembles that of the mid-front vowel /e/
iv. the dorsal target of the trill is posterior to and typically above that of the lateral, and resembles that of the mid-back vowel /o/
v. the dorsal target of the tap lies between that of the lateral and the tap, and is typically located in the region of the mid-central vowel /ə/

The conclusion to be drawn from this data is that the Spanish liquid consonants share the phonetic characteristic that their production involves a dorsal gesture – a characteristic which differentiates them from the coronal stops, whose production appears to involve the articulation of a coronal gesture only.

## 4.4 Phonetic Characterization of Spanish Coda Liquids

Having examined the articulation of Spanish liquids in intervocalic environments, where they are maximally contrastive, consonant production was next examined in coda positions to gain more insights into the phonetic nature of liquid neutralization and svarabhakti vowels.

### 4.4.1 Stimuli

Each consonant was elicited in word-medial coda position (V_.CV, where C is a labial consonant) using the corpus in Table B.3, and in word-final coda position (V_#) using the corpus in Table B.4. Stimuli were presented in five lists of words which the subjects were asked to read in the order listed. Each list was repeated three times by each subject; the two repetitions which imaged most clearly were analysed for each token.

### 4.4.2 Results: Acoustic Characterization of Word-Final Rhotics

A considerable amount of acoustic variation was observed amongst the rhotics produced in word-final position by the speakers in this study. Rhotic length, quality, number of coronal closures, and degree of spirantization varied between subjects, vocalic context and utterance.

#### Classification of Word-Final Rhotics

The most important observation to be made about the phonetic properties of rhotics produced in word-final position is that they cannot be universally classified as taps. Subject W3 (Cuban) produced all of her word-final rhotics with a single-contact, characteristic of the tap-like rhotics which she produced in all phonological environments (mean 1.05 contacts/rhotic). In contrast, word-final rhotics uttered by speaker M1 (Nicuraguan) were long trills (Fig. 4.34), produced with up to three, and an average of 1.9 contacts per rhotic. The trilling observed in M1's word-final rhotics was also consistent with the high number of contacts found in his rhotics in other environments (mean 2.10 contacts/rhotic).

The prototypical word-final rhotic produced by the other three subjects (W1, W2, W4) was a single contact tap, however each of these speakers also produced word-final trills in some utterances – most typically after low and back vowels. The mean number of contacts observed in word-final coda rhotics across all speakers in the study was 1.32, compared with a mean of 1.69 contacts observed in rhotics in all positions (Table C.8).

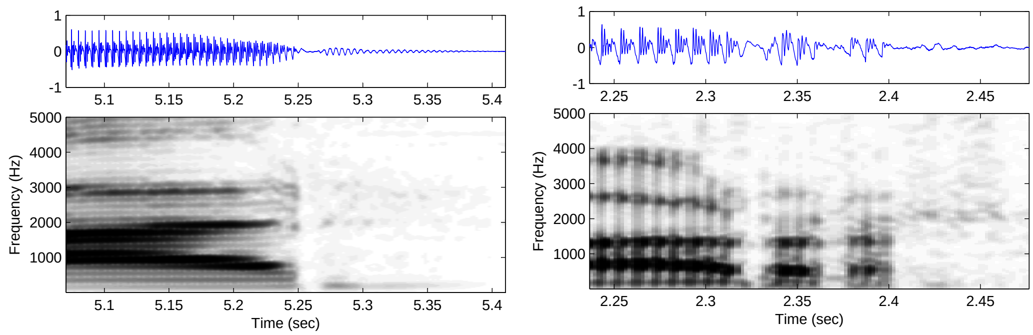



FIGURE 4.34: **Variation in Spanish word-final rhotics – number of coronal closures**: Left: [ar], subject W2; right: [ar], subject M1.

Mean numbers of coronal closures observed in word-final rhotics are compared with rhotics in other environments in Figure 4.35. The data show that although it is not the case that all coda rhotics are taps, the mean numbers of contacts produced in coda environments are smaller than in onsets, and that overall, the mean number of contacts produced in word-final codas is smaller than in medial codas, except for speakers M1 and W4, who trill their word-final rhotics more than in medial coda environments.

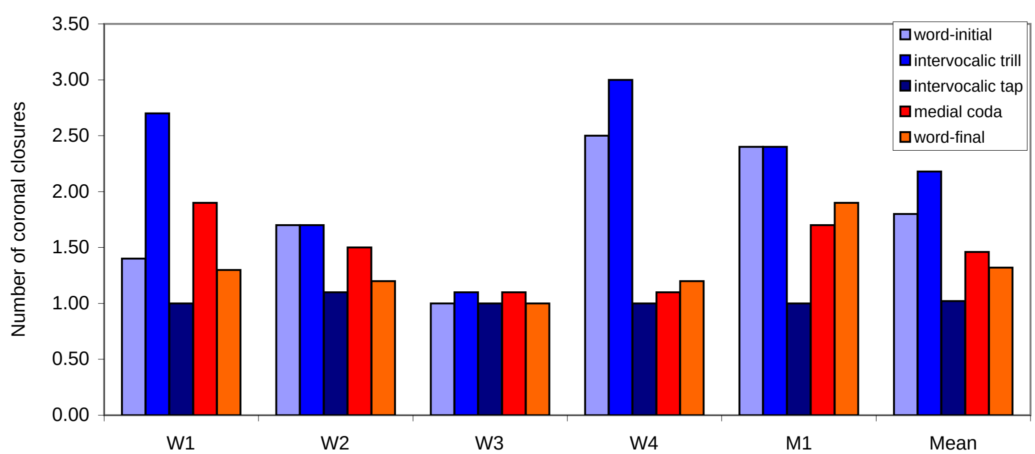



FIGURE 4.35: **Number of Coronal Closures in Spanish rhotics**. Mean numbers of contacts per rhotic for each phonological environment, estimated from numbers of attenuated intervals in acoustic signal.

### Acoustic Quality of Word-Final Rhotics

Rhotics produced in word-final position were found to be especially prone to lenition and spirantization. In general, the amplitude and delineation of resonant intervals between coronal closures were not as pronounced as those in intervocalic trills. Spirantization was especially noticable in the word-final rhotics produced by speakers W3 and W4 (Fig. 4.36).

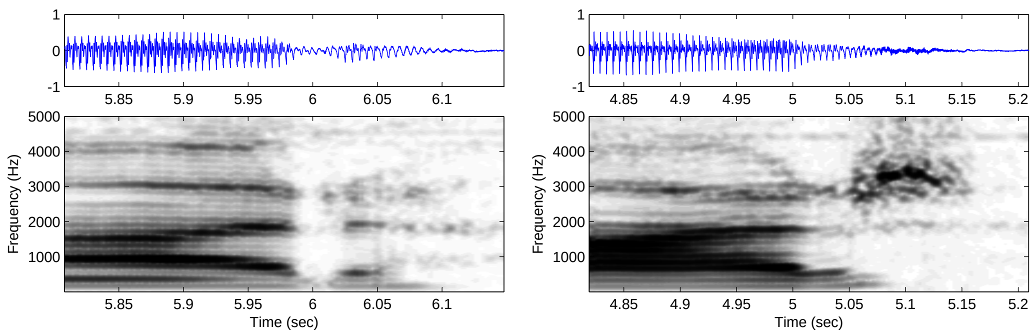



FIGURE 4.36: **Spirantization of Spanish word-final rhotics**: [ar]. Left: subject W3; Right: W4.

### Articulation of Word-Final Rhotics

Ultrasound analysis reveals that, despite their acoustic variability, rhotics are realized in word-final position using the same patterns of articulation that characterize their production in intervocalic environments. Word-final taps, trills, fricatives, and approximants were all observed to involve a dorsal articulatory component which typically preceded tongue-tip movement.

To illustrate this articulatory consistency, two word-final rhotics produced in the same vocalic enviroment by a speaker of Cuban Spanish are compared below: a prototypical tap in Fig. 4.37, and a heavily spirantized rhotic with no distinct coronal closure in Fig. 4.38. The figures show that both rhotics are produced with exactly the same patterns of articulation: the tongue dorsum first raises and advances to a mid vocalic constriction location, before the tongue blade approximates to the alveolar ridge.

The data in Figs. 4.37–4.38 suggests that the acoustic differences between the two rhotics might result from differences in aerodynamic factors, tongue stiffness, intergestural timing or degree of constriction of the coronal gestures. All of these factors which will influence the aerodynamic enviroment of the vocal tract, creating conditions under which the initiation of trilling or frication will be more or less likely. It is noteworthy that the tapped rhotic was stressed, while the spirantized rhotic occurred in the coda to an unstressed syllable – a prosodic environment in which we

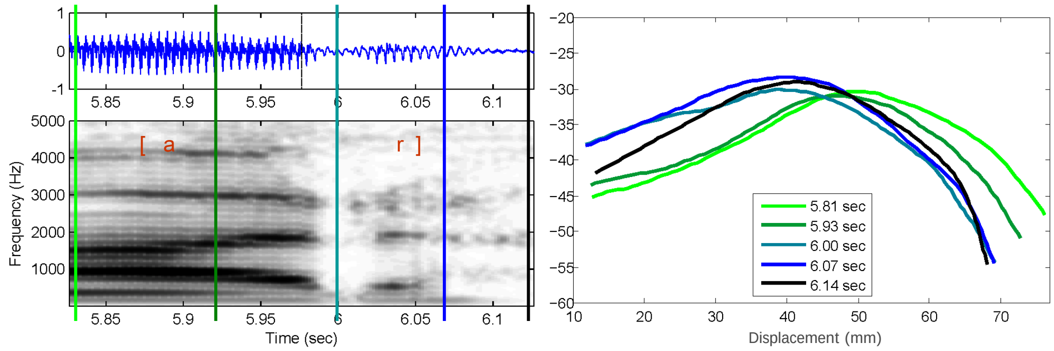



FIGURE 4.37: **Dorsal articulation in tapped word-final rhotic**: [aɾ], subject W3. Left: waveform and spectrum; Right: midsagittal articulation at five points in time.

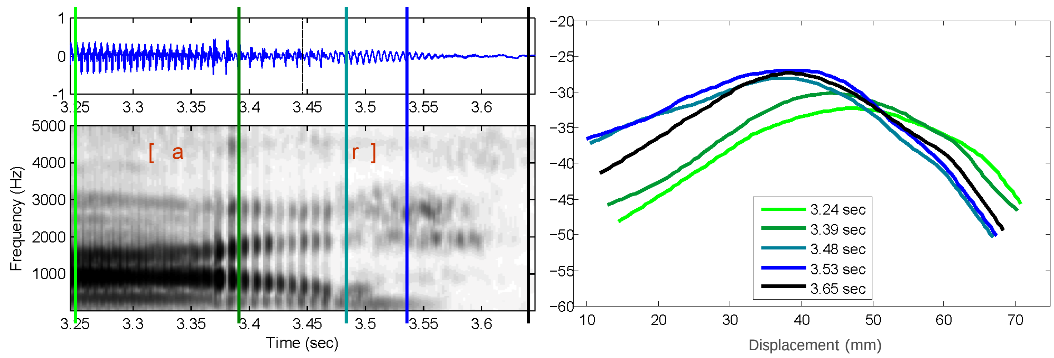



FIGURE 4.38: **Dorsal articulation in spirantized word-final rhotic**: [aɾ], subject W3. Left: waveform and spectrum; Right: midsagittal articulation at five points in time.

might expect lenition to be more prevalent; however, the extent to which prosodic factors influence the articulation of coda rhotics has yet to be investigated.

### 4.4.3 Svarabhakti in Coda Rhotics

Svarabhakti fragments were ubiquitous in the medial rhotic coda clusters elicted in this experiment. Waveforms and spectra of typical coda liquids produced before labial nasals by two speakers of Carribean Spanish varieties are compared in Fig. 4.43. In each case, a svarabhakti fragment is evident between the rhotic closure and the following nasal.

If, as Bradley (2004) argues, svarabhakti result from underlying vowels (Section 3.3.2), then they should possess the same acoustic and articulatory qualities as the preceding nucleic vowel. However, the spectra in Fig. 4.43 show that the svarabhakti fragments have their own formant structure, which suggests that the resonant fragments are either epenthetic, or an intrinsic component of the rhotic.

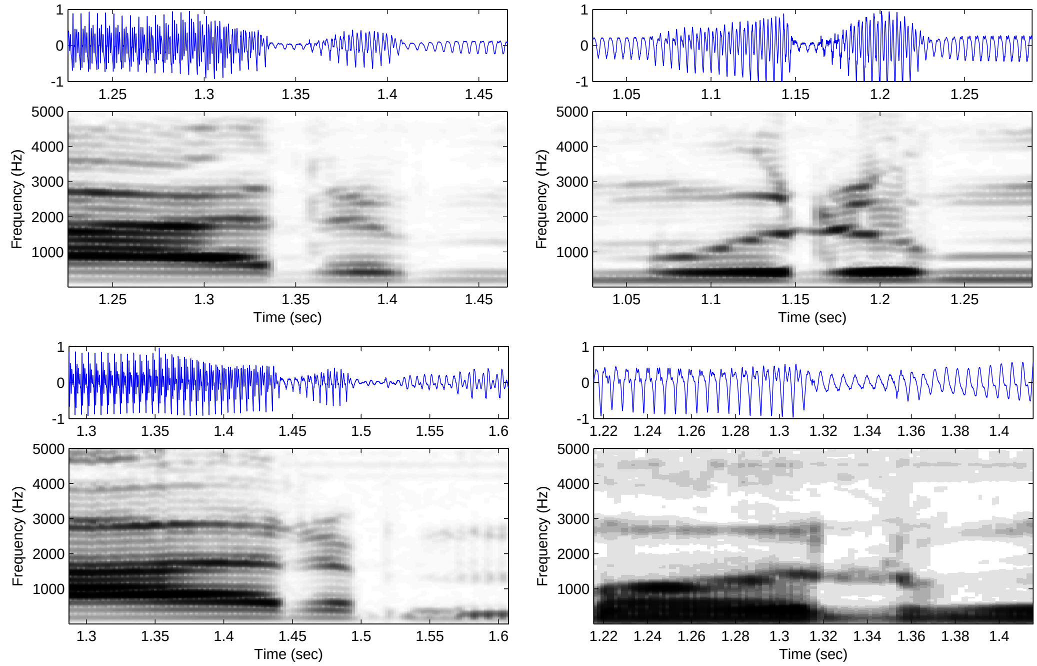



FIGURE 4.39: **Svarabhakti fragments in medial coda rhotics**: Top left: subject W1 [arm]; Top right: [urm]; Bottom left: subject W3 [arm]; Bottom right: [urm].

Ultrasound data tracking lingual articulation into and out of these resonant intervals are consistent with the hypothesis that medial coda svarabhakti are intrinsic to the rhotic, rather than intrusive. Midsagitttal articulation during the center of the rhotic resonance in the word /arma/ *'weapon'* is shown in Fig. 4.40, where it is compared with the articulation of the preceding and following vowels.

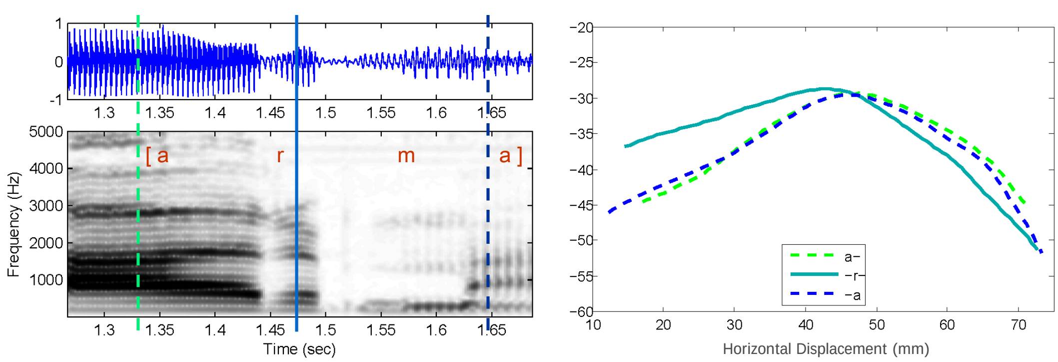



FIGURE 4.40: **Dorsal articulation in coda svarabhakti**: Left: [arma] waveform and spectrum (subject W3); Right: midsagittal articulation at three points in time: [a]–[r]–[a].

The data show the tongue dorsum to be raised and advanced mid-production of the svarabhakti fragment – the same articulation observed during the production of intervocalic rhotics in a low vowel context. Furthermore, the same pattern of articulation – advancing and raising of the dorsum, counter to the articulatory requirements of the context vowels – is observed in medial coda laterals (Fig. 4.41), but not in the coda stop (Fig. 4.42), where the dorsum drops during coronal closure.[5]

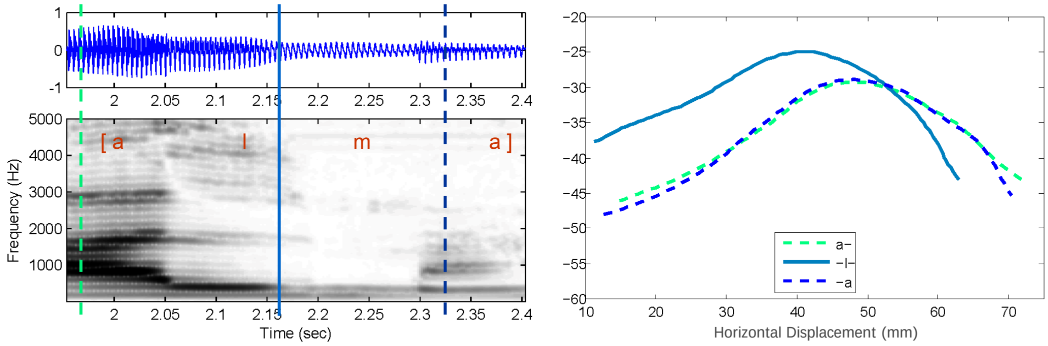



FIGURE 4.41: **Dorsal articulation of Spanish medial coda lateral** (subj. W3): Left: [alma] waveform and spectrum; Right: midsagittal articulation at three points in time: [a]–[l]–[a].

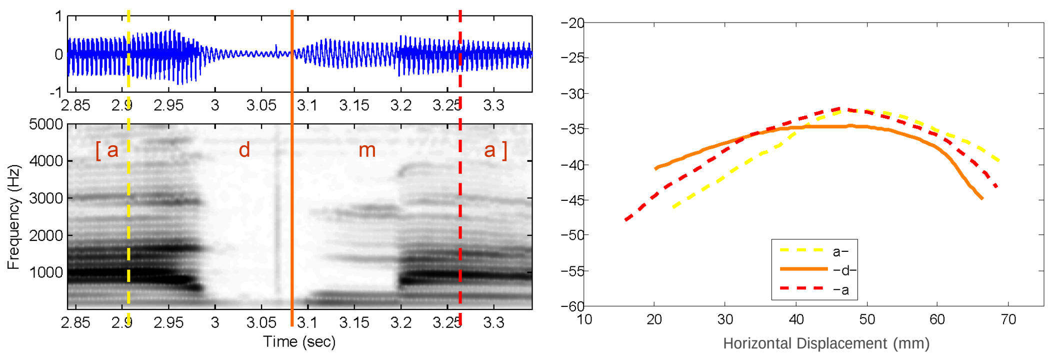



FIGURE 4.42: **Dorsal articulation of Spanish medial coda stop** (subj. W3): Left: [adma] waveform and spectrum; Right: midsagittal articulation at three points in time: [a]–[d]–[a].

Since the consonantal tongue edges shown in each of the Figures 4.40-4.42 were extracted at the end of the coronal consonant production (immediately before the start of the labial nasal), the data suggests that the dorsal gesture of the liquids persists into the nasal – a pattern of articulation associated with vowels (Öhman 1966; Gafos 1999).

A comparison of mid-coda consonant production in three different vowel contexts provides further evidence that dorsal articulation in svarabhakti fragments – and in liquid codas in general – is intrinsic to the consonant. As in intervocalic environments, dorsal articulation during the production of coda rhotics (and laterals) is

5 The absence of any resonant fragment between the stop and nasal in the sequence /adma/ (Fig. 4.42) is further evidence against the alternative analysis of svarabhakti as intrusive vowels. If these elements were introduced because of the Spanish preference for open syllables, then we would also expect to find /-dm-/ clusters broken through the use of schwa-epenthesis: /adma/ → [a.də.ma].

highly resistant to perturbation by vocalic coarticulation (Fig. 4.43 top and center), suggesting that the dorsum is controlled by the liquid. In contrast, dorsal articulation during the production of coda coronal stops appears to be uncontrolled by the consonant, and therefore highly susceptible to vocalic coarticulation (Fig. 4.43 bottom).

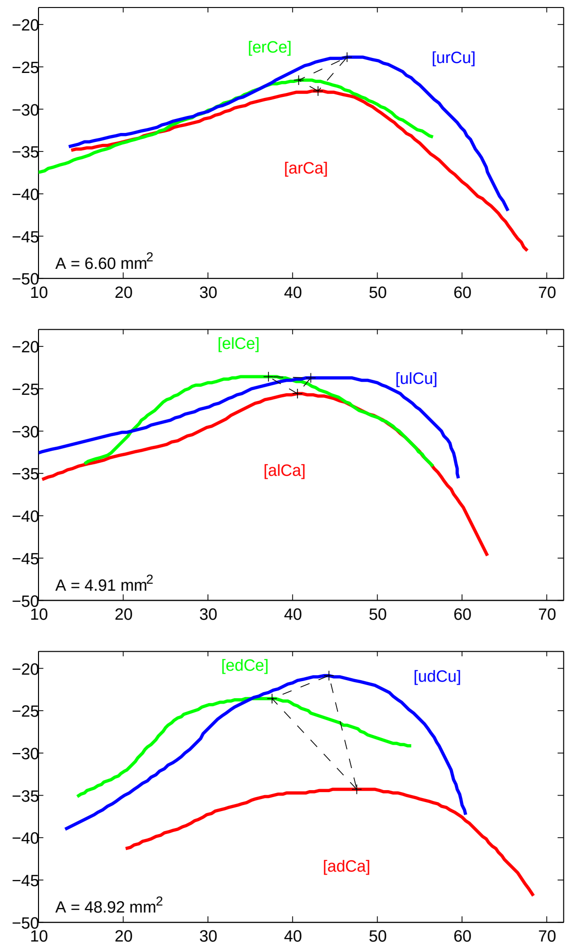



FIGURE 4.43: **Mid-consonantal articulation of Spanish medial coda consonants in three vowel contexts** (subject W3): Top: [ɾ] in VrmV; Middle: [l] in VlmV; Bottom: [d] in VdmV.

## 4.5 Conclusions

In this chapter, the phonetic properties of Spanish liquids have been examined in detail. Evidence has been presented that there is a phonetic basis for the class of Spanish liquids which differentiates these consonants from coronal stops: the presence of an intrinsic dorsal gesture.

The dorsal gesture associated with all three liquids was shown to be a relatively open constriction resembling that of a mid vowel. Dorsal constriction locations varied between tokens and subjects, but the tongue body gesture of the intervocalic lateral was typically located near that of the mid front vowel /e/, anterior to the dorsal gesture observed in the trill, which resembled that of the mid-back vowel /o/. The dorsal gesture of the tap was typically located in a more central location, resembling schwa.

The dorsal gestures of both coda laterals and rhotics appear to begin before their associated coronal gestures, and persist throughout the production of the liquid. Articulatory and formant analysis of coda rhotics suggests that it is the persistence of this gesture through to the release of the coronal closure which is responsible for the appearance of svarabhakti fragments in medial rhotic-initial clusters.

Acoustic and articulatory data examined in these experiments indicate that there is not always a clear phonetic distinction between taps and trill. In both onset and coda positions, rhotics vary in the degree of spirantization and number of coronal contacts observed: intervocalic 'trills' can be produced with a single contact, while word-final 'taps' are often realized with multiple contacts. These data are inconsistent with the hypothesis that Spanish taps are produced in the same manner as coronal stops, but consistent with an account in which all Spanish rhotics involve the coordination of a stabilizing dorsal gesture with a tongue-tip approximation gesture – an articulatory configuration under which a wide variety of rhotic allophones will result from differences in airstream conditioning, tongue stiffness, gestural timing and stricture.

The results of this study are consistent with the broader hypothesis that liquids are characterized by the global coordination of lingual gestures. Having characterized the phonetic distinction between the Spanish liquids and the voiced coronal stop, we next consider the way in which these contrasts might be represented phonologically, and the phonological implications of these representations (Chapter 5).

# Chapter 5

# Articulatory Modeling of Spanish Liquids

In this chapter, phonological representations of the Spanish liquids will be outlined, and a gestural account of the major phonological properties of the class will be proposed.

Experimental evidence presented in Chapter 4 indicates that the Spanish liquid consonants share the phonetic characterization that they are all produced with both coronal and dorsal gestures. In Chapter 3 it was shown that the Spanish liquids are phonologically characterized by their common distribution within the syllable and their interchangeability within the class. I propose that these essential phonetic and phonological properties are best reconciled under a gestural model in which a coronal liquid segment corresponds to a stable, coordinated pattern of tongue tip and tongue body gestures.

The structure of this chapter is as follows. Representations of Spanish coronal consonants under an articulatory phonology framework (Browman & Goldstein 1985a, 1992) will first be proposed. The gestural organization of Spanish coronal consonants within the syllable will be discussed. Data from TADA simulations demonstrating the validity of the gestural model of liquid articulation will be presented, and the limitations of the model will be addressed. Finally, articulatory analyses of some phonological phenomena involving liquids in Spanish will be proposed.

## 5.1 Gestural Characterization of Spanish Coronal Consonants

The conclusion drawn from the experiments in Chapter 4 is that the liquid consonants are characterized by the presence of a dorsal articulatory component, unlike coronal stops, which are produced with a tongue-tip gesture alone. This contrast can be represented at the planning level by the presence or absence of a tongue body gesture coupled to the tongue-tip gesture (Figure 5.1).

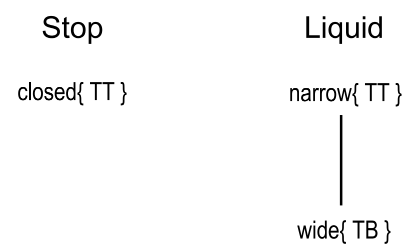



FIGURE 5.1: Contrasting coupling graphs: **Spanish coronal stops and liquids**.

Consonants do not occur in isolation, but are intrinsically bound to a companion vowel in a syllabic unit (Liberman et al. 1967). In syllable onsets, this relationship can be modeled as the synchronous coupling of a coronal gesture with the vocalic gesture of the syllabic nucleus. In a liquid onset, there are three gestures which need to be coordinated: the liquid tongue tip gesture, the liquid tongue body gesture, and the vocalic tongue body gesture. If Spanish onset liquids are organized in the same manner as multi-gestural segments in English (Krakow 1999, Goldstein et al. 2006), we can propose a three-way coupling relationship between each of these gestures, consistent with the hypothesis that all gestures in the onset are coupled in-phase with the nucleus (Browman & Goldstein 1985a, 1992; Gafos 2002).[1] The two onset structures are contrasted in the phonological representations of the Spanish words *da* 'he gives' and *la* 'her' (Fig. 5.2).

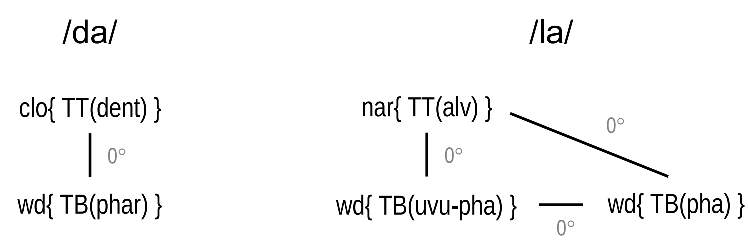



FIGURE 5.2: **Gestural organization in Spanish stop and liquid onsets**.

1 It remains to be seen whether segment-internal gestures in Spanish onsets are best modeled in a synchronous coupling relationship – like English initial laterals (Browman & Goldstein 1995) – or an asynchronous relationship, as has been proposed for complex onsets in languages which display a 'C-Center' effect (Browman & Goldstein 2000).

The articulation of the gestural constellation /da/ is straightforward: both tongue-tip and tongue-body tract variables have single goals, and the articulators which are recruited to achieve these goals commence their activity at the same time because the gestures are coupled synchronously (Fig. 5.3 left).

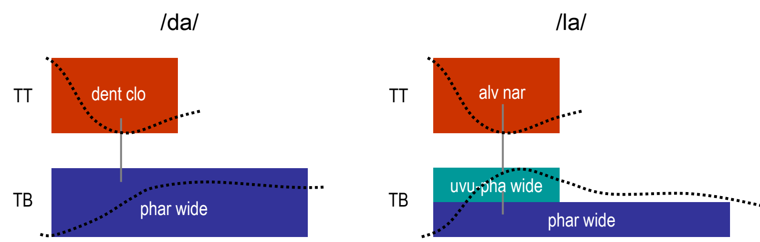



FIGURE 5.3: **Gestural timing and lingual trajectories in Spanish stop and liquid onsets**.

The liquid onset differs from the stop in that the tongue body is recruited for both consonantal and vocalic gestures. Because both consonantal and vocalic dorsal gestures begin at the same time, the trajectory which the dorsum will follow will be the result of 'blending' between the two gestures. If the consonantal gesture dominates, and is shorter in duration than the vocalic gesture, the result of this interaction will be that the dorsum will follow a trajectory which best satisfies first the tongue body target of the liquid (in that vocalic context – the result of the gestural blending), followed by the vocalic target. In the case of a clear lateral onset to a low back vowel, for example, this means that the dorsum will first raise and advance before returning to the pharyngeal target of the nucleus (Fig. 5.3 right) – a pattern of dorsal movement observed in the ultrasound data presented in Section 4.3.5.

### 5.1.1 Gestural Characterization of Spanish Liquids

The difference in gestural constituency contrasted in Figure 5.1 captures the essential difference between the classes of coronal stops and liquids; individual liquid consonants will differ in their specifications for location and degree of constriction of both tongue tip and tongue body gestures. The location of the tongue body gesture in the trills produced by the Spanish speakers in this study, for example, is typically forward of the mid-back vowel /o/, which can be described as a wide uvular-pharyngeal tongue body target. A preliminary set of gestural specifications for the Spanish coronal consonants, based on the results of the articulatory study, are proposed in Table 5.1.

Two additional aspects of liquid articulation which will need to be addressed as the model is refined are labial articulation, and the representation of lateralization.

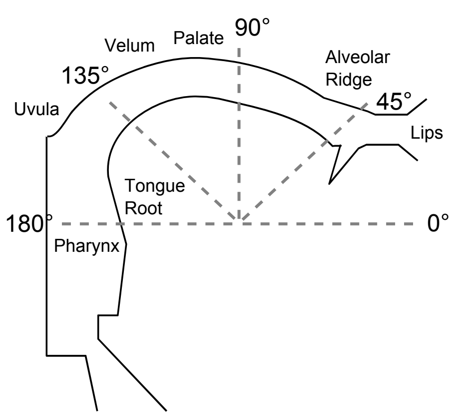
| TV | /d/ | /l/ | /ɾ/ | /r/ |
|---|---|---|---|---|
| **TTCL** | dental | dental | alveolar | alveolar |
| **TTCD** | closed | narrow | narrow | narrow |
| **TBCL** | – | palatal | uvular | uvular-pharyngeal |
| **TBCD** | – | wide | wide | wide |

TABLE 5.1: **Tract variable specifications for Spanish voiced coronal consonants**.

Ladefoged & Maddieson (1996) observe that the side channels in an English lateral are formed largely as a result of the elongation of the tongue, and Browman and Goldstein (1995) demonstrate that a purely midsagittal specification for synchronized coronal and dorsal gestures is capable of adequately modeling the articulatory and acoustic properties of English /l/. It remains to be seen whether lateralization can be modeled in the same way in a clear lateral, where the relative proximity of the dorsal and tongue tip gestures mean that the tongue is less elongated than in a dark lateral, which uses a more retracted tongue body gesture.

### 5.1.2 Articulatory Modeling of Spanish Liquids

In order to test the representations of Spanish coronal consonants proposed in Table 5.1, articulatory simulations were conducted using TADA. The gestural parameters used to model the three liquids are shown in Figure 5.4.




| ARPA | Organ | Osc | TV | Constr | Target | Stiff | Dmp | Alph |
|---|---|---|---|---|---|---|---|---|
| L | TT | nar | TTCL | DENTALV | 45 | . | . | . |
| | TT | nar | TTCD | NAR | 2 | . | . | . |
| | TT | rel | TTCL | REL | 24 | 8 | 1.0 | . |
| | TT | rel | TTCD | REL | 11 | . | . | . |
| | TB | voc | TBCL | VEL | 100 | . | . | . |
| | TB | voc | TBCD | V | 11 | . | . | . |
| R | TT | nar | TTCL | ALVPAL | 60 | . | . | . |
| | TT | nar | TTCD | NAR | 2 | 10 | 0.3 | . |
| | TT | rel | TTCD | REL | 24 | . | . | . |
| | TT | rel | TTCL | REL | 11 | . | . | . |
| | TB | voc | TBCL | UVU | 125 | . | . | . |
| | TB | voc | TBCD | V | 10 | . | . | . |
| | Lips | voc | LA | NAR | 2 | . | . | . |
| RR | TT | nar | TTCL | ALVPAL | 60 | . | . | . |
| | TT | nar | TTCD | NAR | 2 | 20 | 0.2 | . |
| | TT | rel | TTCL | REL | 24 | . | . | . |
| | TT | rel | TTCD | REL | 11 | . | . | . |
| | TB | voc | TBCL | UVUPHAR | 150 | . | . | . |
| | TB | voc | TBCD | V | 6 | . | . | . |
| | Lips | voc | LA | NAR | 2 | . | . | . |

FIGURE 5.4: Left: **Semi-polar coordinate system** used to specify constriction location in TADA; Right: **Gestural parameters used in TADA simulations of Spanish Liquids**.

The Spanish lateral, for example, is modeled using six tract variable specifications corresponding to two gestures: a tongue tip approximation (and release), and a tongue body constriction. The gestural target for the tongue tip is a narrow constriction (TTCD = 2 mm) in the alveolar region (TTCL = 45°). The tongue body target is specified as a vowel-like constriction (TBCD = 11 mm) in the velar region (TBCL = 100°). Two additional sets of parameters (TTCL REL = 11°; TTCD REL = 24 mm) specify a tongue tip release target.[2] Parameters not explicitly specified in Figure 5.4 were modeled using default values for consonants.[3]

### Modeling Spanish Laterals

Data from a simulation of Spanish lateral articulation are shown in Figure 5.5. The acoustic waveform and time course of the tongue tip (TTCD) and tongue body constriction degree (TBCD) tract variables generated in a simulation of the word /pala/ *'spade'*, using the gestural specifications in Figure 5.4, are shown on the right. Midsagittal articulation during the pre-consonantal vowel and the point of closest coronal approximation of the lateral are shown on the left.

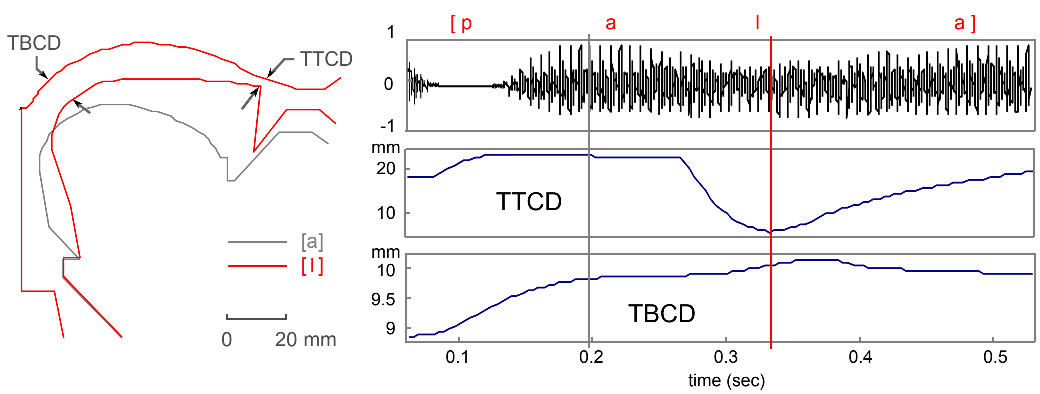



FIGURE 5.5: **TADA simulation of Spanish intervocalic lateral articulation: [pala] *'spade'*.** Left: midsagittal articulation during pre-consonantal vowel and mid-consonant; Right: acoustic waveform and time course of tongue tip and tongue body constriction degree tract variables.

TADA simulations of laterals produced in different vowel contexts exhibit the same changes in dorsal articulation which were observed in the ultrasound study. Data from three simulations of Spanish intervocalic laterals have been shown in Figure 5.6 (left). Midsagittal lingual profiles captured at the point of closest coronal approximation in [ele], [pala] and [pulula] simulations have been superimposed. Comparing the laterals with stops produced in the same contexts (Fig. 5.6,

2 For discussion of the need to specify separate release gestures see Browman (1994) and Nam (2007).

3 For explanations of differences between vocalic and consonantal stiffness, damping and blending parameters, see Nam et al. (2004). For details of implementation and default values used in TADA, see Goldstein et al. (2008).

right), the same resistance to vocalic coarticulation can be observed in the simulated liquids as was shown to characterize the laterals produced by Spanish speakers (4.3.6).

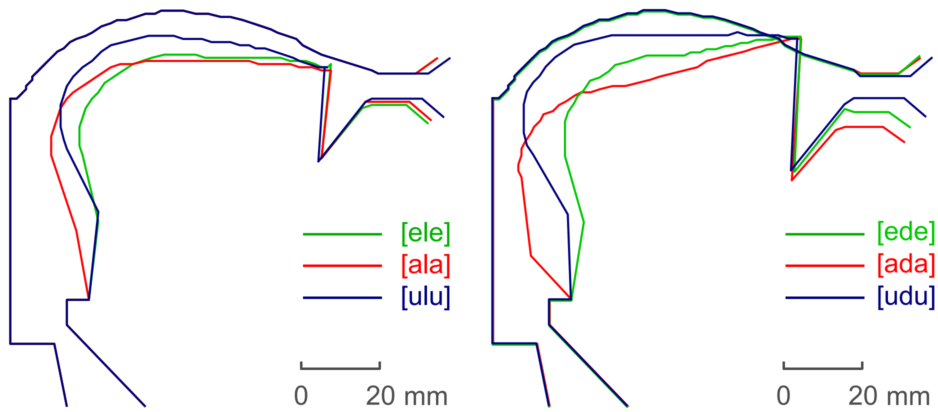



FIGURE 5.6: **Simulated vocalic coarticulation in Spanish intervocalic stops and laterals**. Left: comparison of midsagittal articulation in laterals produced in three different vowel contexts in /ele/, /ala/ and /ulu/ simulations; Right: midsagittal articulation in simulated coronal stops: /ede/, /ada/ and /ulu/.

The results of these simulations demonstrate that the model of gestural organization proposed for onset liquid consonants – in which liquid dorsal gestures blend with, and dominate, the synchronous but longer vocalic gestures – is capable of modeling a critical property of Spanish liquids: their resistance to vocalic coarticulation.

The spectrogram of an intervocalic lateral synthesized from the articulatory simulation is shown in Figure 5.7, where it is compared to spectra of intervocalic laterals produced by male and female Spanish speakers. The primary way that the synthesized lateral differs from the Spanish laterals is in the higher formants – in particular F4, which is not high enough in the context vowel and does not lower into the lateral.[4] As a result, the synthesized lateral, although sounding clearer than a dark [ɫ] , has an excessively 'palatal' quality.

Nevertheless, the important characteristic of the synthesized spectrum is that the lower two formants follow the same trajectories as in the real speech – a lowering of F1 and a raising of F2 in the transition into the lateral from the pharyngeal context vowel, consistent with a tongue body constriction target anterior to and above that of the pharyngeal vowel. The acoustic and articulatory output of the TADA simulation suggests that the gestural specification of a dorsal target resembling that of /e/ is an appropriate model for the clear lateral of Spanish.

[4] Discrepancies in the higher formant trajectories of the synthesized spectra appear to be due to the absence of side channels in the midsagittal model, which have the effect of introducing a spectral zero around 2 kHz, lowering both F3 and F4 (Fant 1960).

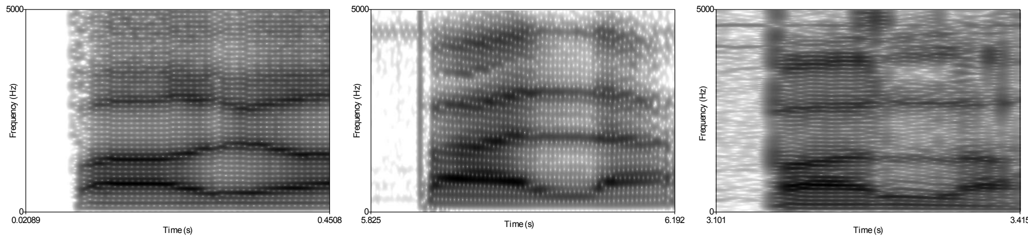



FIGURE 5.7: **Spectra of simulated and spoken Spanish intervocalic laterals**. Left: Speech synthesized from articulatory sequence [pala] simulated in TADA; Center: [pala] spoken by female subject W1; Right: [pala] spoken by male subject M1;

### Modeling Spanish Rhotics

Articulatory trajectories and synthesized waveforms from TADA simulations of the two Spanish rhotics are shown in Figures 5.8 and 5.9. The data show that the trill has been successfully modeled as a multi-contact coronal consonant, and the tap as single-contact. Spectra compared in Figure 5.10 show the simulated rhotic to be characterized by the same stability of formants in the back vowel context as observed in the spoken trills.

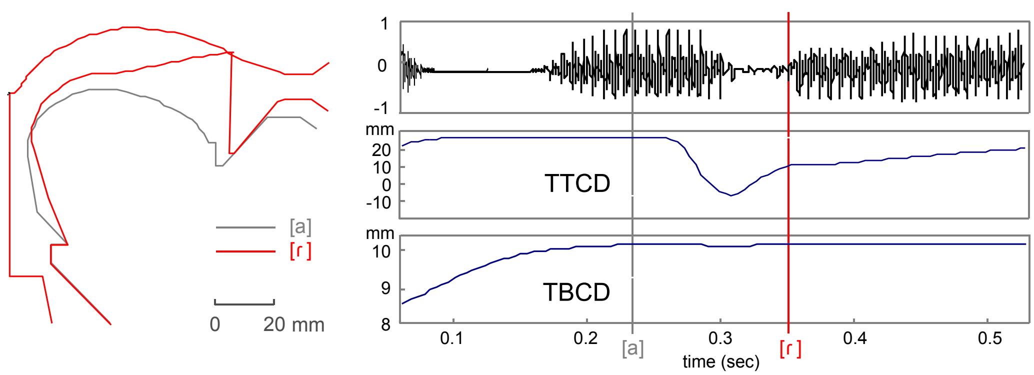



FIGURE 5.8: **TADA simulation of Spanish intervocalic tap articulation: [paɾa] *'for'***. Left: midsagittal articulation of pre-consonantal vowel, and during consonantal closure; Right: acoustic waveform and time course of tongue tip and tongue body constriction degree tract variables.

Although different tongue body constriction locations were specified for the trill and the tap – reflecting the difference in mean dorsal location observed in ultrasound study (Fig. 4.33) – the essential difference between the two rhotics in these TADA simulations is in the stiffness and damping of the tract variable associated with the tongue tip.

In the model of inter-articulator coordination implemented in TADA, the default TV frequency (stiffness) assigned to consonantal gestures is 8 Hz – twice that of gestures associated with a vowel oscillator (4 Hz). This 2-to-1 V:C frequency ratio is

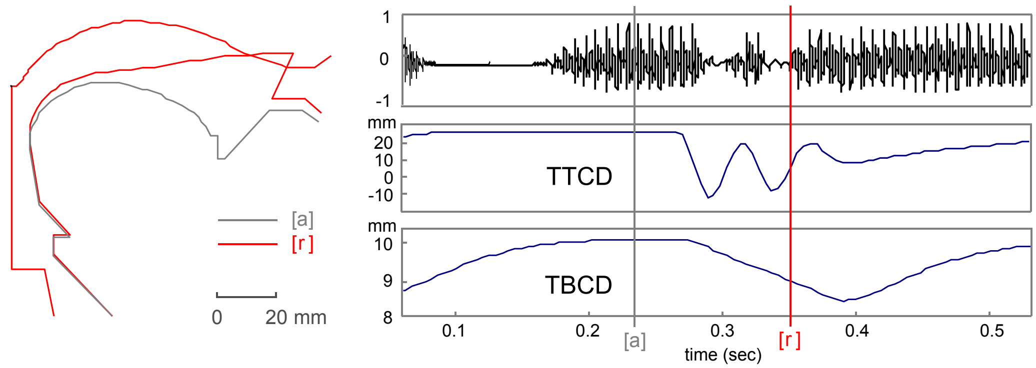



FIGURE 5.9: **TADA simulation of Spanish intervocalic trill articulation: [parra]** ***'vine'***. Left: midsagittal articulation of pre-consonantal vowel, and during consonantal closure; Right: acoustic waveform and time course of tongue tip and tongue body constriction degree tract variables.

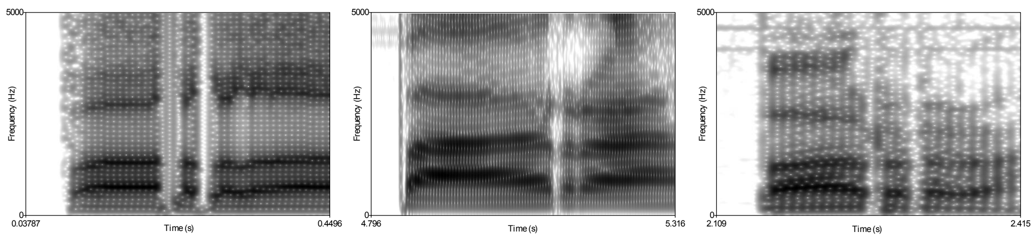



FIGURE 5.10: **Spectra of simulated and spoken Spanish intervocalic trills**. Left: HL-Syn synthesized speech of sequence [para] simulated in TADA; Center: [para] spoken by female subject W2; Right: [para] spoken by male subject M1;

used to model a syllable structure in which all onset gestures begin synchronously with the vowel, but are only activated for half of the duration of the vocalic gesture. In the rhotic simulations illustrated in Figures 5.8 and 5.9, TTCD stiffness was specified to be much shorter (10 and 20 Hz) than the consonantal default, and the tongue tip damping ratio was reduced from the default value of 1. Standard consonantal parameters were used for the tongue body tract variable gesture of the rhotics.

The articulatory configuration being modeled with this set of specifications is one in which a stable tongue body gesture is coordinated with a less rigidly controlled coronal gesture – a lingual configuration which has been shown to be conducive to the onset of trilling (McGowan 1992, Solé 2002). Because it is not possible to specify aerodynamic parameters in TADA, trill initiation is emulated as a brief coronal approximation of a weakly damped tongue tip.

While acknowledging the artificiality and limitations of this type of simulation, the importance of this experiment is to demonstrate that a computational articulatory model is able to capture the essential difference between the rhotics and the coronal obstruents: oscillatory coronal articulation can result from the coordination of a weakly damped tongue-tip approximation with a stable tongue body gesture (rather than the active closure gesture used to simulate coronal stops).

Another important point to be made about the simulations compared in Figures 5.8 and 5.9 is that the same fundamental model has been for both the trill and the tap. This demonstrates that both types of rhotics can be produced using the same articulatory configuration – a configuration in which the number of coronal contacts depends, in part, on the degree of tongue-tip damping. The variability in the frequency of oscillation of the tongue tip observed in different simulations run using this model is consistent with the variability in the number of coronal contacts observed amongst both rhotics produced by the Spanish speakers in this study (Figure 4.35).

Considerable variability was also observed in the degree (and duration) of tongue tip closure produced at different stages in different rhotic simulations. As observed in Section 4.4.2, spirantized rhotics sometimes result from the same basic articulatory configuration used in trill production. In these cases, it seems likely that the different rhotic allophones are the result of small differences in aerodynamics, tongue-tip stiffness, or coronal aperture; if so, the variability in tongue tip articulation produced by the TADA rhotic simulation is consistent with the variability in the degree of spiratization observed amongst the rhotics elicited in the ultrasound study (Section 4.3.2).

## 5.2 Gestural Organization in Spanish Codas

It was demonstrated in Section 3.2 that Spanish has a strong preference for open syllables (Table 3.3), and that codas overwhelmingly consist of one of the consonants {/n/,/r/,/l/,/s/} (Table 3.5). Each of the consonants in this set is a complex segment, consisting of a tongue-tip gesture coordinated with a velic or tongue body gesture (assuming that sibilant production involves dorsal articulation to condition the airstream into the coronal constriction). This suggests that Spanish has a preference for coda structures in which the tongue body gesture of the nucleus can be coupled to the non-coronal gesture of the coda consonant (Fig. 5.11).

Under this model, dorsal or velic coda gestures would always be contiguous with the nucleus; the timing of other coda gestures would depend on their phasing with the dorsal (or velic) gesture. This model of Spanish coda structure is consistent with accounts of syllable-final timing differences in English and other languages. Observing the lag in tongue tip gestures of nasals and laterals, relative to their corresponding velic and dorsal gestures in English, Browman & Goldstein (1995a) pro-

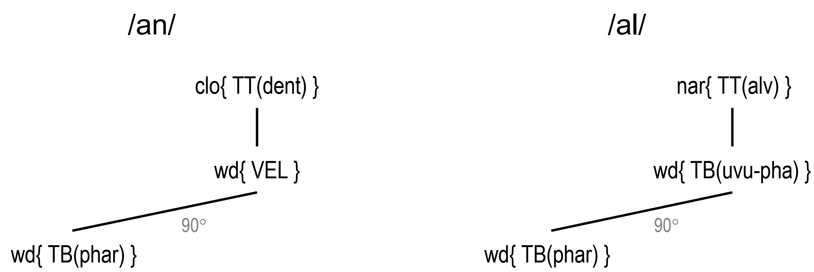



FIGURE 5.11: **Gestural organization in Spanish nasal and liquid codas**.

posed that coda organization in English is governed by the principle that "gestures involving wider constrictions precede those with narrower constrictions". Similar effects have been observed in laterals in Squamish Salish, and the rhotic liquid of Mandarin Chinese (Gick et al. 2006). These timing differences would result from an anti-phase coupling between tongue-body and tongue-tip gestures in the model in Figure 5.11).

Although it is beyond the scope of this dissertation to provide a thorough analysis of intergestural timing in Spanish coda consonants,[5] the articulatory evidence suggests that, as in other languages, tongue body gestures precede coronal activity in coda liquids. Dorsal movement (fronting and raising) toward the target constriction in Figs. 4.37 and 4.38, for example, commences up to 150 msec before the tongue blade is approximated toward the alveolar ridge, and is largely completed before the tongue tip achieves first closure. Articulation of another coda rhotic by the same speaker is shown in greater temporal resolution in Figure 5.12: dorsal advancement commences some -74 msec before any independent movement of the tongue blade can be observed.

It remains to be seen what intergestural timing relationships exist in Spanish coda consonants, and how they are best modeled. Preliminary evidence from the ultrasound data indicates that coronal gestures lag tongue body gestures, which would be consistent with the model of coda structure in which tongue-tip gestures are coupled anti-phase to the tongue-body gestures, which in turn are coupled anti-phase to the nucleus (Fig, 5.11). Such a configuration is broadly consistent with coordination relations which have been proposed for codas in English (Browman & Goldstein 2000) and Morrocan Arabic (Gafos 2002).

[5] Because of the difficulty of reliably tracking tongue tip activity and quantifying gestural timing in ultrasound data, such a study would require the use of an alternative imaging modality such as EMMA.

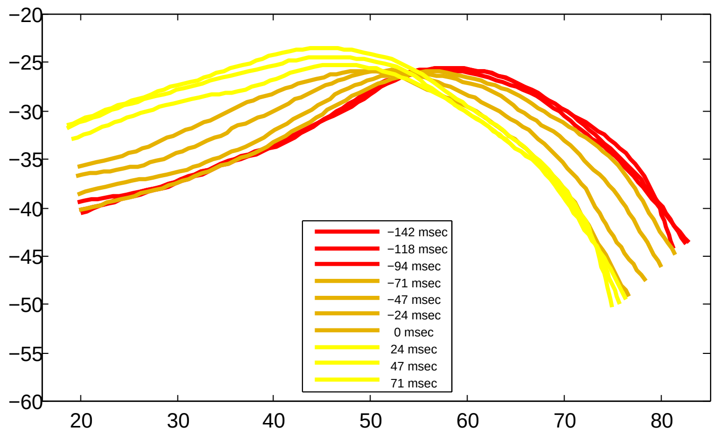



FIGURE 5.12: **Coronal lag in Spanish coda rhotic articulation** – Subject W3, [ar]. Red frames: tongue static in vocalic gesture; Tan frames: tongue fronting as a single unit; Yellow frames: dorsal fronting complete, tongue blade raising independently.

## 5.3 Gestural Organization in Spanish Complex Onsets

The same principle which has been proposed to account for Spanish coda structure – that the most open tongue body gesture is always coupled more closely to the nucleus – will also account for the phonotactics of Spanish onset clusters. As discussed in Section 3.2.1, Spanish uses a limited set of complex onsets in which the segment appearing between the obstruent and the nucleus is always a liquid.

In onset clusters, and onset consonants consisting of multiple components, all gestures are modeled as existing in an in-phase relationship with the vocalic gesture of the nucleus. If these gestures are associated with different articulators, this means that they will all commence synchronously with the nuclear vowel. If multiple gestures are associated with the same articulator, then in order to ensure perceptual recoverability (Chitoran et al. 2002), the competition for control of the single tract variable must be resolved through temporal reordering, to prevent the parallel execution of homorganic gestures. We can model this using an asynchronous coupling relationship between the competing tongue body gestures in the onset (Figure 5.13).

In both rhotic- (/krema/) and lateral-internal clusters (/klima/) in Spanish, for example, each of the tongue body gestures in the onset (dorsal stop and liquid) will be coupled in-phase to the pharyngeal vowel. If the tongue-body gesture of the liquid has a greater affinity for the nucleus, then it will always appear closer to the vowel than the dorsal obstruent, which involves the less inherently sonorant tongue body closure constriction.

If it is the case that there is a universal preference for coupling gestures of greater

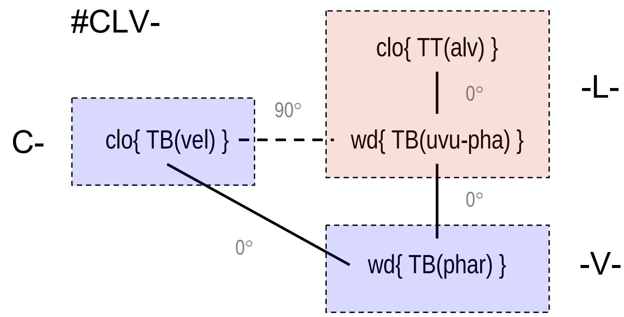



FIGURE 5.13: **Organization of complex Spanish onsets** – /kla-/.

tongue body or velic aperture more 'tightly' to the nucleus in both onsets and codas, this would prove to be an important principle of organization which could account for the sonority-sequencing phenomena observed in many languages, consistent with the principles of organization which have been hypothesized in articulatory theories of syllabic organization.

Principles of gestural organization in complex onsets and codas are discussed in more detail in Chapter 9, where it is proposed that the cluster phonotactics observed in Spanish, as in all languages, result from the interaction of universal and language-specific constraints on gestural coordination and recoverability. According to this view of the syllable, it is because of their intrinsic gestural complexity that liquid consonants play a special role in the structure of clusters.

## 5.4 Articulatory Analysis of Phonological Processes Involving Spanish Liquids

A number of phonological processes involving liquids in Spanish can be explained in terms of changes in the type, timing, and organization of their constituent gestures.

### 5.4.1 Rhotacism, Lambdacism, and Liquid Neutralization

Under the gestural model proposed here, all three Spanish liquid consonants are characterized as having the same fundamental phonological representation – individual consonants being differentiated by their individual specifications for those gestures. Because of this underlying unity in gestural constituency, phonological phenomena such as neutralization and allophonic variation within the class may be considered to be the result of changes in the articulatory parameters of liquid consonants.

Changes in the target location and degree of constriction for tongue body and tongue tip gestures, as well as the stiffness, degree of damping, and blending parameters associated with each of the gestures which constitute a liquid, will all result in changes in the realization of the consonant.

Rhoticization of final laterals in Havana Spanish, for example, could result from a reduction in the degree of damping of the tongue tip gesture, while stiffening of the tongue blade would be a contributing factor in the reverse process of lateralization. The intermediate liquid allophones attested in Puerto Rican Spanish codas – *puerta* [ˈpueʳl.ta] 'door'; *por favor* [poʳl.fa.ˈβol] 'please' (Hualde 2005) – would appear to be realizations in which the coronal gesture is adopting an articulation configuration intermediate to that prototypically associated with the lateral and the tap.

### 5.4.2 Liquid Vocalization

Another phonological process involving Spanish liquids which bears reconsideration under a gestural framework is vocalization. As discussed in Section 3.2.2, in many Spanish varieties, liquids in coda positions are prone to realization as glides or central vowels, e.g. *algo* [ˈai̯.ɣo] 'something', *mujer* [mu.ˈhei̯] 'woman'.

Accounting for liquid vocalization is problematic under feature-based phonologies. In the feature-geometric representations proposed by Walsh Dickey (1997), for example, rhotics and laterals have an inherently different structure – only laterals having a dual place node (Fig. 5.14 left). Furthermore, in the feature geometry of McCarthy (1988), upon which Walsh Dickey bases her hypothesized structures for liquids, both types of consonant have an inherently different structure to vowels (Fig. 5.14 right).

Although lateral vocalization might be explained in part as the result of the delinking of the laminal place node, there is no straightforward account of rhotic vocalization using the feature geometry of Figure 5.14 (center). Furthermore, it is not obvious how to account for the differences in the major class features between vocalized and non-vocalized liquids under this framework, since the structure of the root node differs between laterals and rhotics (±cont), and between the liquids and vowels (±liquid).

Accounting for liquid vocalization is straightforward under the articulatory model being proposed here: it would result from lenition, deletion or masking of the tongue tip gesture of the liquid. The organization of gestures in the word /algo/

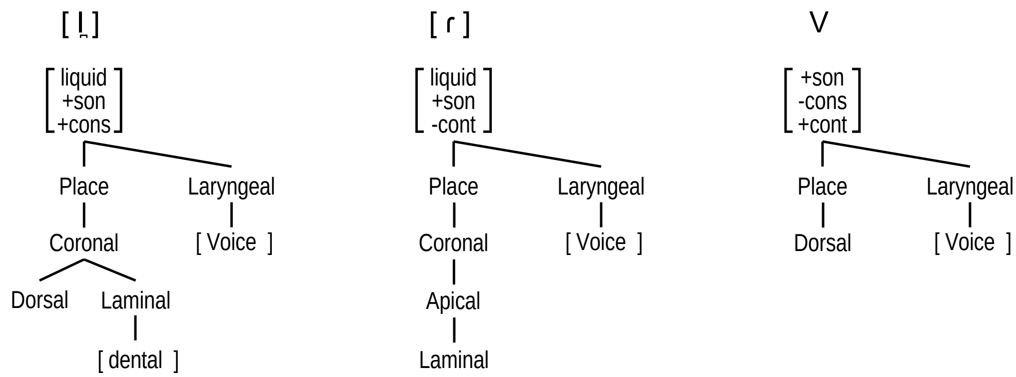



FIGURE 5.14: **Feature Geometries of liquids and vowels** (Walsh Dickey 1997).

*'something'*, for example, is illustrated in the score in Figure 5.15.[6] Prototypically, the coda lateral is articulated with a partial coronal closure, coordinated with a dorsal constriction in the palatal region. If the tongue tip gesture is deleted or undershot, the wide tongue body constriction which will remain is identical to that which defines palatal vowel /alɡo/ → [ˈai̯.ɣo].

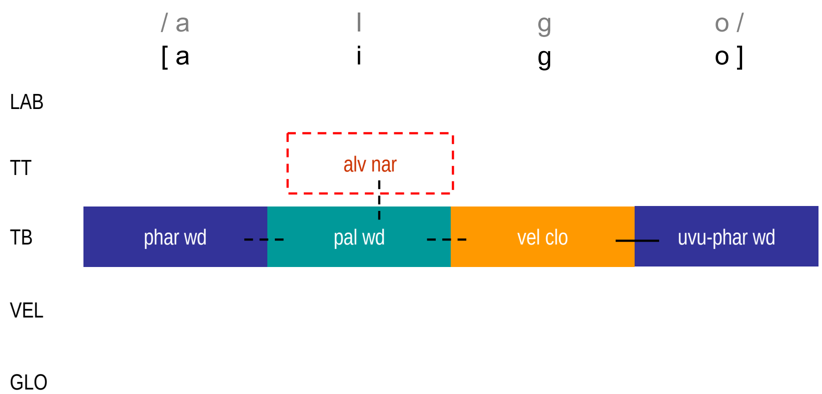



FIGURE 5.15: **A gestural account of liquid vocalization in Spanish codas**: deletion of tongue tip gesture, leaving only vocalic tongue body gesture.

Similar accounts of vocalization have been proposed for dark laterals in Brazilian Portuguese (/l/ → [u], Leidner 1976), British English (/l/ → [ɤ], Hardcastle& Barry 1989) and child Dutch (/l/ → [w], Browman & Goldstein 1995). The fact that coda vocalization affects both laterals and rhotics in Spanish is consistent with the hypothesis that there is a gestural basis to the class of liquids, and constitutes another important piece of evidence that clear laterals, like velarized laterals, are produced

6 The spirantized velar fricative [ɣ] which typically appears in place of the intervocalic stop [ɡ] could result from undershoot of the tongue body clo closure gesture (Parrell p.c.); alternatively, this gesture may be specified as crit in Spanish varieties in which intervocalic stop spirantization is lexicalized.

with a vowel-like dorsal gesture. The fact that the outcome of lateral vocalization in Spanish is typically a high front vowel or a palatal glide is consistent with the hypothesis that the dorsal target of the clear lateral resembles that of a front vowel.

Under a gestural phonology, we are able explain liquid vocalization without having to account for differences in major class features, as there is no inherent difference between the phonological primitives of consonants and vowels. All types of oral sonorants are produced with a wide lingual constriction gesture – the same gesture will correspond to a vowel, glide or liquid, depending on the coordination of this gesture with others in the organization of the syllable.

### 5.4.3 Metathesis

Another phonological process in which Spanish liquids pattern together – for which there is no straightforward explanation under feature-based phonological theory – is metathesis. As observed in Section 3.2.2, the most commonly attested type of metathesis in Spanish involves the interchange of liquids with adjacent vowels: *porfiar* → [pɾofiaɾ] 'to insist', *clueca* → [kuleka] 'broody'. While such phenomena could conceivably be explained in terms of feature spreading and delinking in an autosegmental framework, the asymmetrical structure of the feature hierarchies proposed for laterals and rhotics make a unified account of metathesis problematic – it is unclear which nodes should be spread and how major class features should be handled.

Blevins & Garrett (1998) have argued that rhotic metathesis in Romance results from the spreading of 'long phonetic cues' (specifically, a lowered third formant) into rhotic-adjacent vowels; however, we have seen that there is no such invariant acoustic property which unifies Spanish rhotics, even amongst the five participants in this study. Furthermore, this explanation cannot account for lateral-vowel sequences, which metathesize in the same environments as rhotics in Spanish, as in many other languages (Hume 2004).

Russell Webb & Bradley (200x), following Hall (2003, 2004), propose an optimality theoretic account of diachronic metathesis in which "gestural alignment constraints favor complete overlap of adjacent rhotic and vowel gestures". All of these accounts assume a stage in the historical development of these changes in which obstruent-rhotic clusters are broken through vowel epenthesis (or as a result of underlying vocalic gestures becoming more prominent, cf. Steriade 1990), after which a realignment of gestures results in the metathesized forms.

I propose that the articulatory model of Spanish liquids being developed here suggests a simpler, more unified account of liquid-vowel metathesis. In the organization of a syllable, the fundamental difference between onset and coda consonants is their phasing with respect to the nucleus (Nam & Saltzman 2003). Comparing the gestural constituency of the first syllable of the word *porfiar* 'to insist' with that which would result in the metathesized version [pɾo] (Fig. 5.16 left), we can see that the relocation of the rhotic is the result of the shift of its tongue tip and tongue body gestures so that they are timed with respect to the beginning, rather than the end of the vowel.

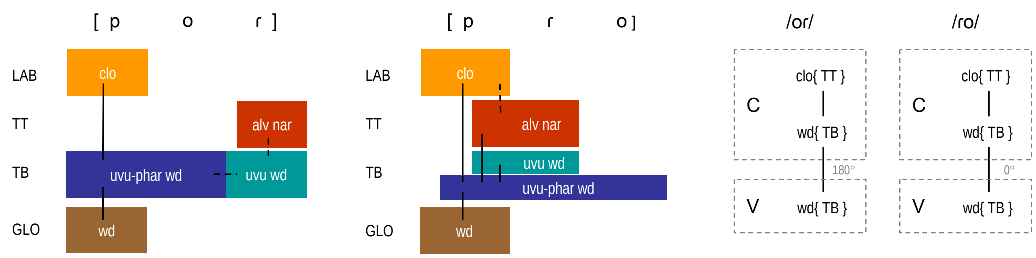



FIGURE 5.16: **Metathesis of Spanish coda liquids**: change in phasing of liquid and nucleus tongue body gestures.

VL metathesis may therefore be modeled as a phase change in the coupling relationships between the gestures corresponding to the liquid and the nucleus (Fig. 5.16 right). While both in-phase (onset) and anti-phase (coda) couplings correspond to stable states of inter-gestural organization in the syllable, the in-phase relationship appears to be more stable than the anti-phase (Nam & Salzman 2003). Evidence from speech error experiments suggests that changes in gestural phasing can occur spontaneously between syllables (Pouplier 2005), and experiments into gestural organization amongst populations of interactive agents indicate that in-phase structures tend to emerge as the preferred coupling relationship over time (Browman & Goldstein 2000). These results are consistent with the Spanish preference for open syllables, as well as the tendency for metathesis to move rhotics out of coda positions into onsets, even when the change results in a complex onset.

### 5.4.4 Rhotic Svarabhakti

The phonetic analysis of the svarabhakti phenomena presented in Section 4.4.3 suggests an alternative account to that proposed by Bradley (2004). The resonant fragments which have been interpreted as intrusive or underlying context vowels are instead argued to result from the same dorsal gestures, intrinsic to the rhotic, which were observed in intervocalic environments. In medial coda position, these fragments are more salient because they are immediately followed by a heterosyllabic consonant. In certain realizations, if the coronal component of the rhotic does not mask the dorsal component (as it invariably does in coda laterals because the coronal gesture is sustained), the coda rhotic will be perceived as a CV sequence. The timing relationships which could result in the appearance of svarabhakti are illustrated in the gestural score in Figure 5.17.

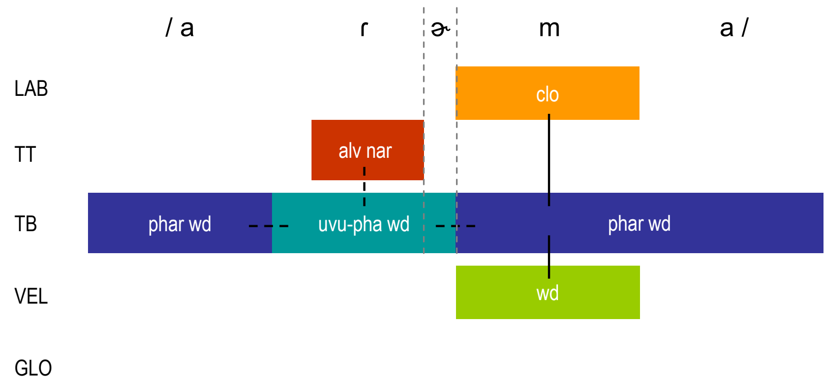



FIGURE 5.17: **A gestural account of svarabhakti** in Spanish medial rhotic-final clusters: resonant fragments inherent to rhotic.

Although the activation interval for the TTCD tract variable indicates that the coronal gesture of the rhotic ends earlier than the associated tongue body gesture, svarabhakti could also result if the tongue tip gesture persisted into the interval of activation of the following labial. Because Spanish rhotics are articulated with sporadic coronal contact, there will be intervals of time during which the dorsum adopts a vowel-like posture while there is no coronal closure – an articulatory configuration which may be perceived as short intrusive vowel.

## 5.5 Conclusions

In this chapter, the class of Spanish liquids has been characterized as consisting of a subset of recurrent phonological structures in which a tongue-tip gesture is coordinated with a vowel-like tongue body constriction. The three liquids are argued to be differentiated by their target tongue body constriction locations, and the stiffness and damping of their tongue tip gestures. Allophonic variation and neutralization of liquids is argued to result from changes in these gestural parameters.

Articulatory simulations have demonstrated that gestural models specified for these characteristics are capable of capturing some of the essential phonetic behaviors of liquids. Trajectories of the lower two formants in modeled intervocalic liquids are consistent with those observed in spoken Spanish. Variation in coronal articulation was successfully simulated by manipulating the degree of tongue tip damping, consistent with the hypothesis that trills and taps are characterized by the same underlying articulatory configuration.

The phonotactic properties of Spanish liquids – uniquely appearing as nucleus-adjacent segments in onset clusters; preferentially appearing in codas – are argued to result from a preference in Spanish syllabic organization for coupling relationships between the nucleus and adjacent tongue-body gestures. Under this model, liquid-vowel metathesis might arise from changes in the phasing of these gestures.

The picture which emerges from the analysis of laterals and rhotics in Spanish is that the production of coronal liquids prototypically involves the coordination of a vowel-like dorsal gesture with a tongue tip approximation – a representation which is also broadly consistent with phonetic descriptions of trills in Catalan (Recasens ref) and Serbo-Croatian (Gick et al. 2006), and approximant liquids in English (Delattre & Freeman 1968; Giles & Moll 1975) and Mandarin (Gick et al. 2006). It remains to be seen whether this characterization holds true in languages which use secondary articulation to contrast pairs of consonants. To examine this question, we next consider the phonological behavior and phonetic properties of liquids in Russian.

# Chapter 6

# The Phonology of Russian Liquids

Russian is a language of particular interest in the study of liquids because its consonantal phonology is distinguished by two major characteristics: contrastive palatalization, and typologically unusual phonotactics.

Because the contrast between palatalized and non-palatalized phonemes affects all types of consonant in Russian, the first question to be considered is whether or not liquids differ from obstruents in terms of their gestural constituency. Specifically, it has been claimed that Russian non-palatalized consonants are inherently velarized (Trubetzkoy 1969, Cubberley 2002). If so, we would expect to find evidence for a dorsal gestural component in all non-palatalized consonants, including obstruents. In Chapter 1, it was proposed that the class of liquids might be characterized by a shared dorsal gesture, which raises the question of whether liquids differ articulatorily from the other non-palatalized consonants of Russian, and if so, how? Additionally, we need to consider the extent to which palatalized liquids pattern with the other liquids of Russian, and the way in which they might be represented in the articulatory model proposed in Chapter 5.

Another important issue in Russian liquid phonology is the way in which the sonorants feature in some typologically irregular phonotactic distributions. Russian words, for example, can begin with a sonorant followed by an obstruent (лгать [lgatʲ] *'to lie'*, рдеть [rdetʲ] *'to glow'*, мстить [mstʲitʲ] *'to revenge'*), an onset structure which is typically prohibited in most languages. The case was made in Chapter 2 that one of the essential properties of liquids is their tendency to appear closer to the nucleus in consonant clusters; therefore any treatment of the phonology of Russian liquids must address this phenomenon, and offer some account of their distribution in clusters.

In this chapter, a brief survey of Russian consonantal phonology will be presented.

Evidence for the class of liquids in Russian will be considered. Previous phonetic studies of Russian liquids will be reviewed, and the phonetic characterization of the class will be discussed. Finally, the goals of a phonetic study of Russian liquids will be set out, before these experiments are presented in Chapter 7.

## 6.1 Russian Consonantal Phonology

Russian uses 33 consonants, and a system of five vowels which are realized as a rich set of allophones governed by stress and phonological enviroment. Each Russian word bears one lexically specified stressed syllable, and non-stressed vowels are reduced (Timberlake 2004). The phonemic inventory of Contemporary Standard Russian (CSR) is illustrated in Table 6.1. Although Cubberley (2002) and Timberlake (2004) classify all coronal consonants as dental, considerable variation can be seen in their realization between dental and alveolar places of articulation (Fant 1960, Bolla 1981).

TABLE 6.1: **Phonemic inventory of Contemporary Standard Russian** (adapted from Jones & Ward 1969). [a]

| | LAB | LDENT | DENT | ALV | PALV | PAL | VEL | |
|---|---|---|---|---|---|---|---|---|
| Stop | p, b | | t, d | | | | k, g | |
| | $p^j$,$b^j$ | | $t^j$,$d^j$ | | | | $k^j$ | |
| Affricate | | | ts | | | | | |
| | | | | tʃ | | | | |
| Fricative | | f, v | | s, z | ʃ, ʒ | | x | |
| | | $f^j$,$v^j$ | | $s^j$,$z^j$ | | | | |
| Nasal | m | | n | | | | | |
| | $m^j$ | | $n^j$ | | | | | |
| Rhotic | | | | r | | | | |
| | | | | $r^j$ | | | | |
| Lateral | | | l | | | | | |
| | | | $l^j$ | | | | | |
| Glide | | | | | | j | | |
| Vowel | | | | | | i | | u |
| | | | | | | e | | o |
| | | | | | | | a | |

[a] The marginal phonemes /$ʃ^j$/, /$g^j$/ and /$x^j$/ have not been included in this inventory. See Timberlake (2004) for treatment of their phonemic status.

### 6.1.1 Contrastive Palatalization in Russian

A characteristic feature of Russian consonantal phonology is that most sounds have both a palatalized ('soft') and a non-palatalized ('hard') form, each of which is considered to be a distinct phoneme (Timberlake 2004). Palatalization is contrastive in word-final and heterorganic medial coda positions. Except in historical loan words, non-palatalized consonants do not generally occur before /e/ (Padgett 2003). Palatalization is contrastive before the high front vowel /i/, which is realized as its high central allophone [ɨ] after non-palatalized consonants to facilitate the distinction.[1] The contrast between palatalized and non-palatalized coronal obstruents is neutralized to non-palatalized in homorganic medial clusters, e.g. путь [putʲ] *'way'* → путьниј [ˈputnɨj] *'approximate'* (Kochetov 2006).

The difference between these 'mutable pairs' of consonants is typically described as one of secondary articulation (Jones & Ward 1969, Catford 1988, Ladefoged & Maddieson 1996). It is not only the palatalized consonants which are considered to involve a secondary articulation; the 'plain' consonants are commonly described as velarized (Reformatskii 1958, Öhman 1966, Trubetzkoy 1969), yet the evidence for this claim is unclear.

Russian non-palatalized consonants have been described as velarized on purely perceptual grounds, to account for their characteristically 'dark' or 'hard' qualities, which contrast with the 'light', 'soft' or 'sharped' nature of their palatalized equivalents (Halle 1959; Cubberley 2002). The characterization of Russian consonants as occurring in palatalized/velarized pairs has also been made through analogy with other languages which feature similar phonological contrasts, such as Marshallese (Bender 1969), Irish (Ní Chiosáin 1991) and Arabic (Catford 1988). It has also been proposed that Russian non-palatalized consonants might be velarized because the realizations $C^j$ and $C^\gamma$ represent an optimal solution to the problem of maximizing contrast between two underlyingly similar consonants, for example in Dispersion Theory (Padgett 2003), or in a phonological system predicated on relationships of "proportional opposition" (Trubetzkoy 1969).

#### The Phonetic Realization of Contrastive Palatalization

Kavitskaya (2006) has demonstrated, used gating experiments, that "cues for palatalization are at least as perceptually salient for the speakers of Russian as cues for voicing or place of articulation", which raises the question of how such a phono-

[1] The phonemic status of the vowel [ɨ] is still a matter of some debate. The existence of the minimal pair ыкать [ɨkatʲ] *'to say* ɨ*'*/икать [ikatʲ] *'to say i'*, for example, has been used to argue for the phonemic independence of the two high non-back vowels in Russian (Leed 1963).

logically robust contrast is implemented phonetically. Kochetov (2006) argues that plain and palatalized consonants are phonetically distinguished in Russian by two types of acoustic cue: primarily by their effect on the formant transitions of adjacent vowels, but also in the qualities of their release bursts.

Russian palatalized consonants are generally characterized by the presence of a raised second formant, and also some raising of the higher formants, in adjacent vowels (Halle 1959, Jakobson et al. 1963, Fant 1960). Non-palatalized (coronal) consonants, in contrast, are typically characterized by a lowered F2 and a raised F1 (Fant 2004). Similar differences between palatalized and non-palatalized consonants have been observed in other studies of Russian and other languages, which suggests that F2 transitions – rising in VC sequences and falling in CV sequences – provide a robust phonetic cue to palatization (Bondarko 1977, Purcell 1979, Padgett 2001). In high front vowel contexts palatalization appears to be cued by zero F2 transitions (Halle 1959), while plain consonants result in a falling F2, although the distinction appears to be less salient than in other vocalic environments (Jones & Ward 1969, Kochetov 2006).

Although we have a reasonable understanding of the acoustic manifestation of the Russian palatalization contrast, the articulatory basis of this distinction is not well understood. Partly due to a lack of articulatory data, many assumptions have been made about the production of Russian non-palatalized consonants, or hypotheses drawn about their articulatory characterization, based on the results of acoustic studies. A fundamental problem with this approach is that these hypotheses assume a more straightforward relationship between the acoustic properties of the speech signal and the underlying articulation than is necessarily the case. For example, based on area functions derived from X-ray images, Fant (1960) predicted a 530 Hz difference between the second formant loci of plain and palatalized coronal stops, but both he and Bondarko (1977) observed a much smaller difference in their acoustic measurements of F2 in a low vowel context (Kochetov 2006).

Fant (2004) has proposed that the formant trajectories associated with Russian non-palatalized (coronal) consonants (lowered F2, raised F1) result from the approximation of the back of the tongue to the back wall of the pharynx, and has therefore characterised these consonants as velarized. Padgett (2001) concluded that Russian (but not Irish) non-palatalized consonants are velarized by comparing the F2 trajectories of consonants produced by three speakers of Russian and Irish. Yet Ladefoged & Maddieson (1996) conclude from spectral and X-ray analysis that only in Marshallese are the non-palatalized consonants systematically velarized, and propose that only the non-palatalized lateral should be classified as velarized in Russian.

Midsagittal images of Russian consonant articulation captured in X-ray studies by Skalozub (1963) and Bolla (1981) do not show non-palatalized consonants other than the lateral to be consistently produced with a distinctively retracted or raised dorsum, which supports the conclusions of Ladefoged & Maddieson. However, because neither of these studies examined dynamic articulation in multiple vowel contexts by multiple speakers, we are not able to make strong claims about the gestural characterization of the non-palatalized consonants based on this limited data.

Kedrova et al. (2008) used MRI to examine the articulation of hard and soft consonant pairs in four speakers of Russian. They concluded that "while position and form of the tongue shape and body characteristic for every hard consonant highly depend on its role in the entire sound system of the language associated with a certain bundle of distinctive features, all soft consonants seem to be produced with a roughly similar articulatory pattern." However, the authors did not attempt to quantify the articulatory differences which they observed, and only illustrate contrasts for one speaker in the [a_a] context, so it is difficult to know what to conclude from their study.

In summary, although the acoustic properties of Russian consonants have been well described, we do not have a clear idea of the way in which mutable consonant pairs are contrastively articulated. In particular, the articulatory characterization of Russian non-palatalized consonants is not well understood – to what extent these consonants are consistently and contrastively velarized, and if so, what the precise dorsal gestural target is. This is an issue which must be addresed in a phonetic study of Russian liquids, since we will not be able to describe their goals of production without also understanding the ways in which other pairs of consonants are contrastively articulated in Russian.

## 6.2 Russian Liquids

There are four liquid consonants in Russian: two trills /r/ and /rʲ/, and two laterals /l/ and /lʲ/. All four liquids are contrastive in word-initial, intervocalic, heterorganic medial coda and word-final environments (subject to the same constraints before front vowels as the other consonants). Examples of each of these contrasts are given in Table 6.2.

| Environment | Example | IPA | Gloss |
|---|---|---|---|
| Word-Initial | рука | /ruˈka/ | *'hand'* |
| | рюкзак | /ˈrʲukzak/ | *'rucksack'* |
| | лук | /luk/ | *'onion'* |
| | люк | /lʲuk/ | *'hatch'* |
| Medial Onset | парад | /paˈrat/ | *'parade'* |
| | наряд | /naˈrʲat/ | *'costume'* |
| | палата | /paˈlata/ | *'chamber'* |
| | палят | /paˈlʲat/ | *'they scorch'* |
| Medial Coda | горка | /ˈgorka/ | *'hill'* |
| | горько | /ˈgorʲko/ | *'bitterly'* |
| | полка | /ˈpolka/ | *'shelf'* |
| | полька | /ˈpolʲka/ | *'polka'* |
| Word-Final | удар | /uˈdar/ | *'blow'* |
| | ударь | /uˈdarʲ/ | *'hit*-IMP*'* |
| | дал | /dal/ | *'gave'* |
| | даль | /dalʲ/ | *'expanse'* |

TABLE 6.2: **Liquid contrasts in Russian**

## 6.3 Evidence for the Class of Liquids

There are two main sources of evidence for the existence of a class of liquids in Russian. The liquids pattern together in phonological processes in ways that suggest they form a subclass of the sonorants. However, as in many other languages, the primary evidence for a class of liquids in Russian is their shared phonotactic distribution within the syllable.

### 6.3.1 Phonotactics of the Russian Syllable

A characteristic feature of Russian phonology is the wide range of consonant clusters which it uses. From a typological perspective, these clusters are noteworthy for their length and unusual phonotactics. Russian allows longer clusters than most languages – up to four consonants in both onsets (вскрыл [ˈfskrɨl] *'he opened'*) and codas (чёрств [tʃorstf] *'stale'*). Most remarkably, it tolerates sonorant-obstruent combinations which violate the Sonority Sequencing Principle (SSP: Sievers 1881; Kiparsky 1979), both word-initially (ртуть [r̲tutʲ] *'mercury'*) and word-finally (жезл [ʒez̲l̲] *'staff'*).

The existence of these words would seem to suggest that Russian phonological structure is not subject to the same principles of syllable-level organization which generally apply in languages which allow complex onsets and codas. However, a closer examination of the origins of SSP-violations, their distribution, and the morphophonological behavior of the words which contain them, reveals that Russian phonology is generally sensitive to a sonority hierarchy in which the liquids play an important role as a subclass of the sonorants. Because these phenomena can only be understood in a historical context, the diachronic development of Russian syllable structure will briefly be described, before the role of liquids in the phonotactics of the modern language is examined more carefully.

**Historical Origins of Russian Consonant Clusters**

The rich set of consonant clusters found in modern Russian arose from a series of phonological developments which occurred as the language emerged from Late Common Slavic (LCS). Common Slavic originally featured two high, lax vowels ь and ъ, which have been reconstructed as */ɪ/ and */ʊ/ respectively (Carlton 1991). In LCS, the jer vowels developed into weak and strong allophones, determined by their position in a word: the right-most jer becoming weak, the penultimate jer strong, continuing leftwards in an alternating pattern of weak and strong vowels (Havlík 1889, Carlton 1991). The eventual outcome of this process in the East Slavic languages was that all weak jers were deleted ('the fall of the jers'), and strong jers were strengthened ('the vocalization of the jers').

Two important outcomes of these developments in Russian were the emergence of contrastive palatalization (Padgett 2003), and the change from a canonical CV syllable structure to more complex phonotactics (Pugh 2007). The loss of jers in word-final and other positions resulted in closed syllables, and produced many monosyllabic words from earlier multisyllabic forms ([$d^j$e$n^j$] < *дьнь [dɪnɪ] *'day'*). In both onsets and codas, a number of previously unattested consonant clusters arose through widespread syncope of intervening vowels. Most remarkable of these new clusters were those sonorant-obstruent combinations in which the ordering of consonants was in violation of the SSP (Table 6.3; examples taken from Carlton 1991; Yearley 1995; Wade 1996).

Although many more examples of sonority reversals can be found in the lexicon, on the whole, these forms can be seen as historical anomalies which do not reflect syllable structure preferences in Modern Russian. Two types of evidence indicate that this is the case. Most importantly, the words which contain these problematic clusters are much rarer than words in which consonant sequencing conforms to the sonority hierarchy. Secondly, a variety of repair strategies which seek to avoid these SSP-violations can be observed in both diachronic and synchonic phonologi-

| C.Slavonic | Russian | Gloss |
|---|---|---|
| */rɪtotɪ/ | /r̯tutʲ/ | *'mercury'* |
| */rɪdiaː/ | /r̯ʒa/ | *'rust'* |
| */lɪbɪ/ | /l̯ba/ | *'forehead-gen.sg'* |
| */lɪgamu/ | /l̯gatʲ/ | *'to lie'* |
| */lɪstɪtʃɪ/ | /l̯ʲstʲets/ | *'flatterer'* |
| */bobrɪ/ | /bobr̯/ | *'beaver'* |
| */ʃɪdlʊ/ | /ʒezl̯/ | *'baton'* |

TABLE 6.3: **Russian 'reverse sonority' clusters** arising from jer deletion.

cal processes in Russian.

**Sonority Sequencing in Russian Syllable Structure**

Yearley (1995) observes that most sonority sequencing violations in Russian clusters occur at word boundaries. Medial tautosyllabic clusters, on the other hand, tend to avoid the sonority plateaus and reversals which can be found in peripheral clusters. Word-medial syllable onsets, for example, typically consist of an obstruent-sonorant sequence, e.g. [po.smer.tno] *'posthumously'*, [u.po.tre.blʲatʲ] *'to use'*. Word-medially then, Russian liquids (along with the nasals) perform the same role in syllabic organization as they do in other languages with complex onsets – acting as cluster-enabling consonants, located closer to the nucleus than the less sonorant consonants with which they combine.

In order to examine SSP-violations in more detail, a corpus analysis was conducted to determine which consonant combinations are found in Modern Russian word-peripheral clusters, and their frequencies of occurence. Three corpora were used: a list of the 10,000 most frequent words of Russian compiled by Brown (1996); the Uppsala corpus of 1 million words of written Russian (Lönngren 1993); and a list of all words with a frequency of occurence greater than one instance per million words, compiled by Sharoff (2002, 2008) from a composite corpus of 16.3 million words of written Russian.

Amongst the 10,000 most frequent words of Russian listed by Brown, 451 /r/-initial words were found; only six of these (1.3%) begin clusters, and none have a frequency ranking greater than 3327rd (рвать [rvatʲ] *'to tear'*). There are no /rʲ/-initial clusters in the corpus, although 101 words begin with the palatalized rhotic. Two lateral-initial clusters can be found in 71 /l/-initial words (лгать [lgatʲ] *'to lie'* (3725th), лживый [lʒɨvɨj] *'mendacious'* (6571st)), and only three /lʲ/-initial clusters, all of which are very low frequency (льгота [lʲgota] *'privilege'* (9272nd), льдина [lʲdʲina] *'block of ice'* (9273rd), льстить [lʲstʲitʲ] *'to flattter'* (9824th)).

Trapman (2007) notes that sonority-violating clusters were also found to occur with low frequencies in both onsets and codas in the million-word Uppsala corpus. Lexical frequency analysis of the same corpus reveals that SSP-complient onset clusters, in contrast, are ubiquitous word-initially, and that many of the most frequent words of Russian begin with obstruent-liquid clusters: для [dlʲa] *'for'* (41st most frequent), другой [drugoj] *'different, other'* (47th), слово [slovo] *'word'* (86th), глаз [glaz] *'eye'* (87th), спросить [sprositʲ] *'ask'* (108th), etc. (frequencies taken from Brown 1996).

We can gain further insights into the phonotactic preferences of Russian consonant clusters by examining even larger corpora. The frequencies of all word-peripheral obstruent-liquid and liquid-obstruent clusters found in Sharoff's 69,307 word list are listed in Fig. 6.1. The corpus was digitized to allow for automatic analysis, and Perl scripts were written to compile phonotactic statistics. Each line indicates the number of times each obstruent appeared adjacent to a liquid in word-initial and word-final clusters in the corpus. For example, 4402 words were found to begin with the cluster /pr-/, and 414 words were /pl-/-initial, but no words in the corpus begin with the combinations /rp-/ or /lp-/.[2]

| Onsets | $C^{(j)}r^{(j)}$- | $r^{(j)}C^{(j)}$- | $C^{(j)}l^{(j)}$- | $l^{(j)}C^{(j)}$- |
|---|---|---|---|---|
| p | 4402 | 0 | 414 | 0 |
| b | 321 | 0 | 280 | 5 |
| t | 626 | 0 | 3 | 0 |
| d | 208 | 0 | 42 | 8 |
| k | 678 | 0 | 262 | 0 |
| g | 501 | 0 | 226 | 8 |
| ʦ | 0 | 0 | 0 | 0 |
| ʧ | 18 | 0 | 8 | 0 |
| f | 74 | 0 | 40 | 0 |
| v | 154 | 49 | 134 | 5 |
| s | 118 | 0 | 531 | 2 |
| z | 35 | 0 | 75 | 0 |
| ʃ | 5 | 0 | 55 | 0 |
| ʒ | 13 | 18 | 2 | 6 |
| x | 142 | 0 | 80 | 0 |
| | **7295** | **67** | **2152** | **34** |

| Codas | -$C^{(j)}r^{(j)}$ | -$r^{(j)}C^{(j)}$ | -$C^{(j)}l^{(j)}$ | -$l^{(j)}C^{(j)}$ |
|---|---|---|---|---|
| p | 1 | 1 | 1 | 1 |
| b | 2 | 5 | 8 | 2 |
| t | 27 | 38 | 0 | 8 |
| d | 9 | 14 | 0 | 1 |
| k | 2 | 10 | 3 | 9 |
| g | 4 | 10 | 0 | 1 |
| ʦ | 0 | 1 | 0 | 0 |
| ʧ | 0 | 2 | 0 | 0 |
| f | 3 | 3 | 0 | 2 |
| v | 3 | 3 | 1 | 1 |
| s | 0 | 7 | 3 | 4 |
| z | 0 | 1 | 1 | 14 |
| ʃ | 0 | 3 | 0 | 1 |
| ʒ | 0 | 1 | 0 | 0 |
| x | 2 | 6 | 0 | 0 |
| | **53** | **105** | **17** | **44** |

FIGURE 6.1: Frequencies of occurence of **obstruent-liquid and liquid-obstruent onset and coda clusters** in Sharoff's (2008) corpus of most frequent words in Contemporary Standard Russian.

Based on the data summarized in Fig. 6.1, we can estimate that only 1.06% of Russian onset clusters feature sonority violations. Rhotic onset clusters are particularly

[2] In order to simplify the phonotactic analysis, palatalized/non-palatalized consonant pairs were not distinguished when compiling obstruent-liquid clustering frequencies in Fig. 6.1.

averse to SSP violations – no rhotic-stop onsets were found in the corpus, and all anomalous rhotic-initial clusters involved one of the two fricatives /v/ and /ʒ/. Sonority reversals are rather more prevalent in codas; nevertheless, coda clusters which include a liquid still show a strong preference to be obstruent-final (70.7%).

The conclusion to be drawn from the corpus analysis is that even in word-peripheral clusters, SSP-violations are relatively rare in Russian: there are many fewer words which contain these reverse-sonority clusters, and those words which do are less frequently used in the modern language than words built from SSP-compliant syllables.

In the inflectional morphophonology of Modern Russian, sonority-sequencing violations are often avoided where they would have otherwise arisen, through the use of repair strategies such as epenthesis and deletion. Pugh (2007) observes that epenthetic vowels have appeared in some words where there was no original jer, in order to avoid inherited liquid-final clusters (/sestër/ *'sister-gen.pl'* < /sestrá/). In the verbal inflectional system, the masculine singular past tense marker /-l/ never attaches directly to a consonant-final stem (e.g. ВЕСТ- [vest-] *'drive, lead'*): either the stem-final consonant deletes ([vʲel] *'drove'*-M.SG.DEF.IMPF), or an vowel-final or epenthetic allomorph is used ([vodʲil] *'drove'*-M.SG.INDEF.IMPF) to avoid the infelicitous cluster. Allomorphy of this type suggests that liquid-obstruent clusters which violate the sonority sequencing principle are generally dispreferred in Russian.

Collectively, these data show that the modern lexicon of Russian demonstrates an overwhelming preference for syllable structures in which onsets, and to a lesser extent also codas, conform to typologically-standard sonority sequencing principles.

**The Role of Liquids in Russian Cluster Phonotactics**

In many of the phonotactic phenomena described so far, the liquids pattern with the other sonorants in terms of their distribution with respect the obstruents. Additional evidence for the existence of a separate class of liquids may be found when we examine the phonotactics of clusters more closely.

A list of all two-consonant word-initial onset clusters, along with the number of times they are found in the Sharoff (2008) corpus, has been compiled in Fig. 6.2. The data reveal an overwhelming preference for sonorant-final clusters (71.5%), rather than obstruent-obstruent onsets (28.5%). Furthermore, the data show that liquids are the prefered cluster-enabling consonant in Russian word-initial syllable onsets of this complexity: 64.2% of all #CC- clusters are liquid-final, while only 7.2% are nasal-final.

| CL- | n | CC- | n | CF- | n | CN- | n |
|---|---|---|---|---|---|---|---|
| pr | 4396 | st | 878 | sv | 497 | sm | 311 |
| kr | 678 | sp | 439 | dv | 181 | sn | 177 |
| tr | 624 | sk | 303 | zv | 140 | zn | 153 |
| sl | 531 | sʧ | 184 | vz | 91 | vn | 121 |
| gr | 500 | sd | 115 | vs | 88 | gn | 67 |
| pl | 414 | ʃt | 91 | tv | 77 | mn | 57 |
| br | 321 | sb | 81 | ps | 73 | kn | 56 |
| bl | 280 | ʃk | 59 | xv | 60 | dn | 33 |
| kl | 262 | zd | 54 | kv | 51 | vm | 20 |
| gl | 225 | vp | 51 | rv | 49 | xm | 17 |
| dr | 207 | vt | 45 | ʦv | 44 | ʃn | 12 |
| vr | 154 | vd | 34 | sʒ | 35 | zm | 11 |
| xr | 141 | vk | 33 | sx | 32 | ʃm | 8 |
| sr | 118 | sg | 30 | ʃv | 31 | pn | 8 |
| vl | 134 | pt | 26 | vv | 30 | ʒm | 6 |
| xl | 80 | ʃp | 26 | vx | 28 | tm | 5 |
| fr | 73 | sʦ | 19 | dʒ | 21 | ʧm | 3 |
| zl | 75 | vʧ | 15 | gv | 20 | xn | 1 |
| dl | 42 | ʒd | 13 | rʒ | 18 | | |
| ʃl | 35 | ʦʧ | 12 | sf | 13 | | |
| fl | 40 | ʒg | 10 | pʃ | 7 | | |
| zr | 35 | ʧt | 10 | lʒ | 6 | | |
| mr | 32 | rt | 9 | sʃ | 6 | | |
| nr | 31 | ld | 8 | lv | 5 | | |
| ml | 19 | tk | 7 | mx | 4 | | |
| ʧr | 18 | vb | 7 | ʃx | 4 | | |
| ʒr | 13 | mʧ | 6 | vʃ | 3 | | |
| ʧl | 8 | lb | 5 | ʒv | 2 | | |
| ʃr | 5 | bd | 5 | kx | 1 | | |
| ʒl | 2 | vʦ | 5 | vʒ | 1 | | |
| tl | 3 | lg | 4 | ms | 1 | | |
| | | lg | 4 | sz | 1 | | |
| | | pʧ | 3 | tf | 1 | | |
| | | gd | 1 | dz | 1 | | |
| | | ʒb | 1 | | | | |
| | | zt | 1 | | | | |
| | | xt | 1 | | | | |
| | | kt | 1 | | | | |
| | 9496 | | 2596 | | 1622 | | 1066 |

FIGURE 6.2: **Russian two-consonant word-initial clusters** and frequencies of occurence in Sharoff (2008). Onsets grouped by column into liquid-final, stop-final, fricative-final and nasal-final clusters.

As cluster complexity increases, consonant sequencing in Russian clusters becomes even more constrained, and further asymmetries between liquids and the other sonorants are revealed. Frequencies of occurence of all three-consonant word-initial clusters found in Sharoff (2008) are given in Fig. 6.3. The preference for sonorant-final clusters (75.9%) is even greater in onsets of this complexity, and 95% of all three-consonant sonorant-final clusters end with a liquid (e.g. взрыв [vzrɨv] '*explosion*'), вклад [fklad] '*contribution*', справка [sprafka] '*information*').

Russian four-consonant onset clusters are much rarer, but even more highly constrained: all onsets of this length consist of a #FFCL- sequence (e.g. взброс [vzbros] '*upthrust*', всплеск [fsplesk] '*splash*'). No four-consonant clusters can be formed with a nasal in Russian.

| CCL- | n | CCC- | n | CCN- | n |
|---|---|---|---|---|---|
| str | 391 | vsp | 62 | vzm | 17 |
| skr | 108 | vst | 54 | mgn | 11 |
| spr | 105 | vzv | 36 | tkn | 6 |
| skl | 68 | vzd | 34 | vsm | 7 |
| vkl | 35 | vsk | 29 | vzn | 3 |
| vzr | 33 | skv | 24 | sgn | 1 |
| spl | 21 | sdv | 20 | | |
| vzl | 17 | stv | 12 | | |
| zdr | 16 | vzb | 8 | | |
| sbr | 13 | mst | 7 | | |
| vpr | 14 | vdv | 3 | | |
| vgl | 9 | mzd | 1 | | |
| vsl | 8 | vzg | 1 | | |
| mgl | 5 | kst | 1 | | |
| vkr | 5 | | | | |
| sbl | 4 | | | | |
| vdr | 3 | | | | |
| sgl | 3 | | | | |
| vpl | 3 | | | | |
| vtr | 2 | | | | |
| sgr | 2 | | | | |
| sdr | 2 | | | | |
| smr | 2 | | | | |
| stl | 2 | | | | |
| vbl | 1 | | | | |
| vbr | 1 | | | | |
| | 873 | | 292 | | 45 |

FIGURE 6.3: **Russian three-consonant word-initial clusters** and frequencies of occurence in Sharoff (2008). Onsets grouped by column into liquid-, obstruent- and nasal-final clusters.

Further asymmetries between the liquids and the nasals become apparent when we consider sonorant-sonorant clusters in Russian. The frequencies of all nasal-liquid and liquid-nasal clusters found in the Sharoff corpus are tabulated in Fig. 6.4. The data reveal an overwhelming preference for liquid-internal clusters – only three sonority reversals were found amongst the 113 sonorant-sonorant clusters in the corpus. These data provide further evidence that the liquids, by virtue of their clustering properties with respect to nasals, behave as subclass of the Russian sonorants.

| Onsets | $N^{(j)}r^{(j)}$- | $r^{(j)}N^{(j)}$- | $N^{(j)}l^{(j)}$- | $l^{(j)}N^{(j)}$- |
|---|---|---|---|---|
| m | 32 | 0 | 22 | 0 |
| n | 31 | 0 | 0 | 1 |
| | **63** | **0** | **22** | **1** |

| Codas | -$N^{(j)}r^{(j)}$ | -$r^{(j)}N^{(j)}$ | -$N^{(j)}l^{(j)}$ | -$l^{(j)}N^{(j)}$ |
|---|---|---|---|---|
| m | 0 | 14 | 1 | 4 |
| n | 1 | 4 | 0 | 3 |
| | **1** | **18** | **1** | **7** |

FIGURE 6.4: Frequencies of occurence of **Russian nasal-liquid and liquid-nasal onset and coda clusters** in Sharoff's (2008) corpus of most frequent words in CSR.

### 6.3.2 Diachronic Processes Involving Liquids

In Section 6.3.1, the syllable-level phonotactics of Russian were examined to demonstrate that the liquids function as a distinct class of sonorants by virtue of their distribution in clusters. Diachronic evidence may also be found for a class of liquids: the rhotics and laterals, uniquely amongst the sonorants, patterned together in a number of historical sound changes which have reflexes in modern Russian. Two of the most important of these sound changes are briefly mentioned here.

#### Preservation of Liquid-Adjacent Jers

Where jers followed liquids in medial positions, they disappeared completely in Southern Slavic, leaving syllabic liquids. In North Eastern Slavic, jers were preserved and strengthened in the same position, leaving liquid-vowel sequences in Modern Russian (Bethin 1998; Table 6.4).

| PROTO-SLAVIC | SOUTH CENTRAL LCS | NORTH EAST LCS |
|---|---|---|
| */kruu̯i/ *'blood'* | Macedonian /kr̩v/ | Russian /krovʲ/ |
| */sliza/ *'tear (n.)'* | Czech /sl̩za/ | Russian /slʲeza/ |

TABLE 6.4: **Development of liquid-jer sequences** in Slavic (Bethin 1998).

Such changes were not restricted to post-liquid vowels – Bethin (ibid.) notes a general trend in which "Russian tended to preserve jers in the vicinity of liquids", which does not hold for the other sonorants. Thus we find Late Common Slavonic *CVL.C sequences preserved in Modern Russian but collapsed into syllabic liquid forms (CV̩C) in their cognates in the Southern languages (Table 6.5, examples taken from Carlton 1990; Bethin 1998).

| PROTO-SLAVIC | SOUTH CENTRAL LCS | NORTH EAST LCS |
|---|---|---|
| */pɪrstʊ/ *'finger'* | Serbian /pr̩st/ | Russian /pʲerst/ |
| */vɪlkʊ/ *'wolf'* | Czech /vl̩k/ | Russian /volk/ |
| */gʊrba/ *'hump'* | Macedonian /hr̩b/ | Russian /gorb/ |
| */sɪrpʊ/ *'sickle'* | Slovenian /sr̩p/ | Russian /sʲerp/ |

TABLE 6.5: **Preservation of pre-liquid jers** in North Eastern Slavic.

#### Liquid Metathesis

Where liquids followed the mid-back vowel in Proto-Slavic sequences of the form *#oLC, many of these sequences have metathesized in the daughter forms found in Modern Russian. This sound change was a process which affected both coda rhotics and laterals (Table 6.6), but not the other sonorants.

| PROTO-SLAVIC | RUSSIAN |
|---|---|
| */orv-mʊ/ *'even'* | /rov(e)n/- |
| */ordlo/ *'plough'* | /ralo/ |
| */olkotɪ/ *'elbow'* | /lok(o)t/- |
| */olk-omʊ/ *'hungry'* | /lakom/- |

TABLE 6.6: **Metathesis of vowel-liquid sequences in Russian** (adpated from Cubberley 2002)

### 6.3.3 Asymmetries between Russian Laterals and Rhotics

In all of the phonological phenomena reviewed so far, both laterals and rhotics participate in the same processes, or share the same distribution; however, there are also some asymmetries within the class of liquids which should be considered.

The Russian palatalized trill depalatalizes before homorganic consonants, while the palatalized lateral does not: e.g. царь [tsar$^j$] *'tsar (n)'* but царский [tsarsk$^j$ij] *'tsar (adj)'*; c.f. боль [bol$^j$] *'pain'* and больнои [bol$^j$noj] *'ill'* (Kochetov 2005). Kochetov observes that palatalized rhotics are also more susceptible to depalatalization than palatalized laterals in Irish and Ukranian.

In Russian consonant clusters, palatalized consonants commonly trigger progressive assimilations. However, in some varieties of Russian (e.g. Perm), only the palatalized lateral assimilates preceding non-palatalized coronals, while the palatalized trill does not: /pet$^j$l$^j$i/ *'loop-PLU'*, but /smotr$^j$it/ *'(he) looks'* (Kochetov 2005).

### 6.3.4 Summary – The Status of the Class of Liquids in Russian

In this section, phonological and phontactic evidence has been presented to argue for the existence of a class of liquids in Russian. Rhotics and laterals have patterned together in processes including metathesis, and preservation of adjacent vowels.

However, as in many other languages, the primary evidence for a class of liquids in Russian is their shared distribution within the syllable. In complex onsets, and to a lesser extent in complex codas, liquids serve as cluster-enabling segments, typically (and often mandatorily) filling the position closest to the syllable nucleus. Although cases of sonority sequencing violations may be found in Russian, these words have been shown to be historical relics with low frequencies of occurance, which do not reflect the syllable structure preferences of the modern language.

If, as this evidence suggests, the defining characteristic of the class of liquids in Russian is their distribution within the syllable, this raises the question of whether there might be a phonetic basis to the class. Before considering ways in which to test this question experimentally, previous investigations into the phonetics of Russian liquids will briefly be surveyed.

## 6.4 Phonetic Studies of Russian Liquids

The most comprehensive articulatory study of Russian liquids was conducted by Fant (1960), who used midsagittal X-rays to examine the production of a single set of Russian consonants by a 38 year old male Moscovite. X-ray and palatographic studies of Russian liquids have also been conducted by Matusevich (1976), Skalozub (1963), and Bolla (1981). Kochetov (2005) used Electromagnetic Midsagittal Articulatometry (EMMA; Perkell et al. 1992) to examine word-final liquids produced by three female speakers of Russian speakers.

A basic picture of the essential articulatory characteristics of the four Russian liquids can be gleaned from the collective findings of these studies. The coronal articulation of the laterals appears to be dental-alveolar, while both rhotics are produced with a more retracted coronal contact in the alveolar region. The coronal gesture of each of the non-palatalized liquids is generally reported to be apical, while that of the palatalized liquids appears to be laminal to some extent.

Both palatalized liquids are produced with a central dorsal gesture in these studies: relatively open for the lateral, and a high narrow dorsal approximation in the mid-palatal region in the case of the trill. The non-palatalized lateral was produced with an uvular-pharyngeal/upper pharyngeal approximation of the back of the tongue, while the non-palatalized trill was generally accompanied by a high-back dorsal gesture in the uvular region. For the speaker in Fant's (1960) study, both rhotics appear to have been produced with a more constricted tongue root than the laterals.

Although these studies have provided valuable insights into the articulation of

Russian liquids, each is also limited in some important respects. Other than Kochetov (2005), each of these studies examined the speech of only a single speaker, and in most cases, only one sustained token of each consonant was imaged, produced independently of any context vowel. None of the X-ray studies provide dynamic data about the formation and release of the consonants, and Kochetov does not examine the dynamics of intervocalic liquids. As with all EMMA studies, the location of the tongue inbetween tranceiver fleshpoints cannot be directly determined, and must be interpolated.

## 6.5 Summary

In this chapter, the consonantal phonology of Russian has been reviewed, and the behavior of liquid consonants within this system has been described. Diachronic phonological evidence, and evidence from the syllable-level phonotactics has been presented to argue for the existence of a class of liquids in Russian. Two important properties of this class are a preference to appear closer to the nucleus in the organization of clusters, and a tendency to interact with the nucleus (metathesis, liquid diphthongs, interaction with the jers).

A survey of the phonetic literature has revealed a lack of articulatory data on Russian consonants in general, and liquids in particular. More data is required to better understand nature of the palatalized/non-palatalized contrast, and the goals of production of the liquids. In Chapter 7, an experimental study designed to shed more light on the phonetic characterization of the class of Russian liquids will be described. The goal of this study is to examine the dynamic articulation of the four liquids of Russian, and in particular:

i. compare the production of the liquids with the production of coronal obstruents in Russian
ii. characterize the articulatory realization of the palatalized/non-palatalized consonantal contrast
iii. compare the dorsal articulation of the liquids with that of the non-palatalized obstruents

# Chapter 7

# Experimental Investigation of Russian Liquid Production

In this chapter, an experiment examining the phonetics of Russian liquid consonants will be described. The broad aim of this experiment is to come to a better understanding of the goals of production of Russian liquids through an examination of dynamic articulatory and acoustic data.

Evidence from previous studies reviewed in Chapter 2 indicates that liquid approximants in English and other languages are produced with dorsal and pharyngeal gestures, and in Chapter 4 experimental evidence was presented showing that the coronal liquid consonants of Spanish are produced with an vowel-like dorsal gesture. In Chapter 6, it was shown that rhotics and laterals constitute a phonological class in Russian, by virtue of their common phonotactic distribution in the syllable and their shared participation in some phonological processes.

In this chapter, we will consider the extent to which the class-like behavior of the Russian liquids might be grounded in the phonetic domain. The hypothesis to be examined is that the Russian trills and laterals share the common property of being produced with a dorsal gesture, although it remains to be seen exactly how the palatalized liquids differ from their non-palatalized counterparts.

## 7.1 Method

A high-speed ultrasound study was conducted to compare liquid and stop consonant production by four speakers of Contemporary Standard Russian. Articulatory and acoustic data were acquired using the HOCUS system described in Section 4.2.

### 7.1.1 Subjects

Four native speakers of Russian – three female and one male – participated in the experiment.[1] All subjects were born in the Soviet Union or Russian Federation, and raised in an environment in which standard Russian was spoken. Two subjects (M1, W1) are L1 speakers of Russian with varying degrees of competence in English as a second language. Subject W2 is an L1 speaker of Russian, an L2 speaker of Kyrgyz, and has some competence in English as a third language. Subject W3 is a bilingual speaker of Russian and American English. Subjects' ages ranged from 18 to 32 years at the time of the study (Table 7.1). Subjects were paid for their participation in the experiment, and were naïve as to the purpose of the experiment.

| Subject | Age | Hometown | Other Languages | Time in US |
|---|---|---|---|---|
| M1 | 24 | Kadamjay, Kyrgyzstan | US English, Turkish | 2 years |
| W1 | 32 | Kiev, Ukraine | US English, Ukrainian | 7 years |
| W2 | 23 | Bishkek, Kyrgyzstan | Kyrgyz, US English | 6 months |
| W3 | 18 | Zelenograd, Russia | US English | 16 years |

Table 7.1: **Participants in Russian liquids study.**

### 7.1.2 Experimental Procedure

Seated participants were asked to read out lists of pseudo-words presented in large font Cyrillic script. The experimental protocol was the same as that used in the Spanish liquids experiment, described in detail in Chapter 4: tongue motion was captured using ultrasound at 127 frames per second, speech was recorded at 22kHz, and the audio and video were later aligned from a synchronization pulse introduced into each signal. Midsagittal lingual articulation was analyzed using the method described in Section 4.2.4.

[1] One additional male Russian speaker participated in the experiment, but because the ultrasound images were not of sufficient quality, data from Subject M2 could not be included in the analysis.

### 7.1.3 Corpora

Russian coronal consonants were elicited in intervocalic environments in order to determine the salient articulatory differences between liquids and stops, and palatalized and non-palatalized coronal consonants.

Each of the four Russian liquids /r/-/rʲ/-/l/-/lʲ/ was elicited in four different intervocalic environments: front [e_e], back [u_u], low [a_a] and high [i_i/ɨ].[2] Voiced stops /d/-/dʲ/ were elicited in the same contexts for comparison. Artificial stimuli were used to ensure that each segment appeared in an identical phonological environment, and to reduce lexical frequency and prosodic effects as much as possible. The full experimental corpus is listed in Table D.1.

### 7.1.4 Dynamic Analysis of Lingual Articulation

The midsagittal profile of the tongue was tracked over time. For each consonant token, a sequence of frames was extracted from the ultrasound video, starting from the midpoint of the preceding vowel and extending to the midpoint of the post-consonantal vowel. Within this interval of 250 to 450 msec, every third video frame was selected, cropped, and corrected for head movement, resulting in a sequence of 12 to 22 video frames (depending on the duration of the utterance) sampled at 42.3 Hz.

Each video sequence was processed using EdgeTrak software (Li et al. 2005) and manually corrected where necessary. The resulting sequence of tongue edges was color-coded and superimposed on the same plot, producing a graphical representation of the tongue movement throughout the production of each VCV sequence.

In each of the following plots, the x- and y- axes represent horizontal and vertical displacement in millimeters from an arbitrary but consistent origin, and each of the colored curves represents the location of the midsagittal tongue edge at a given point in time. For each VCV token, the temporal origin was chosen at the midpoint of consonantal articulation. The formation of the consonantal closure is shown in frames with negative time values, and the consonantal release is captured in the sequence of frames with positive time values.

[2] Vowel contexts cannot be not perfectly balanced in Russian, because all consonants which appear before the vowel [i] are inherently palatalized, and the high front vowel appears as the allophone [ɨ] after non-palatalized consonants. Although the high front vocalic context provides the greatest articulatory contrast with the other vocalic environments, consonants produced in this environment were often poorly imaged by the ultrasound, and tongue edges could not be consistently identified for all tokens and all subjects. For this reason, the mid-front vowel context [e_e] was used to contrast with [u_u] and [a_a].

## 7.2 Results: Articulation of Non-Palatalized Coronal Consonants

### Articulation of Non-Palatalized Stops

The articulation of the token [ada] by a speaker of Russian is illustrated in Fig. 7.1. The first half of the sequence – ten frames beginning at the mid-point of the pre-consonantal vowel (yellow) and ending at the point of consonantal closure (red) – is illustrated in the left panel (-213 to 0 ms). The second half of the production sequence – ten frames commencing at the point of stop release (red) and ending at the midpoint of articulation of the post-consonantal vowel (yellow) – is shown in the right panel (0 to 189 ms).

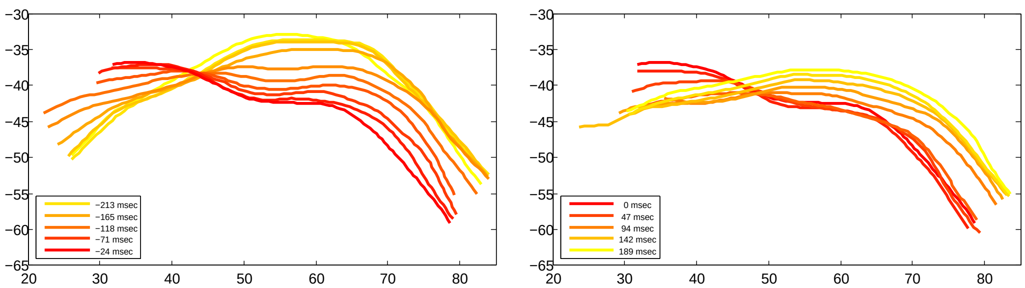



FIGURE 7.1: **Dynamic midsagittal lingual articulation of Russian non-palatalized coronal stop: [ada]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

The lingual motion captured in Fig. 7.1 reveals that the tongue dorsum begins and ends in a retracted position corresponding to the pharyngeal articulation of the context vowel. During stop closure, the dorsum is pulled forward and allowed to drop, but the back of the tongue remains shaped and broadly positioned in a lowered and retracted posture corresponding to the articulatory target of the context vowel /a/.

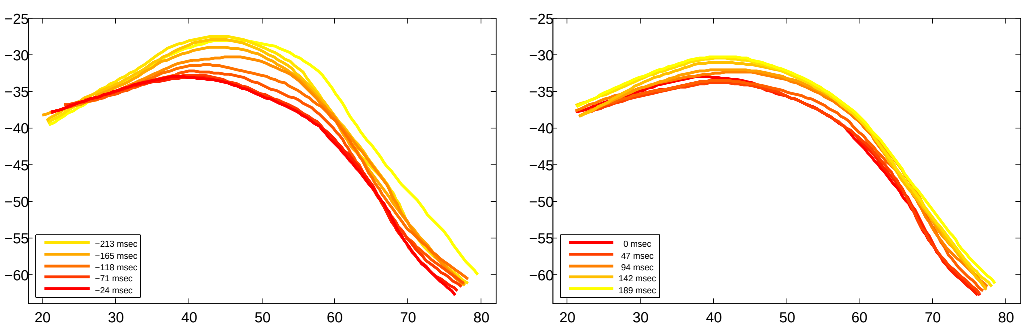



FIGURE 7.2: **Dynamic midsagittal lingual articulation of Russian non-palatalized coronal stop: [ede]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

Articulation of the voiced coronal stop by the same speaker in a front vowel context [ede] is illustrated in Fig. 7.2. Throughout the whole sequence, the tongue dorsum remains in an advanced position corresponding to the wide palatal target of the context vowel. As also observed in the back vowel context, the dorsum lowers (7 mm) and fronts (6 mm) during the formation of the stop – a total displacement of 9 mm in the direction dictated by the requirements of the coronal closure.

Similar patterns of articulation were observed in the other two vowel contexts, and for all four Russian subjects. In summary, all tongue body movement observed during the production of medial onset voiced coronal stops was consistent with one of two articulatory goals: maintaining the dorsal posture associated with the context vowel, and achieving coronal closure of the stop.

### Articulation of Non-Palatalized Rhotics

The production of the Russian non-palatalized trill involves a different pattern of lingual movement to that observed in stop production. During trill formation (Fig. 7.3, left panel), the anterior lingual dorsum fronts to a raised, mid-oral position, while the posterior lingual dorsum advances slightly into a stable posture which is maintained throughout. The second half of the sequence is characterized by a remarkable degree of dorsal stability, during which the body of the tongue maintains a raised, advanced posture which is antagonistic to the pharyngeal target constriction of the context vowel (Fig. 7.3 right).

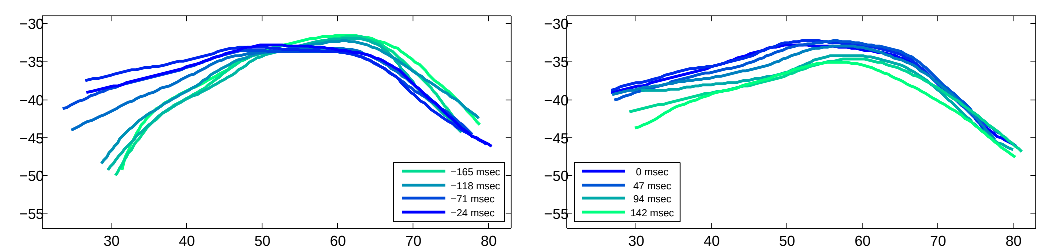



FIGURE 7.3: **Dynamic midsagittal lingual articulation of Russian non-palatalized trill: [ara]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

The independence of the rhotic dorsal constriction target can be seen even more clearly from the lingual trajectory of subject M1 producing the non-palatalized trill in the same context (Fig. 7.4): approximately 100 msec before the first coronal contact the dorsum raises to a mid-back position, where it remains throughout the trill produciton.

Trill articulation in a front vowel context is illustrated in Fig. 7.5. Dorsal motion is in the opposite direction to that observed during the production of the stop in

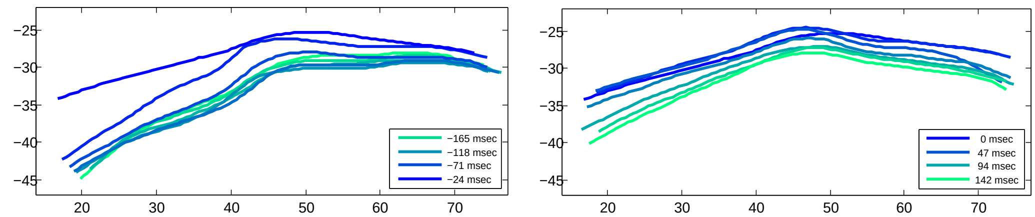



FIGURE 7.4: **Dynamic midsagittal lingual articulation of Russian non-palatalized trill: [ara]** – subject M1. Left panel: consonant formation; Right panel: consonantal release.

the same context (Fig. 7.2): during trill formation (Fig. 7.5 left) the apex of the tongue dorsum retracts (and raises) 10 mm. Since this is movement counter to that required for context vowel articulation or coronal closure, the data suggests that the tongue dorsum is being actively recruited in the production of the trill.

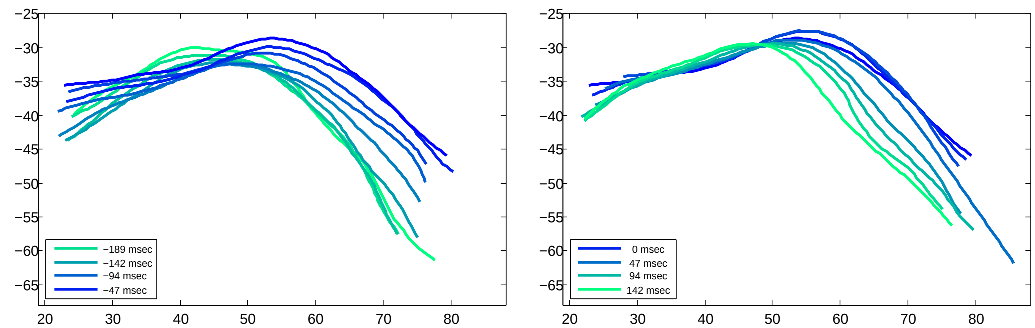



FIGURE 7.5: **Dynamic midsagittal lingual articulation of Russian non-palatalized trill: [ere]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

### Articulation of Non-Palatalized Laterals

Even greater dorsal articulatory independence can be observed in the production of the Russian lateral (Fig. 7.6). Articulation of the posterior lateral constriction, located in the uvular-pharyngeal region (x = 71, y = -35), involves dorsal raising and retraction from the constriction posture associated with the pharygeal context vowel. Like the trill, and unlike the coronal stop, the production of the lateral is characterized by greater stability in the upper pharayngeal region ($75 < x < 90$mm) throughout the entire VCV token.

The same broad pattern of articulation observed in the trill can be seen during the production of the lateral in the front vowel context (Fig. 7.7). In this case, the dorsal gesture is even more pronounced than that observed in the trill: a retraction of 21 mm towards an uvular-pharyngeal target can be observed. The two non-palatalized liquids produced in the mid-front vowel context by speaker W3 exhibit

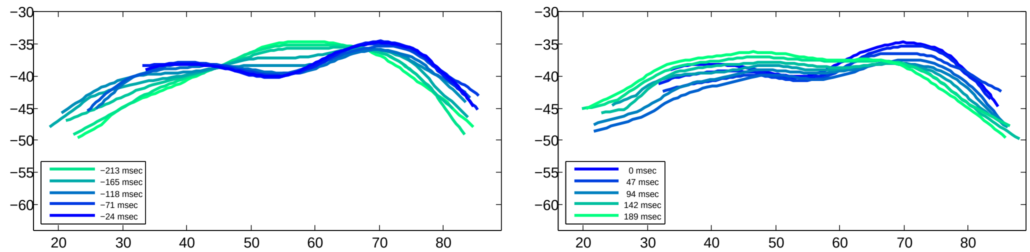



FIGURE 7.6: **Dynamic midsagittal lingual articulation of Russian non-palatalized lateral: [ala]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

a remarkable symmetry in their overall patterns of dynamic midsagittal articulation.

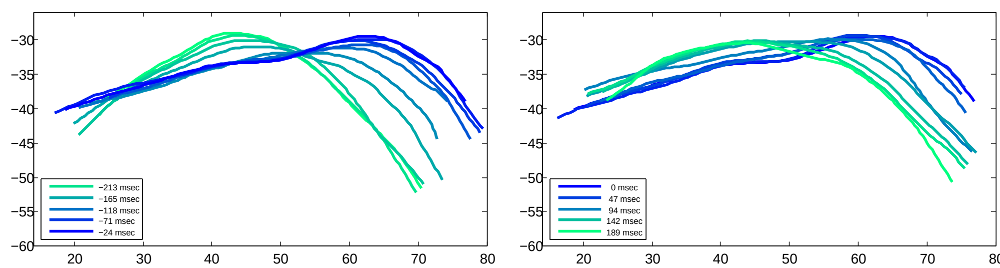



FIGURE 7.7: **Dynamic midsagittal lingual articulation of Russian non-palatalized lateral: [ele]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

### 7.2.1 Results – Comparison of Midconsonantal Dorsal Articulation

The dynamic analysis of Russian non-palatalized consonant production presented so far has revealed that one of the most important differences between the non-palatalized obstruents and liquids appears to be the way in which the tongue dorsum is articulated. In order to quantify this difference, the dorsal articulation at the mid-point of consonantal production can be compared across vowel contexts.

**Effect of vowel context on stop articulation.**

A comparison of the midsagittal articulation of the coronal stop uttered in three different vowel contexts by subject F3 is shown in Fig. 7.8. Tongue edges captured from two productions each of the tokens [ada], [ede] and [udu] have been superimposed in each panel. The tongue shapes in the left panel are taken from the first frame in the sequence, corresponding to the midpoint of the pre-consonantal vowel; those in the central panel are taken from the middle frame, corresponding to the mid-consonantal articulation; the tongue edges in the right frame are taken from the last frame in the sequence, corresponding to the midpoint of articulation of the post-consonantal vowel.

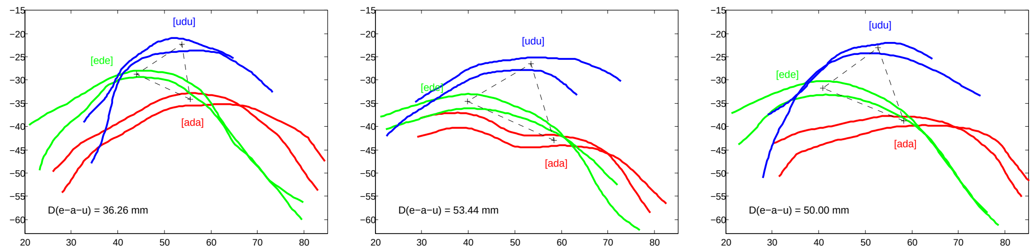



FIGURE 7.8: **Midsagittal lingual articulation of Russian non-palatalized coronal stops in three different vowel contexts**: [ada] (red), [ede] (green) and [udu] (blue) – subject W3. Left panel: pre-consonantal vocalic articulation; center panel: mid-consonantal articulation; right panel: post-consonantal vocalic articulation

The most important observation to be made about the stop production is that the tongue dorsum does not converge on a common constriction, but remains articulated in the gesture corresponding to the context vowel – low and back in the [ada] context, mid-front in the [ede] context, and high and back in the [udu] context.

### Effect of vowel context on liquid articulation.

A comparison of the midsagittal articulation of a Russian non-palatalized trill uttered in three different vowel contexts by subject F3 is shown in Fig. 7.9. Two productions each of the tokens [ara], [ere] and [uru] have been superimposed in each panel: pre-consonantal (left), mid-consonantal (middle), and post-consonantal articulation (right). In Fig. 7.10, two productions each of the tokens [ala], [ele] and [ulu] have been superimposed to compare the midsagittal articulation of the non-palatalized lateral uttered in three different vowel contexts by subject F3.

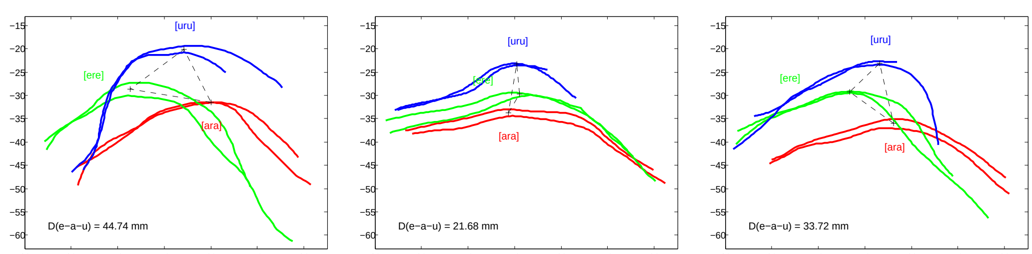



FIGURE 7.9: **Midsagittal lingual articulation of the Russian non-palatalized trill in three different vowel contexts**: [ara] (red), [ere] (green) and [uru] (blue) – subject W3. Left panel: pre-consonantal vocalic articulation; center panel: mid-consonantal articulation; right panel: post-consonantal vocalic articulation

Unlike in the stop production, the midconsonantal dorsal articulation of each liquid converges towards a central location. For speaker W3, the dorsal target con-

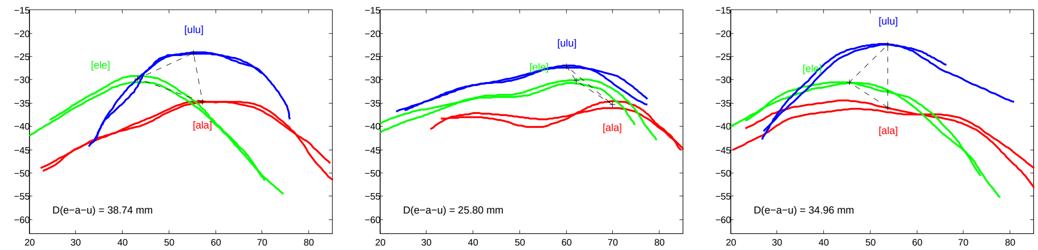



FIGURE 7.10: **Midsagittal lingual articulation of the Russian non-palatalized lateral in three different vowel contexts**: [ala] (red), [ele] (green) and [ulu] (blue) – subject W3. Left panel: pre-consonantal vocalic articulation; Center panel: mid-consonantal articulation; Right panel: post-consonantal vocalic articulation

striction for the trill appears to be in the vicinity of a mid-central vowel, while the target constriction for the lateral appears to be in the vicinity of a mid-back vowel.

### Quantification of Vowel-Consonant Coarticulation

The effect of vocalic coarticulation on consonantal production was quantified by calculating the area of a triangle constructed between the dorsal apices of consonants produced in different intervocalic environments. Differential dorsal displacements of Russian non-palatalized coronal stops and liquids, calculated using the method described in Section 4.3.6, are given in Fig. 7.11.

| w1 | V | C | V | w2 | V | C | V | w3 | V | C | V | m1 | V | C | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| /d/ | 88.2 | 37.4 | 79.0 | /d/ | 72.6 | 73.8 | 94.3 | /d/ | 84.7 | 129.1 | 126.5 | /d/ | 19.4 | 22.1 | 46.0 |
| /d/ | 57.8 | 47.5 | 51.3 | /d/ | 57.0 | 40.6 | 69.2 | /d/ | 53.4 | 147.4 | 116.3 | /d/ | 50.8 | 24.5 | 88.8 |
| /l/ | 98.5 | 20.3 | 43.8 | /l/ | 43.8 | 27.9 | 72.4 | /l/ | 73.1 | 3.6 | 44.4 | /l/ | 72.3 | 2.6 | 55.3 |
| /l/ | 80.6 | 22.0 | 36.6 | /l/ | 42.3 | 26.8 | 78.6 | /l/ | 87.5 | 10.8 | 4.9 | /l/ | 87.6 | 12.1 | 143.8 |
| /r/ | 93.8 | 6.9 | 44.8 | /r/ | 61.5 | 56.1 | 72.0 | /r/ | 88.2 | 8.4 | 49.3 | /r/ | 20.1 | 10.4 | 2.0 |
| /r/ | 71.7 | 31.2 | 69.3 | /r/ | 41.1 | 31.2 | 44.1 | /r/ | 81.7 | 12.9 | 46.2 | /r/ | 125.1 | 10.6 | 8.3 |
| Stop | 73.0 | 42.5 | 65.1 | Stop | 64.8 | 57.2 | 81.8 | Stop | 69.0 | 138.2 | 121.4 | Stop | 35.1 | 23.3 | 67.4 |
| Liquid | 86.1 | 20.1 | 48.6 | Liquid | 47.2 | 35.5 | 66.8 | Liquid | 82.6 | 8.9 | 36.2 | Liquid | 76.3 | 8.9 | 52.3 |

FIGURE 7.11: **Consonantal susceptance to vocalic coarticulation**, as measured by total dorsal displacement ($mm^2$) across three vowel contexts [e_e]-[a_a]-[u_u] – all subjects.

To compare susceptance to vocalic coarticulation across subjects, the data in Fig. 7.11 were normalized by dividing by the maximum dorsal displacement for each subject; mean normalized dorsal displacements were then calculated for each consonant across the experimental population, and are compared in Fig. 7.12.

As with the Spanish intervocalic coronal consonants, two main effects can be observed in these data:

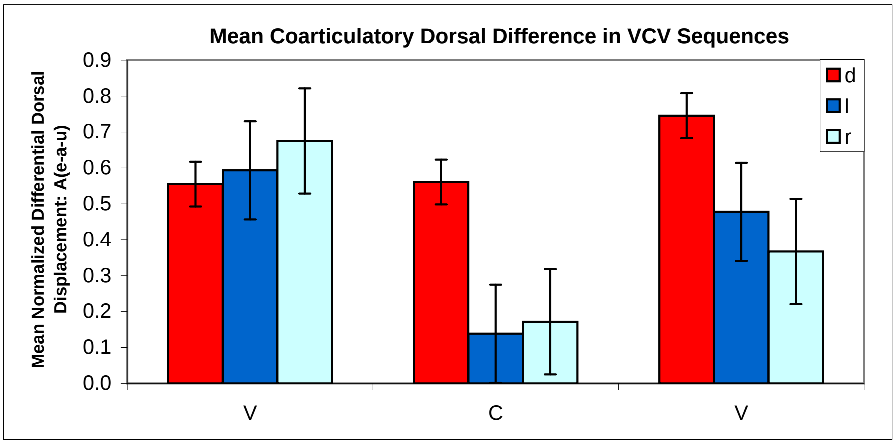



FIGURE 7.12: **Mean normalized differential dorsal displacement**: Russian non-palatalized coronal consonants – all subjects.

i. the effect of vocalic coarticulation (as measured by differential dorsal displacement in the consonant) is greater during the production of stops than liquids

ii. the effect of consonantal coarticulation on the post-consonantal vowel (as measured by differential dorsal displacement) is greater for liquids than stops

To examine these observations more closely, two tests were conducted:

i. a *one-way analysis of variance test* of the null hypothesis that dorsal coarticulatory effects (as measured by the differential dorsal displacement data) are the same for Russian coronal stops and liquids

ii. a *two-sided Wilcoxon rank sum test* of the null hypothesis that the differential dorsal displacement data for stops and liquids are independent samples from identical continuous distributions with equal medians, against the alternative that they do not have equal medians

The results of these tests are shown in Table 7.2. Both tests *accept* the null hypothesis that coarticulation does not differ between stops and liquids during the production of the pre-consonantal vowel (first column). Both tests reject the null hypothesis (at a 0.01 significance level) that coarticulatory differences in dorsal articulation do not differ for stops and liquids during mid-consonantal production (second column). Both tests reject the null hypothesis (at a 0.05 significance level) that coarticulatory differences in dorsal articulation do not differ for stops and liquids during post-consonantal production (third column).

These results suggest that, for Russian intervocalic non-palatalized coronal consonants:

| TEST | $V1_{stop}$ = $V1_{liq}$ | $C_{stop}$ = $C_{liq}$ | $V2_{stop}$ = $V2_{liq}$ |
|---|---|---|---|
| ANOVA | 0 (p=0.2563) | 1 (p = 0.0013) | 1 (p = 0.0284) |
| Rank Sum | 0 (p=0.2573) | 1 (p = 0.0020) | 1 (p = 0.0156) |

TABLE 7.2: **Hypothesis testing of Russian differential dorsal displacement by class** – Coronal Stops vs. Liquids. 1st column: dorsal displacement amongst pre-consonantal vowels; 2nd column: mid-consonantal dorsal displacement; 3rd column: dorsal displacement amongst post-consonantal vowels.

i. VCV sequences are syllabified as V.CV
ii. there is little anticipatory coarticulatory influence of any of the consonants on the preceding vowel
iii. dorsal articulation of coronal stops is a function of the context vowels
iv. dorsal articulation during liquid production is primarily due to components intrinsic to the consonant
v. there is no significant coarticulatory effect of the stops on the following vowel
vi. there is a significant coarticulatory effect of the liquids on the following vowel

**Location of Liquid Dorsal Gestures**

Evidence from the ultrasound data considered so far indicates that Russian non-palatalized liquids, but not coronal stops, are articulated with a dorsal gesture. We now consider the target location of this gesture, and how it differs between rhotics and laterals. As in the Spanish study, we can quantify the relative locations of the gestural targets for Russian liquids by calculating dorsal displacement from a nominal point chosen in the center of the lingual articulatory space, corresponding approximately to schwa.

Midsagittal articulation of intervocalic liquids by subject M1 are shown in Fig. 7.13. Centers of gravity were calculated using the same method described in Section 4.3.6, and used to provide an estimate of the mean dorsal target for each of the liquids. For subject M1, in the utterances compared below, the dorsal target of the lateral (x = 65.8, y = -18.4 mm) is located approximately 13 mm anterior to (12.2 mm forward of, and 4.3 mm below) that of the trill (53.6, -22.7). Mean lingual displacements from pre-consonantal vocalic centers for each liquid and each subject are given in Table 7.3).

Displacements of intervocalic liquid dorsal targets from the vocalic center are plot-

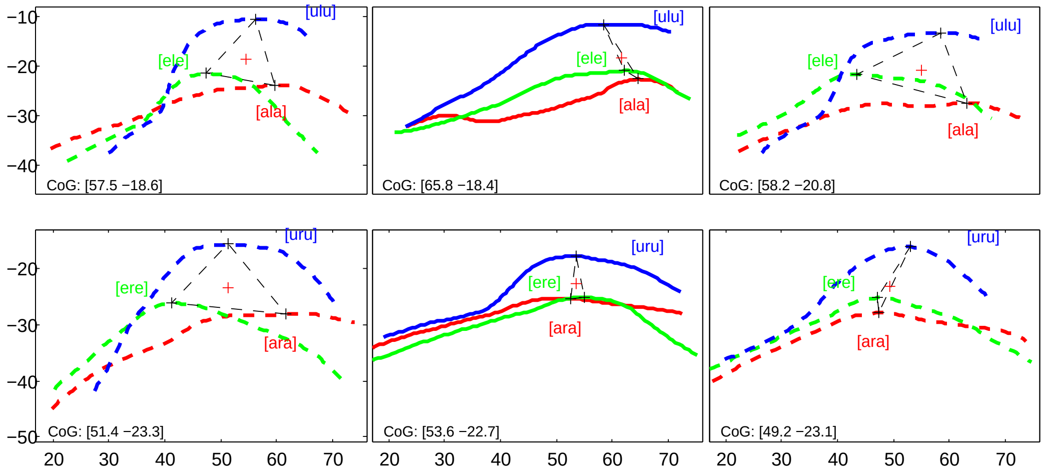



FIGURE 7.13: **Location of Russian non-palatalized liquid dorsal gestures**, estimated using centers of gravity of dorsal apices across vowel contexts [e_e]-[a_a]-[u_u] – subject M1.

| | /l/ | | /r/ | |
|---|---|---|---|---|
| | **dx** | **dy** | **dx** | **dy** |
| W1a | -11.38 | 5.86 | 0.61 | 5.41 |
| W1b | -12.09 | 7.02 | -2.60 | 5.99 |
| W2a | -2.17 | -2.03 | 1.32 | -0.07 |
| W2b | -1.82 | -1.40 | 9.74 | -0.16 |
| W3a | -13.36 | 1.05 | 0.15 | 1.76 |
| W3b | -10.06 | 1.06 | -0.88 | 1.41 |
| M1a | -12.14 | -2.73 | -0.19 | -0.26 |
| M1b | -8.24 | -0.24 | -2.25 | -0.56 |
| Mean | -8.91 | 1.07 | 0.74 | 1.69 |

TABLE 7.3: **Mean displacements (mm) of dorsal targets from pre-consonantal vocalic center**: Russian intervocalic non-palatalized liquids – all subjects.

ted in Figure 7.14. The data confirm the observations made in Section 7.2 that the dorsal target of the Russian non-palatalized lateral is posterior to that of the trill.

### 7.2.2 Summary of Results: Russian Non-Palatalized Consonants

Analysis of the Russian consonants /d/, /r/ and /l/ produced in intervocalic position by the four speakers in this study has revealed the following:

i. the tongue dorsum does is not actively recruited during the production of the

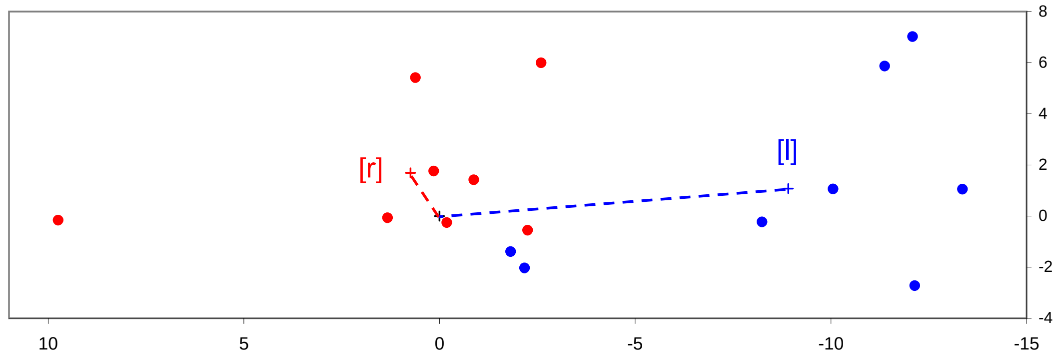



FIGURE 7.14: **Mean locations of Russian non-palatalized liquid dorsal targets with respect to 'schwa'.** Blue: intervocalic laterals; Red: intervocalic trills. Dashed lines indicate mean dorsal displacement from pre-consonantal vocalic center.

voiced coronal stop

ii. the trill is produced with a dorsal gesture with a mid-central target

iii. the lateral is produced with a dorsal gesture with a mid-back target

## 7.3 Results: Articulation of Palatalized Coronal Consonants

### Articulation of Palatalized Stops

The articulation of the token [edʲe] by a speaker of Russian is illustrated in Fig. 7.15. The first half of the sequence – ten frames beginning at the mid-point of the pre-consonantal vowel (yellow) and ending at the point of consonantal closure (red) – is illustrated in the left panel. The second half of the production sequence – ten frames commencing at the point of stop release (red) and ending at the midpoint of articulation of the post-consonantal vowel (yellow) – is shown in the figure on the right.

The data in Fig. 7.15 show that, as coronal closure is achieved, the dorsum is advanced and allowed to drop, consistent with the behavior of an uncontrolled tongue body. In the interval immediately after stop closure (0 to 94 msec), approximation of the front of the dorsum towards the palate can be observed, before the tongue body lowers towards the mid-front target of the post-consonantal context vowel. Considerable displacement of the back of the tongue (dx $>$ 10 mm) can be observed throughout the production sequence.

Articulation of the palatalized stop by the same speaker in back vowel contexts is illustrated in Figs. 7.16 ([adʲa]) and 7.17 ([udʲu]). In each case, extensive advancement of the tongue back can be observed at the same time that the coronal closure

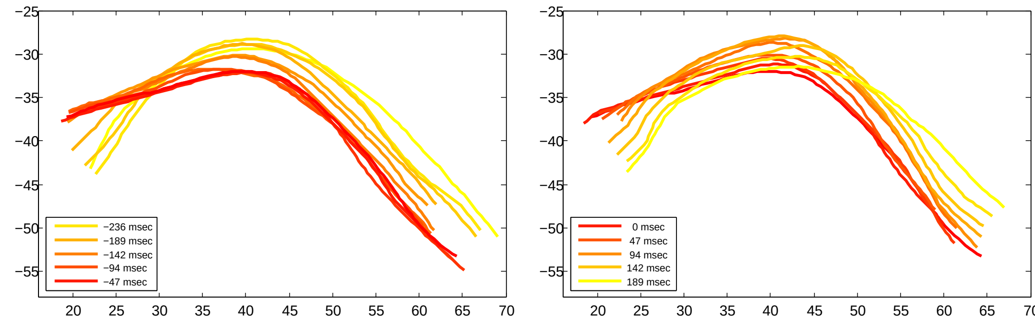



FIGURE 7.15: **Dynamic midsagittal lingual articulation of Russian palatalized coronal stop: [edʲe]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

and palatalization gestures are achieved, before the tongue body recovers towards the back targets of the context vowels. The production of the palatalized stop in the high-back vowel context [udʲu] involves lowering (dx $\sim$ -7 mm) of the dorsum towards the palatal approximation target.

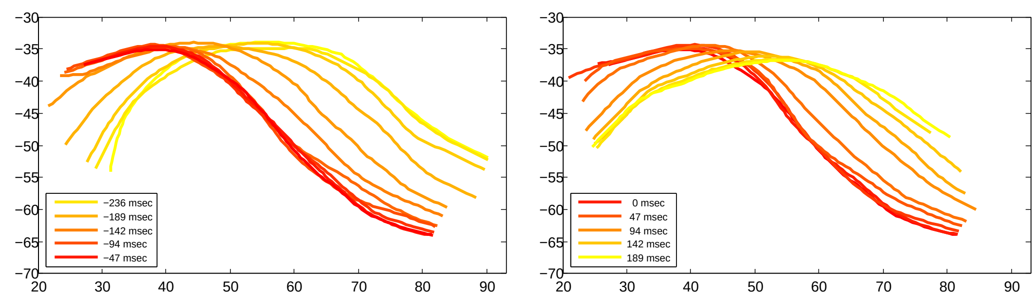



FIGURE 7.16: **Dynamic midsagittal lingual articulation of Russian palatalized coronal stop: [adʲa]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

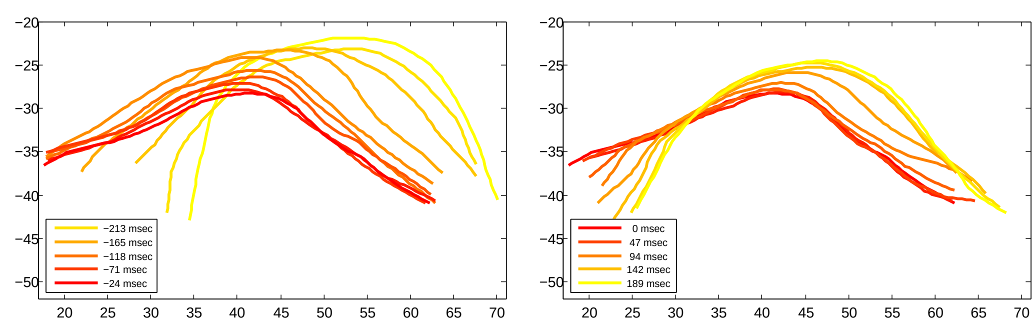



FIGURE 7.17: **Dynamic midsagittal lingual articulation of Russian palatalized coronal stop: [udʲu]** – subject W3. Left panel: consonant formation; Right panel: consonantal release.

Similar patterns of articulation were observed for the other three Russian subjects. In summary, all tongue body movement observed during the production of medial voiced coronal palatalized stops was consistent with one of two articulatory goals: approximation of the tongue blade towards the alveolar ridge, and approximation of the front of the tongue body towards the mid-palatal region. The combined effect of these dual articulatory goals results in the fronting and raising of the whole tongue during consonant production – even in the front vowel context – because there is no antagonistic articulatory goal intrinsic to the consonant which anchors the dorsum or perturbs its advancement.

### Articulation of Palatalized Rhotics

The production of the Russian palatalized trill (Figs. 7.18 to 7.20) involves a different pattern of tongue movement to that observed during stop production. Although the same coronal gesture (approximation of the tongue blade towards the alveolar ridge) and anterior dorsal gesture (approximation of the front of the dorsum towards the palate) can be observed, the back of the tongue does not behave in the same way. In each token, less gross tongue movement can be observed than for the production of the palatalized stop in the same vowel context.

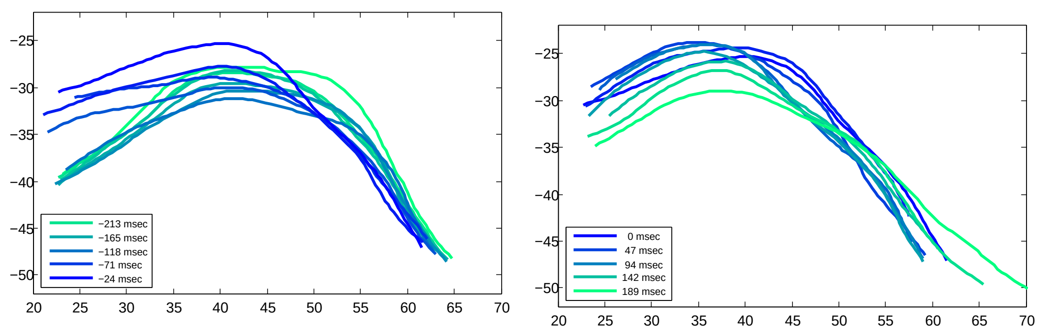



FIGURE 7.18: **Dynamic midsagittal lingual articulation of Russian palatalized trill: [erʲe]** – subject W3. Left panel: consonant formation; Right: consonantal release.

Most importantly, tongue movement during the production of palatalized rhotics appears to be constrained in such a way that, in each token, a single point of the tongue edge can be identified at which horizontal and vertical displacement is minimal (Fig. 7.18: x = 54, y = -37 mm; Fig. 7.19: x = 52, y = -36 mm; Fig. 7.20: x = 44, y = -22 mm). Stationary regions of this nature have been described as 'pivot' points by Iskarous (2004).

### Articulation of Palatalized Laterals

Articulation of the palatalized lateral by a speaker of Russian is shown in Figures 7.21 to 7.23). As with the palatalized trill, but unlike the palatalized stop, a pivot point can be observed in each token. The coordinates of these pivots are similar to those identified for the palatalized trills produced in the same vowel contexts

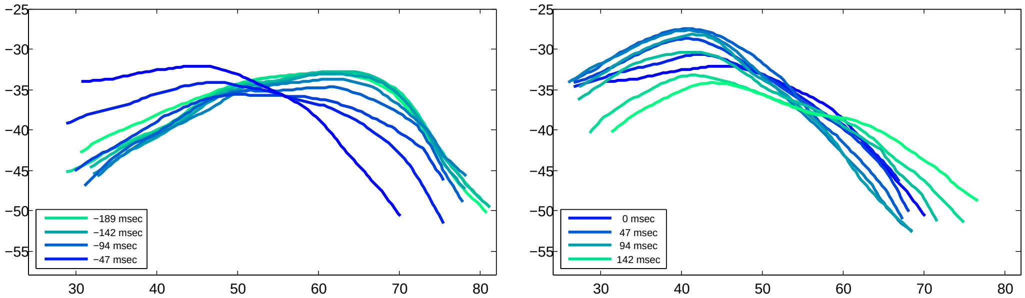



FIGURE 7.19: **Dynamic midsagittal lingual articulation of Russian palatalized trill: [arʲa]** – subject W3. Left panel: consonant formation; Right: consonantal release.

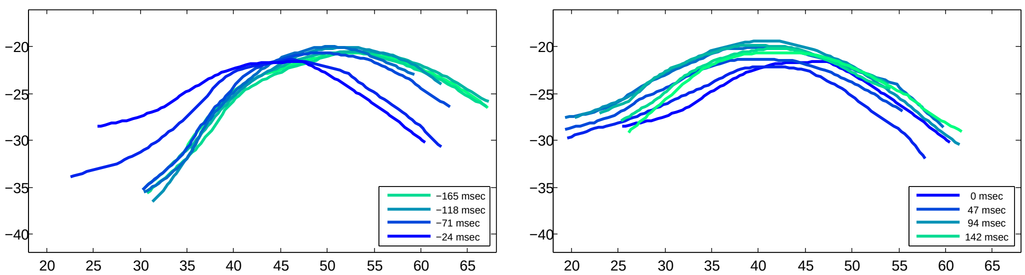



FIGURE 7.20: **Dynamic midsagittal lingual articulation of Russian palatalized trill: [urʲu]** – subject W3. Left panel: consonant formation; Right: consonantal release.

([elje]: x = 49, y = -32 mm; [alja]: x = 49, y = -33 mm; [ulju]: x = 40, y = -25 mm). As with the trills, the presence of these quasi-stationary regions suggests that the dorsum is more highly constrained than during stop production, where the tongue body moves as a whole in ways which are consistent only with the achievement of the coronal and palatalization gestures.

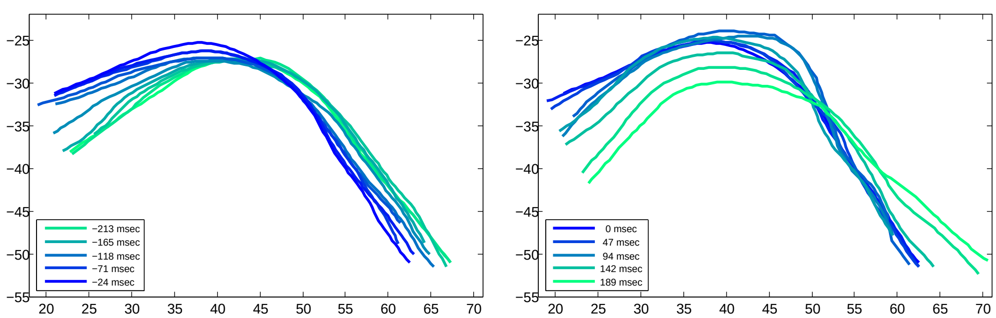



FIGURE 7.21: **Dynamic midsagittal lingual articulation of Russian palatalized lateral: [elʲe]** – subject W3. Left panel: consonant formation; Right: consonantal release.

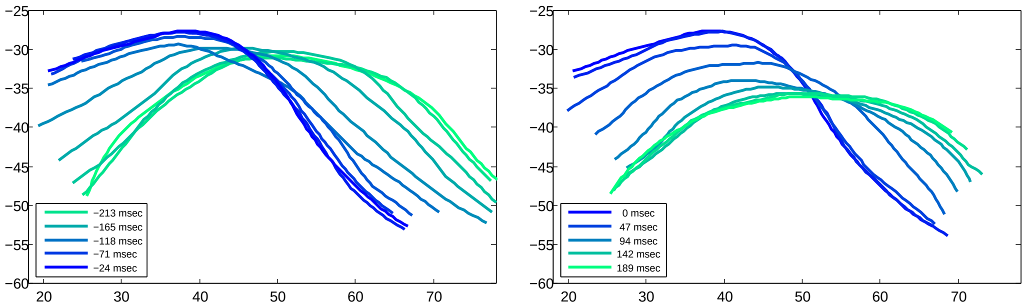



FIGURE 7.22: **Dynamic midsagittal lingual articulation of Russian palatalized lateral: [$al^ja$]** – subject W3. Left panel: consonant formation; Right: consonantal release.

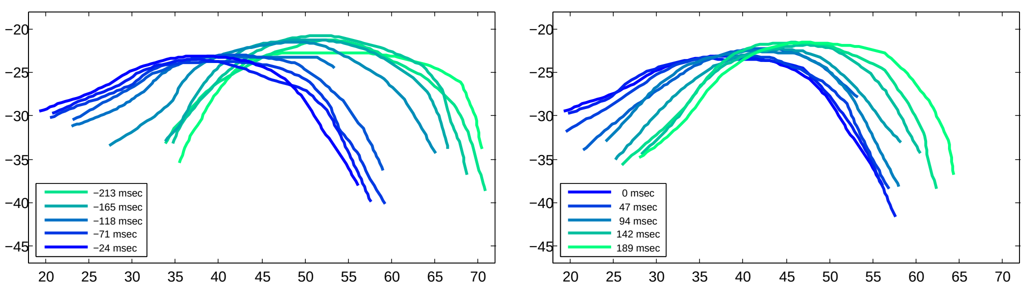



FIGURE 7.23: **Dynamic midsagittal lingual articulation of Russian palatalized lateral: [$ul^ju$]** – subject W3. Left panel: consonant formation; Right: consonantal release.

### 7.3.1 Summary of Results: Russian Palatalized Consonants

While the production of all three palatalized coronal consonants examined in this study (/$d^j$/–/$r^j$/–/$l^j$/) involved an anterior dorsal approximation gesture, the tongue body was found to be more highly constrained during the production of palatalized liquids than during the stop. The evidence for these additional constraints is in a type of tongue movement described as 'pivotal' by Iskarous (2004), who proposes that the "effect of these patterns of tongue deformation is to make the acoustic signal as articulatorily-transparent as possible".

The methodology used to identify the constriction location of dorsal gestures in Spanish and Russian non-palatalized liquid consonants (Section 4.3.6) is not applicable to the Russian palatalized liquids because the dorsal apices are located at regions of the tongue corresponding to the palatalization gesture. More work is required to develop methods of quantifying lingual movement around the lingual pivot point in ways which will inform our knowledge of the linguistic goals of tongue movement in palatalized consonants; however, if we assume that the Russian palatalized liquids have similar dorsal gestural targets to their non-palatalized equivalents, then the patterns of lingual movement observed in this section might be explained as the result of competition on the tongue body to articulate both palatal and intrinsic liquid dorsal gestures. This characterization of palatalized liquids will be examined further, using gestural modeling, in Chapter 8.

### 7.3.2 Conclusions

In this chapter, the articulation of Russian intervocalic liquid consonants has been examined in detail. Non-palatalized liquids were found to be characterized by greater resistance to vocalic coarticulation than the non-palatalized voiced coronal stop. The non-palatalized trill was found to be produced with a dorsal gesture with a mid-central target. The non-palatalized lateral was found to be produced with a dorsal gesture with a mid-back target. These results suggest that, of the three non-palatalized coronal consonants examined in this study (/d/–/r/–/l/), only the lateral can be considered to be 'velarized' /$\text{l}^{\text{ɣ}}$/, although a better characterization of the constriction location of the posterior dorsal gesture of the lateral, for the speakers examined here, is uvular-pharyngeal.

The production of all three palatalized coronal consonants examined in this study (/$\text{d}^{\text{j}}$/–/$\text{r}^{\text{j}}$/–/$\text{l}^{\text{j}}$/) involved an anterior dorsal approximation gesture; however, the tongue body was found to be more highly constrained during the production of palatalized liquids than during the stop. These results suggest that palatalized liquids consist of two different intrinsic tongue body gestures: the palatalization approximation, and an anterior dorsal gesture equivalent to that identified in the non-palatalized liquid equivalent. More work is required to quantify the location and nature of the constituent gestures in Russian /$\text{r}^{\text{j}}$/ and /$\text{l}^{\text{j}}$/.

The results of this study are consistent with the central hypothesis of this dissertation: that liquid consonants are characterized by the coordinative production of intrinsic tongue tip and tongue body gestures. The specific importance of the Russian data is to demonstrate that such a characterization also holds for classes of consonants whose production involves additional gestures, such as a palatal approximation. In Chapter 8, phonological representations of Russian coronal consonants which are consistent with this analysis will be developed, and gestural models of palatalized segments will be examined more closely using computational simulation.

# Chapter 8

# Articulatory Modeling of Russian Liquids

Experimental evidence presented in Chapter 7 indicates that Russian liquid consonants share the phonetic property that they are produced with a more controlled dorsum than coronal stops. In Chapter 6 it was shown that Russian liquid consonants are phonologically characterized by their shared distribution within the syllable and their tendency to interact with adjacent vowels. In this chapter, a gestural model of Russian liquids will be proposed which attempts to reconcile the most important phonetic and phonological properties of the class.

The structure of this chapter is as follows. Representations of Russian coronal consonants under an articulatory phonology framework will first be proposed, and the gestural organization of Russian coronal consonants within the syllable will be discussed. TADA simulations of liquid production will be presented, and the results compared with those of the ultrasound experiments. Finally, articulatory analyses of some of the phonological behavior of Russian liquids will be proposed, and the broader implications of the gestural model will be discussed.

## 8.1 Gestural Characterization of Russian Non-Palatalized Coronal Consonants

The conclusion drawn from the ultrasound study of Russian non-palatalized coronal consonants (Chapter 7) is that the liquids are characterized by the presence of a dorsal articulatory component, unlike the coronal stops, which are produced with a tongue-tip gesture alone. As in Spanish, this contrast can be modeled phonologically as the presence or absence of a tongue body gesture coupled to the tongue-tip gesture (Figure 8.1).

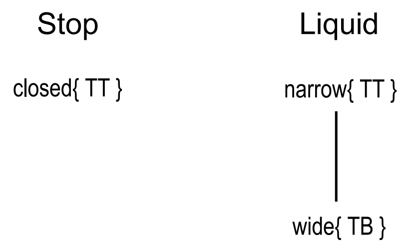



FIGURE 8.1: Contrasting coupling graphs: **Russian coronal stops and liquids**.

The data presented in Section 7.2.1 indicates that the Russian non-palatalized lateral is produced with an uvular-pharyngeal dorsal constriction, similar to that of a mid-back vowel, while the dorsal constriction of the Russian non-palatalized trill has a more anterior target, typically equivalent to that of a mid-central vowel (Fig. 7.14). A preliminary set of gestural specifications for the Russian non-palatalized coronal consonants which are consistent with these results are proposed in Table 8.1.

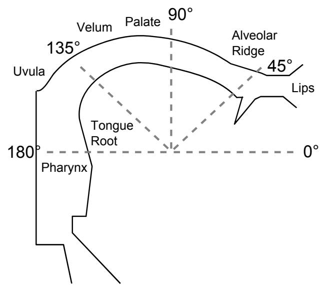
| TV | /d/ | /l/ | /r/ |
|---|---|---|---|
| **TTCL** | dental | alveolar | alveolar |
| **TTCD** | closed | narrow | narrow |
| **TBCL** | – | uvular-pharyngeal | velar |
| **TBCD** | – | wide | wide |

TABLE 8.1: **Tract variable specifications for Russian non-palatalized coronal consonants**.

### 8.1.1 Modeling Russian Non-Palatalized Liquids

The phonological representations of Russian coronal consonants proposed in Table 8.1 were examined by conducting articulatory simulations using TADA. The gestural parameters used to model the two non-palatalized liquids are shown in Figure 8.2.

Comparing the articulatory representations of Russian liquids with those proposed for Spanish (Table 5.1), we can see that the essential difference between the models is the location of the dorsal constriction targets for the laterals. Unlike the open




| ARPA | Organ | Osc | TV | Constrict | Target | Stiffness | Damping |
|---|---|---|---|---|---|---|---|
| L | TT | nar | TTCL | DENT | 45 | . | . |
| | TT | nar | TTCD | NAR | 2 | . | . |
| | TT | rel | TTCL | REL | 24 | . | . |
| | TT | rel | TTCD | REL | 11 | . | . |
| | TB | voc | TBCL | UVUPHAR | 170 | . | . |
| | TB | voc | TBCD | V | 8 | . | . |
| R | TT | nar | TTCL | ALVPAL | 60 | . | . |
| | TT | nar | TTCD | NAR | 2 | 20 | 0.2 |
| | TT | rel | TTCL | REL | 24 | . | . |
| | TT | rel | TTCD | REL | 11 | . | . |
| | TB | voc | TBCL | VEL | 110 | . | . |
| | TB | voc | TBCD | V | 8 | . | . |
| | Lips | voc | LA | NAR | 2 | . | . |

FIGURE 8.2: Left: **Semi-polar coordinate system** used to specify constriction location in TADA; Right: **Gestural parameters used in TADA simulations of Russian non-palatalized liquids**.

palatal constriction of the Spanish clear lateral, the Russian non-palatalized lateral is specified for a much more retracted tongue body constriction location (TBCL = 170°, TBCD = 8 mm), consistent with the upper-pharyngeal dorsal articulation observed in the ultrasound data.

Importantly, in this model, the rhotic is specified for a mid-oral tongue body constriction target (TBCL = 110°, TBCD = 8 mm, similar to that specified for the Spanish), because the data from the ultrasound study does not support the claim that the Russian trill is velarized/pharyngealized by virtue of its non-palatalized status (c.f. Halle 1959).[1]

### Modeling Russian Non-Palatalized Laterals

Data from a simulation of Russian non-palatalized lateral articulation are shown in Figure 8.3. The acoustic waveform and time course of the tongue tip (TTCD) and tongue body constriction degree (TBCD) tract variables generated in a simulation of the sequence /ala/, using the gestural specifications in Figure 8.2, are shown on the right. Midsagittal articulation during the pre-consonantal vowel and the point of closest coronal approximation of the lateral are shown on the left.

Comparing the results of the simulation with the Spanish equivalent (Fig. 5.5), it can be seen that the fundamental difference between the clear and dark laterals of the two languages has been successfully modeled using the gestural specifications in Tables 8.1 and 5.1. Articulation of the non-palatalized Russian lateral, in

[1] It should be noted that the labels used to specify constriction location of a tract variable do not always correspond to specifications for place of articulation with the same name used by the IPA. The primary difference is that the IPA system is essentially a horizontal specification of degree of anteriorness or posteriorness, while TADA tract variables are specified using a midsagittal semi-polar coordinate system. A schwa, for example, could be specified either in terms of tongue body displacement from the rear pharyngeal wall, or from the palate.

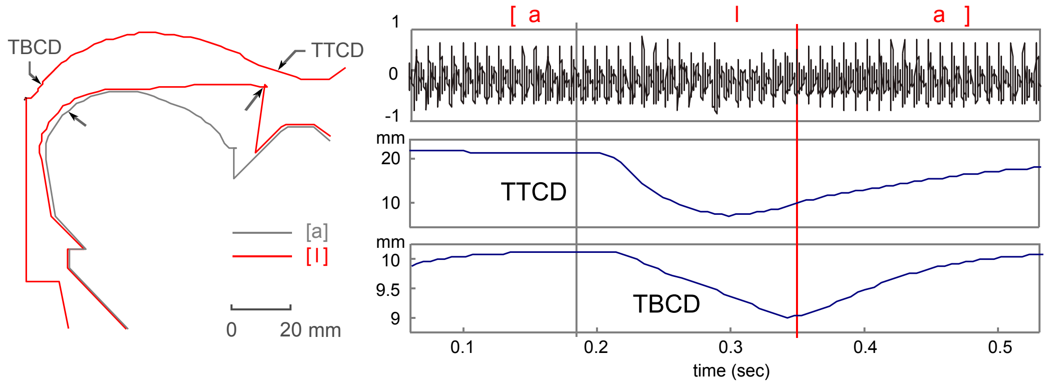



FIGURE 8.3: **TADA simulation of Russian intervocalic non-palatalized lateral articulation: [ala].** Left: midsagittal articulation during pre-consonantal vowel and mid-consonant; Right: acoustic waveform and time course of tongue tip and tongue body constriction degree tract variables.

a low vowel context, involves dorsal retraction and raising towards the velarized tongue body constriction location, unlike the dorsal advancement observed in the production of the clear [l] in Spanish.

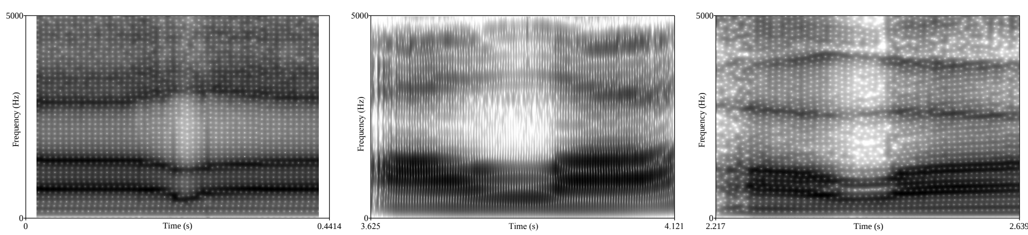



FIGURE 8.4: **Spectra of simulated and spoken Russian intervocalic non-palatalized laterals**. Left: Speech synthesized from articulatory sequence [ala] simulated in TADA; Center: [ala] spoken by female subject W2; Right: [ala] spoken by male subject M1;

The spectrogram of an intervocalic lateral synthesized from the articulatory model is shown in Figure 8.4, where it is compared to spectra of intervocalic laterals produced by female and male Russian speakers. Comparing the spectra with those of the simulated and spoken Spanish laterals (Fig. 5.7), it can be seen that the Russian lateral has been successfully synthesized as a dark [ɫ] , and that the primary acoustic difference between the laterals in the two languages is in the trajectory of F2. Unlike in the clear lateral of Spanish, where the second formant raises in a low vowel context, F2 tracks F1 during the production of the velarized lateral, lowering in the same vowel context, due to its correlation with tongue body backness.

The higher formants of the synthesized Russian lateral more closely resemble those produced by Russian speakers than in the Spanish model, demonstrating that, as in English (Browman & Goldstein 1995; Ladefoged & Maddieson 1996), a certain degree of lateralization results from the intrinsic gestural characterization of the

Russian non-palatalized segment. Because the dorsal target of the Russian lateral is even more raised and retracted than in English, and because this gesture is coordinated with a highly anterior coronal approximation (Russian laterals are typically classified as dental), the tongue is highly elongated, and side channels will form naturally from this lingual posture. The more realistic trajectories of F3 and F4 in the acoustic simulation would appear to result from the articulatory consequences of this gestural characterization in TADA.

### Modeling Russian Non-Palatalized Rhotics

Data from a simulation of Russian non-palatalized rhotic articulation are shown in Figure 8.5. The acoustic waveform and time course of the tongue tip (TTCD) and tongue body constriction degree (TBCD) tract variables generated in a simulation of the sequence /ala/, using the gestural specifications in Figure 8.2, are shown on the right. Midsagittal articulation during the pre-consonantal vowel and a point during the second coronal closure of the trill are shown on the left.

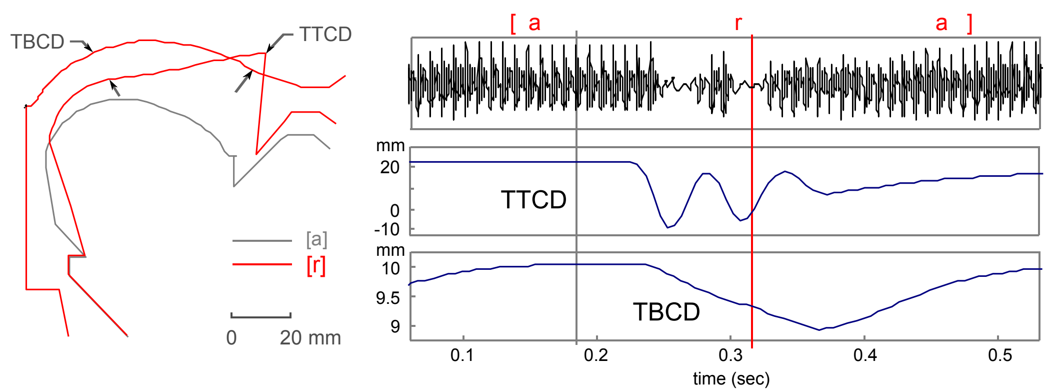



FIGURE 8.5: **TADA simulation of Russian intervocalic non-palatalized rhotic articulation: [ara].** Left: midsagittal articulation during pre-consonantal vowel and mid-consonant; Right: acoustic waveform and time course of tongue tip and tongue body constriction degree tract variables.

The figure shows that the simulation has captured the essential properties of the Russian trill in this intervocalic context: the tongue dorsum raises and moves to a stable mid-central vowel-like posture, at the same time that the tongue tip is set into an oscillatory mode, making contact with the passive articulator in the region of the alveolar ridge. As with the Spanish rhotic simulations, the number of coronal contacts was found to be a function of consonantal duration (stiffness), tongue tip constriction degree, tongue body constriction location, and tongue tip damping specified for the rhotic tract variables.

The spectrogram of an intervocalic lateral synthesized from the articulatory model

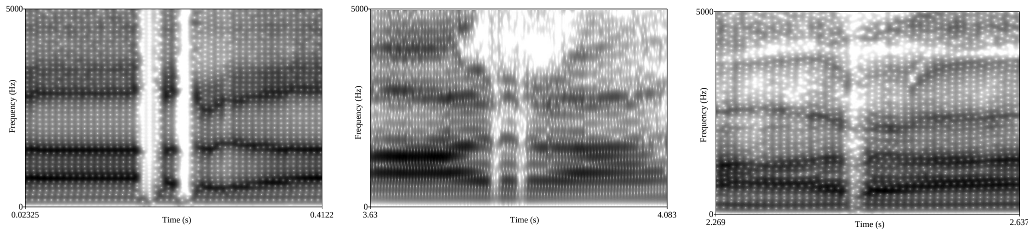



FIGURE 8.6: **Spectra of simulated and spoken Russian intervocalic non-palatalized rhotics**. Left: Speech synthesized from articulatory sequence [ara] simulated in TADA; Center: [ara] spoken by female subject W3; Right: [ara] spoken by male subject M1;

is shown in Figure 8.4, where it is compared to spectra of intervocalic laterals produced by female and male Russian speakers. Comparing the spectra with those of the simulated and spoken Spanish laterals (Fig. 5.7), it can be seen that the Russian lateral has been successfully synthesized as a dark [ɫ] , and that the primary acoustic difference between the laterals in the two languages is in the trajectory of F2. Unlike in the clear lateral of Spanish, where the second formant raises in a low vowel context, F2 tracks F1 during the production of the velarized lateral, lowering in the same vowel context, due to its correlation with tongue body backness.

## 8.2 Gestural Characterization of Russian Palatalized Coronal Consonants

Ultrasound data presented in Section 7.3 revealed that Russian palatalized coronal consonants are all produced with a vowel-like approximation in the palatal region. The same articulation was observed in the production of liquids and obstruents, which suggests that these consonants consist of a tongue body gesture with the same properties as a high front vocoid (/i/ or /j/) coupled to the gestural constellations of the non-palatalized consonantal equivalents. Under this model, the basic phonological representations of Russian palatalized stops and liquids are shown in Figure 8.7.

Building on the models proposed for Russian non-palatalized coronal consonants (Table 8.1), a preliminary set of gestural specifications for the palatalized equivalents are outlined in Table 8.2. In each case, a gesture corresponding to a high front glide has been added to the original constellation.

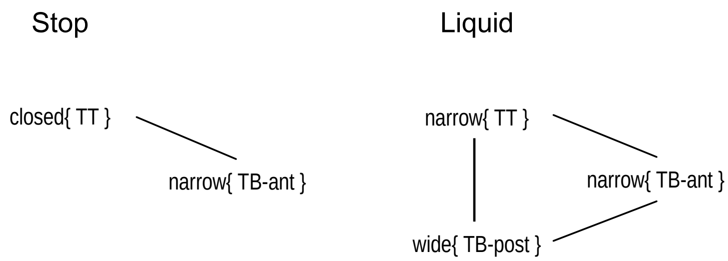


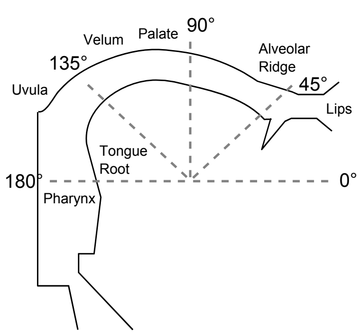

FIGURE 8.7: Coupling graphs: **Russian palatalized coronal consonants**.

| TV | $/d^j/$ | $/l^j/$ | $/r^j/$ |
|---|---|---|---|
| **TTCL** | dental | alveolar | alveolar |
| **TTCD** | closed | narrow | narrow |
| **TBCL** | – | uvular-pharyngeal | velar |
| **TBCD** | – | wide | wide |
| **TBCL** | palatal | palatal | palatal |
| **TBCD** | narrow | narrow | narrow |

TABLE 8.2: **Tract variable specifications for Russian palatalized coronal consonants.**

### 8.2.1 Modeling Russian Palatalized Liquids

The phonological representations of Russian coronal consonants proposed in Table 8.1 were examined by conducting articulatory simulations using TADA. The specific gestural parameters used to model the two palatalized liquids are shown in Figure 8.8.




| ARPA | Organ | Osc | TV | Constrict | Target | Stiffness | Damping |
|---|---|---|---|---|---|---|---|
| LJ | TT | nar | TTCL | DENT | 45 | . | . |
| | TT | nar | TTCD | NAR | 2 | . | . |
| | TT | rel | TTCL | REL | 24 | . | . |
| | TT | rel | TTCD | REL | 11 | . | . |
| | TB | voc | TBCL | PAL | 95 | . | . |
| | TB | voc | TBCD | V | 5 | . | . |
| | TB | voc | TBCL | UVUPHAR | 170 | . | . |
| | TB | voc | TBCD | V | 8 | . | . |
| RJ | TT | nar | TTCL | ALVPAL | 60 | . | . |
| | TT | nar | TTCD | NAR | 2 | 20 | 0.2 |
| | TT | rel | TTCL | REL | 24 | . | . |
| | TT | rel | TTCD | REL | 11 | . | . |
| | TB | voc | TBCL | PAL | 95 | . | . |
| | TB | voc | TBCD | V | 5 | . | . |
| | TB | voc | TBCL | VEL | 110 | . | . |
| | TB | voc | TBCD | V | 8 | . | . |
| | Lips | voc | LA | NAR | 2 | . | . |

FIGURE 8.8: Left: **Semi-polar coordinate system** used to specify constriction location in TADA; Right: **Gestural parameters used in TADA simulations of Russian palatalized liquids**.

### Modeling Russian Palatalized Laterals

Data from a simulation of Russian intervocalic palatalized lateral production are shown in Figure 8.9. The acoustic waveform and time course of the tongue tip (TTCD) and tongue body constriction degree (TBCD) tract variables generated in a simulation of the sequence /alʲa/ are shown on the right. Midsagittal articulation during the pre-consonantal vowel, the point of closest coronal approximation, and the point of closest palatal approximation of the lateral are shown on the left.

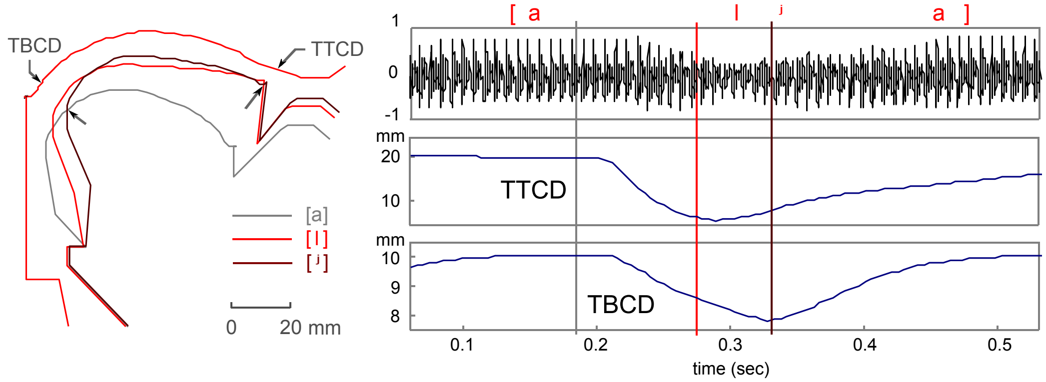



FIGURE 8.9: **TADA simulation of Russian intervocalic palatalized lateral articulation: [alʲa]**. Left: midsagittal articulation during pre-consonantal vowel; mid-consonant; and late in consonantal production (corresponding to the point of maximal palatalization); Right: acoustic waveform and timecourse of tongue tip and tongue body constriction degree tract variables.

The spectrogram of an intervocalic palatalized lateral synthesized from the articulatory model is shown in Figure 8.10, where it is compared to spectra of intervocalic laterals produced by female and male Russian speakers. The data show that the articulatory model has successfully emulated the trajectories of the lower two formants, producing the characteristic rise in F2 late in consonant production in the low vowel context. As with the non-palatalized lateral, the primary difference between the synthesized and spoken speech is in the higher formants.

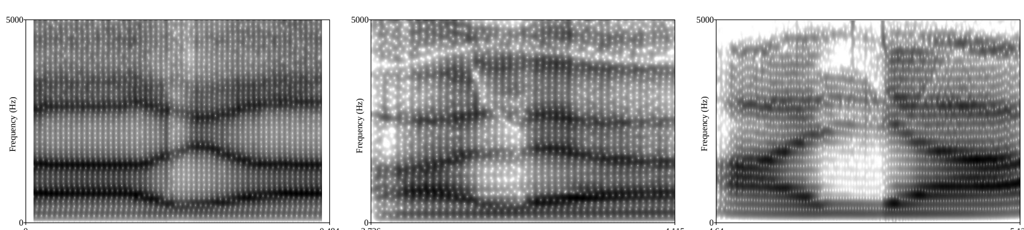



FIGURE 8.10: **Spectra of simulated and spoken Russian intervocalic palatalized laterals**. Left: Speech synthesized from articulatory sequence [alʲa] simulated in TADA; Center: [alʲa] spoken by female subject W2; Right: [alʲa] spoken by male subject M1;

### Modeling Russian Palatalized Rhotics

Data from a simulation of Russian palatalized rhotic articulation are shown in Figure 8.11. The acoustic waveform and time course of the tongue tip (TTCD) and tongue body constriction degree (TBCD) tract variables generated in a simulation of the sequence /ar$^j$a/, using the gestural specifications in Figure 8.8, are shown on the right. Midsagittal articulation during the pre-consonantal vowel, the point of maximal coronal constriction during the second closure, and the point of closest palatal approximation of the trill are shown on the left.

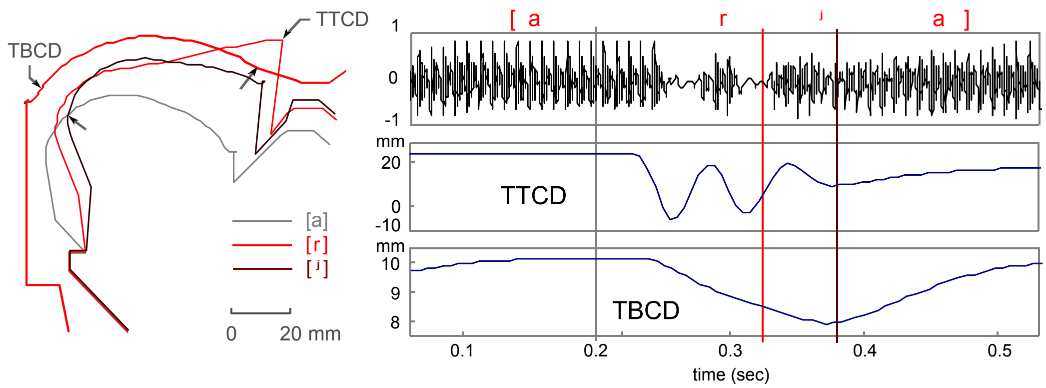



FIGURE 8.11: **TADA simulation of Russian intervocalic palatalized rhotic articulation: [ar$^j$a]**. Left: midsagittal articulation during pre-consonantal vowel, mid-consonant and immediately post consonant; Right: acoustic waveform and time course of tongue tip and tongue body constriction degree tract variables.

The spectrogram of an intervocalic palatalized rhotic synthesized from the articulatory model is shown in Figure 8.10, where it is compared to spectra of intervocalic laterals produced by female and male Russian speakers. The data show that the articulatory model has successfully emulated the trajectories of the lower two formants, producing the characteristic rise in F2 late in consonant production in the low vowel context. As with the non-palatalized lateral, the primary difference between the synthesized and spoken speech is in the higher formants: F3 does not raise during lateral production in this context, and F4 remains too low.

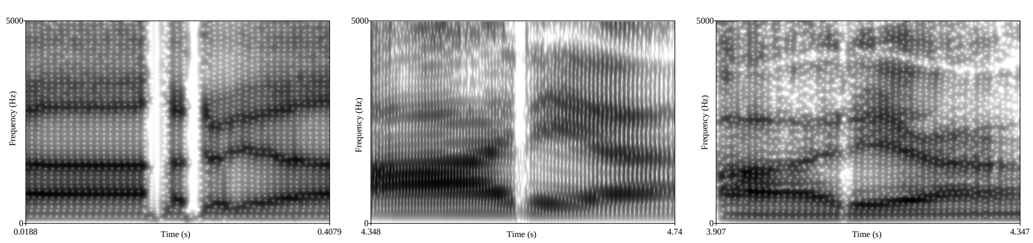



FIGURE 8.12: **Spectra of simulated and spoken Russian intervocalic palatalized rhotics**. Left: Speech synthesized from articulatory sequence [ar$^j$a] simulated in TADA; Center: [ar$^j$a] spoken by female subject W2; Right: [ar$^j$a] spoken by male subject M1;

### 8.2.2 Summary: Gestural Modeling of Russian Liquid Consonants

In this section, phonological representations have been proposed for Russian coronal consonants. Non-palatalized liquids have been modeled as coordinated structures of tongue tip and tongue body gestures. Palatalized liquids are argued to consist of an additional tongue body approximation gesture coordinated with the gestural constellation corresponding to the paired non-palatalized consonant.

TADA simulations have been used to examine the validity of these phonological representations, and have demonstrated that a multi-gestural model is capable of capturing the essential articulatory properties of the four Russian liquids, consistent with the articulatory data obtained from the ultrasound experiment. In contrast to Spanish, where the dorsal target of the lateral is anterior to that of the rhotics, the Russian lateral was modeled using a more retracted tongue body constriction location, consistent with its characterization as a dark lateral.

Speech synthesized from dynamic simulations of intervocalic consonants was recognizable as each of the four liquids, and broadly consistent with the acoustic recordings of the same utterances produced by Russian speakers. In particular, the gestural models were highly successful at modeling the trajectories of the lower two formants, suggesting that the specifications of tongue body gestures are broadly correct.

As in the Spanish experiments, the acoustic simulations were less successful at modeling the behavior of F4, suggesting once more that a strictly midsagittal model of liquid articulation might be too reductive. F3 trajectories, on the other hand, were more accurate in the synthesized Russian non-palatalized lateral and palatalized liquids than in the Spanish liquid simulations, suggesting that the limitations of the midsagittal model are more problematic in languages which use clearer liquids in which the tongue body is more advanced.

## 8.3 Gestural Analysis of Phonological Processess involving Russian Liquids

Having characterized the Russian liquids using the phonological representations proposed above, we now consider how a gestural model might be able to account for some phonological processes involving liquid consonants in Russian.

### 8.3.1 Articulatory Analysis of Liquid Metathesis

Historically, as discussed in Section 6.3.2, liquids have been involved in a disproportionate number of metathesis phenomena in Russian. The most common of these processes involved the interchange of coda liquids with their preceding nuclear vowels (Table 6.6) in the development of Proto-Slavic.

It is noteworthy that the vowel which participated in this processes was the mid-back vowel /o/. It was shown in Chapter 7 that the dorsal gestures of the Russian (non-palatalized) liquids have constriction locations resembling those of the mid-back and mid-central vowels. Under the gestural analysis being proposed here, metathesis of the type *#oLC → *#LoC can be modeled as the result of a change in the coupling relationships between the nucleus and its associated consonantal gestures.

Cubberley (2002) cites the example of Proto-Slavic */olkotɪ/ *'elbow'* developing into Modern Russian /lok(o)tʲ/. A comparison of the gestural organization at the beginning of the two words (Tables 8.3 and 8.4) shows that there is no difference in gestural *constituency* in the first syllable: both words begin a prolonged uvular-pharyngeal vocalic gesture coordinated with a tongue tip closure gesture. The contrast results from the difference in timing relationships between these gestures: tongue-tip closure is synchronous with the tongue body gesture when the lateral is in the onset /lo/, and delayed with respect to the start of the dorsal constriction when the lateral appears in the coda /ol/. We can model these timing differences at the planning level using the coupling graphs contrasted in Figure 8.13.

| | o | l | k | o | t | ɪ |
|---|---|---|---|---|---|---|
| LAB | | | | | | |
| TT | | nar | | | clo | |
| TB | wd{uphar} | | clo | wd{uphar} | wd{pal} | |
| VEL | | | | | | |
| GLO | | | | | | |

TABLE 8.3: Gestural Score: Late Common Slavonic **/olkotɪ/**.

Under this model, diachronic CV metathesis results from a change in the phasing relationships between the constellation of gestures which constitute a syllable. Given a preference for in-phase coordination, the model predicts that historical metatheses of this type would be more likely to proceed in the direction #VC → #CV than the reverse – an account which is consistent both with the historical evidence from Slavic and typological preferences for open syllables.

| | l | o | k | o | $t^j$ |
|---|---|---|---|---|---|
| LAB | | | | | |
| TT | nar | | | | clo |
| TB | wd{uphar} | wd{uphar} | clo | wd{uphar} | wd{pal} |
| VEL | | | | | |
| GLO | | | | | |

TABLE 8.4: Gestural Score: Modern Russian /lokot$^j$/.

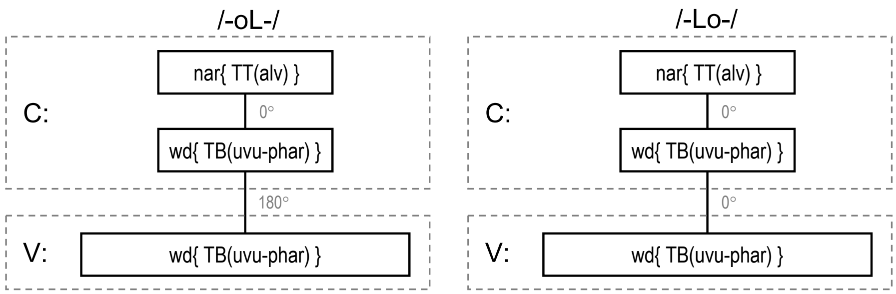



FIGURE 8.13: **Russian -oL- metathesis** resulting from changes in C-V phasing relationships.

### 8.3.2 Articulatory Analysis of Russian Jer Preservation

Another phonological process involving Russian liquids which warrants consideration under an articulatory framework is the preservation of medial jers. As noted in Section 6.3.2, in the development out of LCS, medial jers tended to be preserved when they occurred adjacent to a liquid in the Eastern Slavic languages, while the same sequence resulted in a syllabic liquid in the Southern Slavic languages (Tables 6.4–6.5).

Considering the phonological representation of a LCS word such as */vɪlkʊ/ *'wolf'*, the gestural organization would resemble that indicated in the gestural score in Table 8.5.

The development of this etymon into the forms found in the daughter languages: /vl̩k/ (Czech) and /volk/ (Russian) can be modeled in terms of changes in coupling and timing relationships between the same constituent gestures (as well as the changes in specification of tongue body constriction location which would accompany the changes in vowel quality). The gestural organization in the Modern Russian word /volk/, for example, is shown in Table 8.6: the loss of the final jer has led to the reorganization of the velar stop in coda position: asynchronously coupled to the preceding vowel.

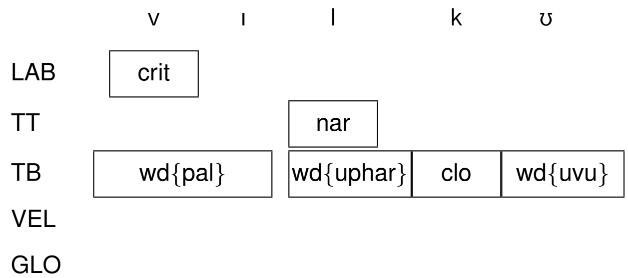



TABLE 8.5: Gestural Score: Late Common Slavonic **/vɪlkʊ/**.

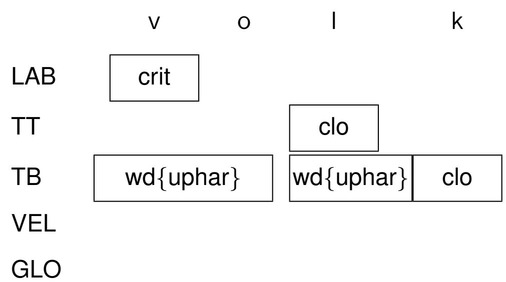



TABLE 8.6: Gestural Score: Russian **/volk/**.

Daughter forms of Common Slavic words in which jer-liquid sequences became syllabic may be seen as the consequence of further gestural reorganization whereby the tongue tip and tongue body gestures of the coda liquid became nucelic; i.e. became the gestures to which all other ambisyllabic gestures become coupled. The phonological representation of the Modern Czech word */vl̩k/ *'wolf'*, for example, is indicated in the gestural score in Table 8.7.

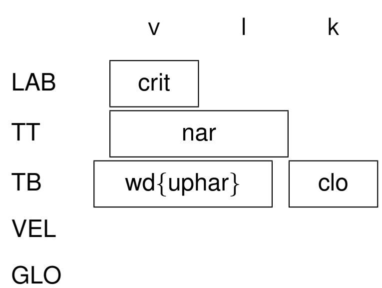



TABLE 8.7: Gestural Score: Czech **/vl̩k/**.

## 8.4 Summary

In this chapter, phonological models of Russian coronal consonants have been proposed. As for Spanish, and consistent with the central hypothesis of this dissertation, the non-palatalized coronal liquid consonants are argued to differ from the obstruents in that they are intrinsically comprised of coordinated tongue tip and tongue body gestures. Phonological representations have been proposed for Russian palatalized consonants in which an additional tongue body approximation gesture is coordinated with the non-palatalized gestural constellations.

Vowel-liquid metathesis has been analyzed as resulting from the reorganization of coupling relationships between tongue body gestures corresponding to adjacent vowels and liquids – an account which is consistent with the identity of the vowel most commonly involved in this process in the dichronic phonology of Slavic. Jer preservation and development of syllabic liquids in Slavic are argued to result from the interaction and syllabic reorganization of adjacent vowel and liquid tongue body gestures.

# Chapter 9

# Discussion

Having developed gestural models to account for the behavior of liquid consonants in Spanish (Chapter 5) and Russian (Chapter 8), we will now consider the implications of these models for some broader aspects of liquid phonology. In this chapter, evidence for the gestural acquisition of liquid consonants is examined. Theories of syllabic organization are addressed, and a gestural basis for some cross-linguistic phonotactic phenomena is considered. Some allophonic and historical changes changes involving liquids are described using a gestural model. Representations of laterals and uvular rhotics are discussed. Finally, the problem of capturing classes of liquids will be reconsidered from a gestural perspective, before some problems with the model are outlined, along with suggestions for future research.

## 9.1 Phonological Acquisition of Liquids

We can account for some trends in phonological development by appealing to a gestural model of liquid structure. Studies of child language acquisition in a variety of languages have reported that:

i. liquids and fricatives are typically acquired later than most consonants
ii. before liquids are mastered, substitution errors are common, and typically involve coronal stops, vowels and glides

This developmental chronology suggests that children first acquire the broad set of gestures involved in liquid production, before refining and differentiating these gestures and establishing the coupling relationships between them.

### 9.1.1 Acquisition of Liquid Gestures

Two year old children who have largely acquired the stop and vowel contrasts in their native languages often produce liquid consonants as glides. Substitution errors of this type have been reported in English: *lap* [jap], *leg* [jeg], *ready* [wed], *sorry* [sawa] (Fletcher & Garman 1986; Ingram 1989), and Estonian: *raha* [jaha] 'money', *ruttu* [jutu] 'fast' (Vihman 1996), as well as in Turkish, Portuguese, Mandarin, Czech, and Swedish (Yavaş & Topbaş 2004).

If the goals of production of liquids were merely to achieve a certain degree of sonority, as suggested by Wiese (2001a), we might expect children to produce a wide range of segments at this stage of their phonological development. Any number of vocalic or nasal segments, for example, have similarly resonant properties to an English approximant rhotic, and should serve as suitable substitute on prosodic grounds alone. However, acquisition studies reveal a remarkable consistency in the segments which children substitute for liquids in a given language.

In syllable onsets, child learners of American English consistently produce the rhotic as [w], and the lateral as [j] (Dinnsen 1992, Smit 1993). The glide [w] is produced with a labial protrusion and a dorsal approximation; both of these gestures are constituents of the adult phonology rhotic in English (Delattre & Freeman 1968; Gick et al. 2003). The palatal glide substituted for the lateral in the child phonology might represent a first approximation to the more anterior dorsal gesture of the clear /l/ found in onset position in adult English. In other environments, liquids are commonly vocalized by child learners – e.g. *apple* [apo]; *bottle* [babu]; *dinner* [dindʌ] (Fletcher & Garman 1986) – tongue body realizations which closely correspond to the dorsal articulations produced in adult English liquids (Gick et al. 2002; Fig. 1.2).

Different trends are observed amongst children learning Spanish. The Spanish tap /ɾ/ is realized as [ð], [l], and [d] (Anderson & Smith 1987; Goldstein & Iglesias 1996), and coronal trills are first produced as [l] by child learners of Spanish (Stoel 1974; Anderson & Smith, 1987).[1] In contrast to English-speaking children, who seem to acquire tongue body gestures first, these data suggest that Spanish learners might be acquiring coronal articulatory goals before mastering the more global control of the tongue necessary to distinguish the liquids from each other and the stop. Collectively, these data suggest that children are sensitive to the gestural constituency of the liquid consonants used in their language, and the syllable position effects which influence the location and organization of those gestures.

### 9.1.2 Acquisition of Gestural Coordination

Not only are liquids acquired late, they are also acquired in stages. A developmental trend observed across languages is that a single liquid consonant is usually acquired first, and additional liquid contrasts follow later (Dinnsen 1992; Yavaş & Topbaş 2003). Studdert-Kennedy & Goldstein (2003) have argued that acquisition of more than one liquid is only achieved when the child masters multiple coordination patterns – a hypothesis supported by studies showing late acquisition in Spanish (Anderson & Smith 1987), where three liquids must be differentiated, and Russian (Zharkova 2005), where palatalization contrasts must also be acquired. In Spanish and other languages that contrast tapped and trilled rhotics, pronunciation of liquids also requires differential control of tongue tip stiffness and damping – an additional phonetic dimension which is mastered late amongst native speakers, and never acquired by some second language learners of these languages.

I propose that the pattern of phonological development suggested by the data reviewed in Section 9.1.1 is one in which liquid acquisition proceeds in four broad stages, exemplified for the case of Spanish in Figure 9.1.

Building on the model of phonological acquisition proposed by Goldstein & Fowler (2003), and Studdert-Kennedy & Goldstein (2003), we can hypothesize that children (i) first learn to differentiate contrasts between different speech organs (lips/tongue tip/tongue body), before (ii) learning the most salient phonological contrasts involved in the production of a liquid. In the case of Spanish, this contrast is a tongue-

1 Trills are initially realized as laterals also by child learners of Italian (Bortolini & Leonard 1991) and Portuguese (Yavaş 1988).

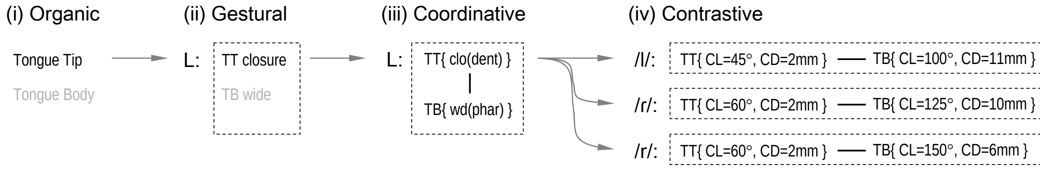



FIGURE 9.1: **Hypothesized stages in the phonological acquisition of liquid consonants**.

tip gesture shared by, but not yet differentiated from coronal obstruents; in English, a tongue body gesture shared by, but not yet differentiated from glides. Children acquire a single liquid when they learn to coordinate tongue tip and tongue body gestures (iii), and finally, acquire multiple liquid segments when they learn how to differentiate the constituent gestures, and control the different coordinate relationships between them.

## 9.2 Accounting for the Distribution of Liquids

In Chapter 2 it was shown that cross-linguistically, one of the most important properties of the class of liquids is their shared distribution in the syllable. Given that the class is partially characterized by its phonotactic properties, a phonological model of liquid consonants should be able to account for this behavior. Specifically, we are interested in explaining the restricted and asymmetrical distribution of liquids in consonant clusters, and considering whether these ordering relationships might be described in a principled way, consistent with broader theories of syllable structure.

### 9.2.1 Sonority-Based Accounts of Liquid Phonotactics

Although class-based restrictions on consonantal ordering in onsets and codas have long been observed (Whitney 1865; Jespersen 1904; Saussure 1915), it is still not clear what principles govern these constraints. Accounts of phonotactic organization in the syllable have traditionally appealed to the concept of *sonority*: a scalar property, intrinsic to all segments, which ranks them on a hierarchy and governs their distribution with respect to other segments.[2] In a given string of segments, syllable nuclei should correspond to local peaks in sonority, onsets to sequences of rising sonority, and codas to sequences of falling sonority (Kenstowicz 1994).

[2] Vennemann (1988) proposes that the same distributions are governed by differences in "Universal Consonantal Strength" – the inverse of sonority.

Clements (1990) proposes the minimal sonority hierarchy formulated by Eq. 9.1.

$$obstruent < nasal < liquid < glide < vowel \tag{9.1}$$

A great variety of phonetic and quasi-phonetic correlates to sonority have been proposed, including *Schallfülle* (Sievers 1881), acoustic energy (Heffner 1950; Ladefoged 1971), relative sound pressure intensity (Parker 2008), F1 (Donegan 1985), voiced airflow (Vennemann 1988), and band-limited resonant energy (Clements 2006). Although many of these parameters have been shown to be correlated with groups of sounds which pattern together phonotactically in some languages, none has proven to be robustly associated with the diverse group of segments which function as liquids across languages, nor even with the sets of rhotics which pattern together in the same language (Lindau 1985; Ladefoged & Maddieson 1996).

The liquids produced by the Spanish speakers in the study in Chapter 4, for example, ranged from stop- (Fig. 4.8) and fricative-like segments (Fig. 4.10) to highly resonant approximants (Fig. 4.7). Sonorities measured by any of the phonetic parameters proposed above would differ radically between some of these segments, yet they all exhibit the same phonotactic behavior. Even larger differences in sonority would be observed between the voiced intervocalic stops produced by these speakers – some of which are canonical plosives (Fig. 4.3); others radically lenited approximants (Fig. 4.6) – yet all of these consonants combine with liquids in the same order in Spanish onset clusters, regardless of their relative sonorities.

Because no satisfactory universal definition of sonority has yet been proposed, nor any independent set of parameters by which it might be robustly quantified, Ohala (1992) points out that phonological arguments for the role of sonority hierarchies in determining syllable shape are essentially circular. Liquids are ranked between obstruents and vowels in the sonority hierarchy because clusters of the form #Cl- and #Cr- are more commonly observed across languages than #lC- and #rC- (Chapter 2). When the class of liquids is expanded in more elaborated versions of the hierarchy, rhotics are typically ranked as less sonorous than laterals because codas of the form -rl# are found in Germanic languages, for example, but not -lr# codas (Wiese 2001). The minimum sonority distance principle is evoked to rank trills amongst the least sonorous of liquids, because only laterals and flaps prototypically appear as the second member of complex onsets in Spanish (Baković 1995; Padgett 2003).

Yet if a language uses clusters which violate the SSP, we are forced to modify the hierarchy for that language, revise our conception of the syllable, or simply declare such examples to be exceptional. Although syllable structure in Spanish invariably conforms to the sonority sequencing principles specified by the hierarchy in Eq. 9.1 (Section 3.2), many syllables in Russian do not (Section 6.3.1). Unless we revise the sonority hierarchy for Russian – and also for Polish (*mdły* 'tastless'), French (/mordr/ 'to bite'), Bella Coola (/pɬtknɬp/ 'bitter cherry tree') and English (*sprints*) – we must appeal to concepts such as extra-syllabicity (Rochoń 2000; Wiese 2001), and additional theoretical apparatus such as syllable appendices (Kiparsky 1979; Vaux 2009).

The circularity of phonological arguments for sonority are also noted by Harris (2006: 1485), who observes:

> "(The sonority hierarchy) is no more than a taxonomic redescription of the patterns it is designed to account for. Its main value is heuristic, aiding the formulation of generalizations about sound sequences that would perhaps otherwise have remained unexpressed or even undiscovered. For the hierarchy to take on explanatory value, it needs to be defined in terms of factors that are independently known to shape the design of phonological systems."

I propose that the relevant set of factors are gestural in nature, and that phonotactic constraints on liquids are not determined by a single parameter, but result from the interaction of a number of factors related to gestural organization and recovery. Although some of these factors vary from language to language, different sonorities are associated with different combinations of gestures which recur in different parts of the syllable, and give rise to the characteristic sonority profiles which are associated with the SSP.

### 9.2.2 The Gestural Basis of Syllablic Organization

In articulatory phonology, a syllable is modeled as a set of coordinated gestures, bound together through stable coupling relationships (Krakow 1989; Nam et al. in press). Phonotactic properties of segments result from the interaction of three different sets of constraints:

i. general principles of intergestural coordination
ii. language-specific preferences for inter-gestural coordination
iii. constraints related to the recoverability of coordinated gestures

The most fundamental phonotactic properties of the syllable derive from parametric differences in the constituent gestures of segments which act as consonants, and those which act as nuclei. Liquids – like any other type of segment – may function as onsets, codas, or nuclei, depending on the phasing and duration of their constituent gestures with respect to others. Unlike traditional accounts of the syllable, there is no need to specify a hierarchical skeleton of structural positions, nor to stipulate which types of segments or features may fill different slots.

Syllable structure in Hawaiian, for example, is limited to the form (C)V(V) – no codas, complex onsets or syllabic consonants are allowed – so the single liquid /l/ is restricted to the same phasing relationship (0°) and oscillator stiffness ratio (2:1) which defines all consonantal-vocalic coupling relationships. The Hawaiian words *la* 'day', *ma* 'toward' and *ka* 'container' share the same phonotactic structure, governed not by the relative sonorities of their onsets and vowels (which would differ if quantified by any phonetic parameter), but by the stability of the in-phase coupling relationships established between their onset and nucleic gestures.

In contrast to the highly restricted distribution of liquids in Hawaiian syllables, Tashlhiyt Berber allows liquids to appear in all positions in the syllable; like Hawaiian, liquids do not pattern any differently from the other consonants in Berber, as all types of consonant – including voiceless stops – may act as syllable nuclei (Dell & Elmedlaoui 2002). While problematic for sonority-based accounts of syllable structure, the phonotactics of Berber can be reconciled with an articulatory model in which a greater range of gestures may function as nuclei, in which case they would be specified for different durations, and enter into different coupling relationships with their ambisyllabic gestures.

In the word *ts.srw.sak* 'she gave you the impression that ...', the gestures of the nuclear rhotic would be specified for the same duration, and coupled in the same relationship with the onset gestures, as the sibilant and vowel which function as nuclei of the the first and third syllables (Fig. 9.2, right). The rhotic onset in the word *s.ru.sas* 'lay down for him!' would consist of the same gestures, but would be shorter in duration, and coupled in-phase with the high back vowel which is now functioning as the nucleus (Fig. 9.2, left).

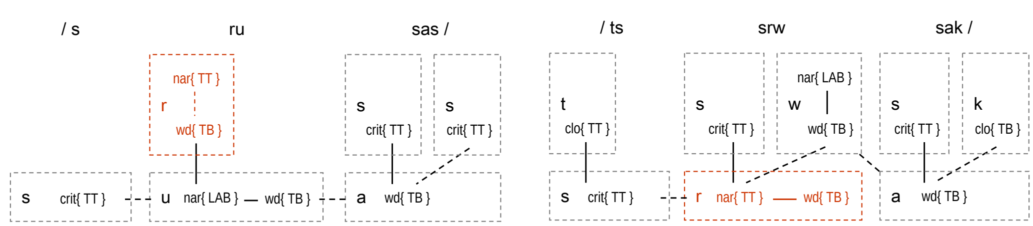



FIGURE 9.2: **Syllabic organization in Tashlhiyt Berber**: liquids – like all other consonants – can appear in syllable nuclei or periphery. The same pair of gestures which serve as a rhotic onset in /s.ru.sas/ (left) can function as a nucleus (/ts.srw.sak/, right) by altering durations and coupling relationships with ambisyllabic gestures.

The phonotactics of liquids in Hawaiian and Berber are maximally different, and reflect two radical types of syllabic organization which resist characterization under frame-and-content theories of syllable stucture governed by scalar sonority hierarchies. The examples above demonstrate that by modeling liquids using a universal set of gestural primitives, we can describe their distributions in all types of syllablic structures in terms of different types coupling relationships, without having to appeal to syllabic templates or to account for issues of sonority.

Given that liquids can appear in all positions in the syllable, the next question to be addressed is why, cross-linguistically, they tend to display the distributional properties identified in Chapter 2 – a capacity to cluster with obstruents, and an ability to function as a nucleus in languages which disallow obstruent nuclei.

### 9.2.3 The Gestural Basis of Liquid Phonotactics

In both Hawaiian and Berber, onsets are restricted to a single consonant. As syllable complexity increases, two additional, related principles of syllable structure become relevant: competition for articulators, and gestural recoverability. If coordinative stability were the only factor governing gestural organization, all onset gestures would be perfectly synchronous because in-phase coupling is the optimally stable coordinative relationship (Nam & Saltzman 2003). Yet if onset gestures corresponding to different segments were all articulated in parallel, they would not be recoverable by the listener (Mattingly 1981; Browman & Goldstein 2000).

One reason that liquids might be preferred segments in clusters is their multigestural constituency. Clusters of hetero-organic gestures such as -/pt/- and -/pk/- can be overlapped, but are more likely to be reliably recovered by the listener if they are partially displaced in time (Chitoran et al. 2002). Clusters of monolithic homo-organic gestures (e.g. -/pb/-, -/st/-, geminates) *must* be linearized simply in order to be pronounced. Because liquids consist of multiple gestures, they present more options for organization with respect to the other gestures in a cluster, in ways which facilitate both parallel production (Liberman et al. 1967) and recovery by a listener who is cognizant of the potential coupling relationships between gestures in her language.

Two ways in which onsets may be reorganized so as to facilitate gestural recovery are the explicit phasing of gestures with respect to each other, and the spontaneous displacement of gestures in opposite directions around a C-center (Browman & Goldstein 2000). Provided that the resulting phasing does not exceed a critical threshold, both of these processes have the effect of introducing asynchronies which will aid perception by a listener, while still maintaining a stable constellation of gestures in the onset which are collectively in-phase with the nucleus (Chitoran et al. 2002). If an onset contains a consonant and a liquid, there are two ways in which this displacement can be achieved: delaying the obstruent gestures to create the temporal ordering #LC-, or moving the gestures associated with the liquid closer to the nucleus, resulting in onsets of the form #CL-.

When clusters are organized such that obstruents appear closer to the nucleus than liquid or nasals, it would appear to be render the syllable less stable. In Germanic languges, for example, codas of the form -CL# or -CN# are generally not possible because the sonorant is syllabified separately, e.g. English: *bottle* [ˈbʌt.l̩], *butter* [ˈbʌt.r̩], *bottom* [ˈbʌt.m̩] (and see Scheer, 2004, on trapped consonants in Germanic). Even in Slavic languages, which do allow some codas of this form, such combinations have proven historically unstable, e.g. Russian: /sestër/ *'sister-gen.pl'* < /sestrá/; /vʲel/ *'drove-*M.SG.DEF.IMPF' < /vest-l/ (Pugh, 2007; and see discussion in Section 6.3.1). Thus, although both -LC# and -CL# configurations are potential solutions to the problem of gestural displacement to aid recovery in codas, the -LC# ordering would be appear to be optimal in terms of preserving the structural integrity of the syllable. For the same reasons, #CL- appears to represent the optimally-stable recoverable configuration for a complex onset.

Evidence from articulatory studies suggest that the same principle applies to intergestural coordination in complex segments, as well as clusters. Sproat & Fujimura (1993) proposed that timing asymmetries in English coda laterals are the result of the "affinity for the nucleus" shown by the vocalic gesture of the approximant. Browman & Goldstein (1995a) accounted for the lag in tongue tip gestures of nasals and laterals, relative to their corresponding velic and dorsal gestures in English, by proposing that coda organization in English is governed by the principle that "gestures involving wider constrictions precede those with narrower constrictions" – a principle which is consistent with intergestural timing asymmetries observed in coda liquids in Squamish Salish and Mandarin Chinese (Gick et al. 2006), and in coda nasals in English (Byrd et al. 2009). The details of intergestural and cluster timing in Spanish and Russian liquids remain to be investigated; however, the ultrasound data presented in Sections 4.4.2 indicates that dorsal gestures precede tongue tip activity in codas in Spanish.

Bloomfield (1914), Jespersen (1928), Goldsmith (1990) and others have proposed that the phonetic basis of sonority does not lie in the acoustic properties of the speech signal (c.f. Sievers 1881, Ladefoged 1971, Clements 2009, etc.) but corresponds primarily to supralaryngeal aperture. In general, there appears to be an inverse correlation between the constriction degree of a supraglottal gesture and its proximity to the nucleus – a distribution shown in Figure 9.3, where the apertures of the constituent gestures in three English words are plotted over time.

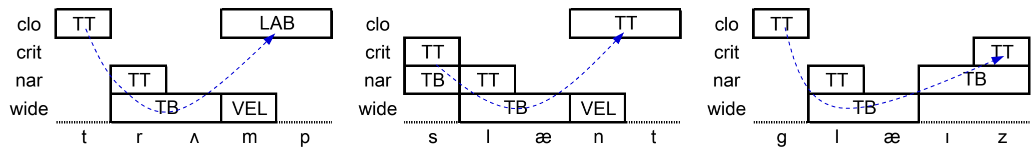



FIGURE 9.3: **Gestural Aperture and Proximity to the Nucleus** – constriction degrees of primary gestures in the English words *trump*, *slant* and *glaze*. Sonority sequencing is an artefact of gestural organization in the syllable.

In summary, if liquids are modeled as coordinative stuctures of consonant-like tongue tip and vowel-like tongue body gestures, then under a coupled-oscillator model of syllable structure, their phonotactic distribution follows from general principles of gestural organization: an interacting set of constraints on coordinative stability, gestural recoverability and language-specific preferences for gestural organization. In both onsets and codas, nasals, liquids and glides tend to distribute closer to the nucleus because they all use an instrinsic gesture (tongue body or velic) of greater aperture than the gestures of the obstruents with which they cluster. A syllable stucture in which these gestures are coupled more closely to the nucleus would appear to be the optimal arrangement for a stable contiguous constellation of gestures which is recoverable by a listener. Under this view, sonority is an artefact of, rather than the governing principle of syllabic organization.

## 9.3 Liquid Allophony and Change

It was shown in Chapter 2 that, other than their shared phonotactics, the most important property that characterizes liquids is their interchangeability within the class, observed cross-linguistically in rhotic-lateral allophony, alternation, neutralization and other phenomena. In Chapters 5 and 8, some phonological processes specific to Spanish and Russian liquids were examined. In this section, a gestural account of some class-based phenomena involving liquids in other languages will be proposed.

### 9.3.1 Liquid Allophony in Small Inventories

A gestural model of liquid structure offers some insights into the allophonic variation observed in languages with small consonant inventories. The Papuan language Rotokas, for example, uses only six phonologically constrastive consonants. The three voiced 'stops' are realized as a wide range of consonants which occur in free variation (Firchow & Firchow 1969; Table 9.1). Three different liquids are attested amongst the allophones of the voiced coronal stop, suggesting that the tongue tip gesture is produced in combination with a variety of uncontrolled dorsal postures.

| | LABIAL | CORONAL | DORSAL |
|---|---|---|---|
| **Unvoiced** | [p] | [t] ∼ [s] ∼ [ts] | [k] |
| **Voiced** | [b] ∼ [β] ∼ [ʋ] ∼ [m] ∼ [mb] | [d] ∼ [ɾ] ∼ [ɹ] ∼ [n] ∼ [l] | [g] ∼ [ɣ] ∼ [ŋ] |

TABLE 9.1: **Consonantal allophony in Rotokas** (Firchow & Firchow 1969; Morén 2007).

Consonantal contrasts in Rotokas appear to be created by coordinating an organically-differentiated constriction (lips/tongue tip/tongue body) with one of two glottal gestures (constricted/open). (Supraglottal) constriction degree is not exploited to create phonological constrast in this system, nor is velic aperture, nor inter-gestural coordination of supraglottal tract variables. Because these other articulatory dimensions are uncontrolled, they can and do modify the salient gestures, resulting in the range of segments which occur as allophones. For example, because nasalization is not contrastive in Rotokas, the velum is phonologically uncontrolled. If it is lowered at the same time that a lip closure gesture is produced, a nasalized allophone of the labial stop will result.

Liquid allophones of voiced coronal consonants are also attested in other languages with small consonant inventories, including Nasioi ([d] ∼ [ɾ] ∼ [l]; Hurd & Hurd, 1966) and Gadsup ([d] ∼ [ɾ]; Frantz, 1976). A liquid allophone of the voiced dorsal stop occurs in Pirahã: [g] ∼ [ɺ͡ɺ̪] (Everett 1982). Each of these allophones may be considered to result from the unplanned coordination of an additional lingual gesture with the monolithic gesture corresponding to the underlying stop consonant. Dorsal retraction at the same time that the tongue tip closes in the Nasioi /d/, for example, could result in a lateral allophone of the stop, while the coordination of a dental tongue-tip approximation with the dorsal gesture of the stop /g/ could produce the rare flap allophone of Pirahã.

Because these combinations of articulations are cognitively unassociated in these languages, they result in allophonic free variation. The same combinations of gestures have been phonologically harnessed in other languages through the development of additional coupling relationships. One of these relationships – the temporal coordination of a tongue tip and tongue body gesture in a manner which affords spontaneous voicing – is the configuration which corresponds to a phonologically constrastive coronal liquid segment. Some languages only use one such configuration for phonological contrast (Japanese, Korean, Gonja), while languages with more than one liquid consonant have exploited multiple coordinative structures of this type, as we have seen in English, Spanish and Russian.

### 9.3.2 Phonological Behavior of Post-Vocalic Liquids

In Chapter 2, it was shown that post-vocalic liquids exhibit some common behaviors in many languages: lengthening or altering the preceding vowel, vocalizing, and deleting. Under a gestural model, we can analyze all of these processes as interactions between the tongue body gestures of the nucleus and the liquid.

The compensatory lengthening which accompanies post-vocalic liquid deletion in non-rhotic varieties of English, for example, could result from the reorganization of dorsal gestures in the coda. The gestural score for the word *heart*, as it would be pronounced in a rhotic dialect, is illustrated in Figure 9.4 (left). Because the dorsal targets of English rhotic approximants and low back vowels are very similar (Delattre & Freeman 1968), the nuclear tongue body constriction will not change signifigantly into the coda. If the tongue tip gesture of the rhotic is deleted, delayed or strengthened, such that it blends with, or is masked by the closure gesture of the coda stop, the resulting ensemble of gestures will correspond to a non-rhotic pronounciation, with compensatory lengthening of the nuclear vowel (Figure 9.4 right).

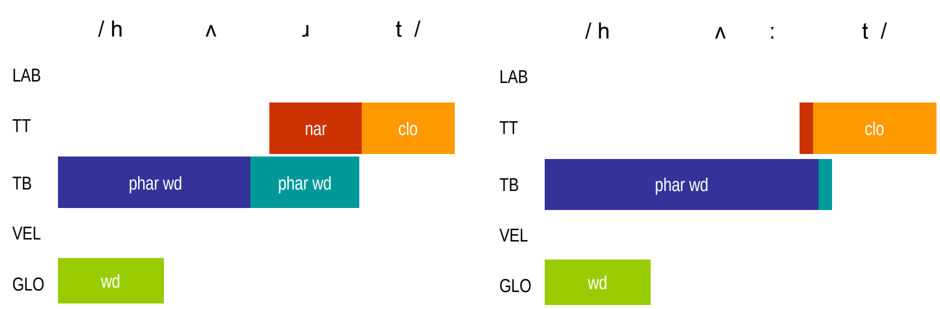



FIGURE 9.4: **Compensatory lengthening resulting from deletion of post-nuclear liquids**: non-rhotic English varieties.

Length-contrastive minimal pairs in Australian English such as *hut* [hɐt]/*heart* [hɐːt] and *huff* [hɐf]/*half* [hɐːf] would appear to be the result of this type of process (Table 2.17). The gestural residue of post-vocalic liquid deletion can be seen even more clearly in words with different types of vowels. When a coda rhotic follows a high or a front non-low vowel in Australian English, the syllable rime is realized as a type of schwa-final diphthong: *tier* [tiːə], *tear (v.)* [tɛːə], *tour* [tʊə]. Each of these words concludes with a low back vocalic gesture resembling that of the tongue body gesture which is intrinsic to the English rhotic approximant. Although the tongue tip gesture (and the labial approximation) which was originally coordinated with the coda /ɹ/ has been deleted in non-rhotic dialects, the tongue body gesture remains.

Post-vocalic liquid deletion with compensatory lengthing is a characteristic feature of the Turkic languages (Kavitskaya 2002), and as in Commonwealth Englishes, a relic of the deleted liquid often remains. In Uyghur, for example, affected vowels are lowered when they are lengthened – a process which could result from blending of the tongue body gestures of the nucleus and the deleted coda rhotic: /kör/ [kʰœː] 'look!', /boldi/ [bɔːˈldɪ] 'he became', /ders/ [dæːs] 'lesson', /tar/ [tʰɑː] 'look!' (Johanson & Csató 1998).

### 9.3.3 Vocalically-Conditioned Liquid Change

It was shown in Chapters 5 and 8 that tongue body constriction location is an essential parameter in the specification and differentiation of liquid consonants. As a result, liquids are prone to change when they occur in some vocalic environments, if the tongue body gestures of the vowels and liquids interact.

An example of this type of vocalically-conditioned change is the rhoticization which occurs in Sphakiá Greek (Section 2.2.7). Trudgill (1989) observes that laterals in this dialect are realized as a retroflex rhotic approximant when they occur before the vowels /u/-/o/-/a/, intervocalically, or after a labial fricative (Table 9.2).

| | | |
|---|---|---|
| /kaˈli/ | [kaˈli] | 'good'-f.sg |
| /kaˈla/ | [kaˈɻa] | 'good'-n.plu |
| /ˈlaði/ | [ˈlaði] | 'oil' |
| /to ˈlaði/ | [tɔˈɻaði] | 'the oil' |
| /luˈtro/ | [luˈtro] | 'Loutro' |
| /sto luˈtro/ | [stɔɻuˈtro] | 'to Loutro' |
| /aˈvlaki/ | [aˈvɻatɕi] | 'ditch' |

TABLE 9.2: **Rhoticization of clear laterals**: Sphakiá Greek (Trudgill 1989).

Liquid variation in Sphakiá Greek appears to result from the blending of the tongue body gestures of the lateral and the tautosyllabic context vowel. The Greek lateral is a clear /l/ (Trudgill 1989), so we can assume that its dorsal gesture, like that of the Spanish lateral (Chap. 4), has an anterior constriction target location. When produced before a front vowel, the coarticulatory influence of the vowel which is coupled to the dorsal gesture of the lateral – even if the vocalic blending parameters dominate the consonant – will not alter its constriction location significantly, so the liquid is realized as a clear lateral: /kali/ → [kali]. It is noteworthy that very little dorsal displacement due to vocalic coarticulation was observed when the Spanish clear /l/ was produced in a front vowel context (Figs. 4.26 and 4.27).

When the lateral is produced before a back vowel, blending of the lateral and vocalic tongue body gestures appears to cause the dorsum to retract to the more posterior posture used in the English rhotic approximant (Fig. 1.2). The fact that the allophone produced in this environment is perceived as a retroflex approximant suggests that the whole tongue is retracted in the back vowel enviroment – if the tongue tip remained fronted, the ensuing elongation of the tongue would likely produce the percept of an English or Russian-like dark lateral.

The fact that the labial fricative is transparent in this process (/ˈpavlos/ → [ˈpavɻɔs]) is consistent with Gafos' (1999) account of articulatory locality: rhoticization does not occur when a dorsal consonant precedes the lateral because the intervening tongue body gesture would block the contiguity of the vocalic gestures.[3] The labial gesture of the consonant /v/, on the other hand, does not prevent the low vowel of the preceding syllable conditioning the lateral allophony by entering into a local articulatory relationship with the onset lateral (Figure 9.5 right).

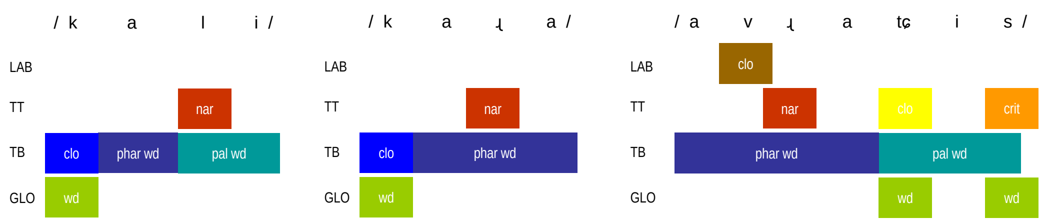



FIGURE 9.5: **An articulatory account of rhoticization of clear laterals in Sphakiá Greek**. Left: clear /l/ coupled to front vowel; Center: rhoticized liquid /ɻ/ coupled to back vowel; Right: articulatory transparency of labial consonant.

## 9.4 Asymmetries between Liquids

A variety of phenomena were surveyed in Section 2.4 which reveal asymmetries within the class of liquids. Evidence from diachronic stability of clusters, consonant sequencing in clusters, potential for syllabicity, propensity for assimilation and other processes suggests that cross-linguistically, when liquids differ in their behavior, rhotics tend to pattern more closely with vocoids, and laterals with obstruents. The results of the experiments into liquid production described in Chapters 7 and 8 suggest two possible phonetic bases for these asymmetries: (i) differ-

[3] Trudgill (1989) does not give an example of clear lateral allophony after non-labial consonants, but asserts that rhoticization does not occur in this environment.

ences in dorsal aperture and stability, and (ii) differences in tongue tip stiffness, between laterals and rhotics.

Articulatory investigation into dorsal articulation revealed that, of the three liquids, the Spanish trill is characterized as having the greatest stability (Section 4.3.5). The dynamic properties of the tongue body gesture observed in trill production in both Spanish and Russian resemble those of vowels in that they are stable over a prolonged interval – a property which may be essential to maintaining stability in trill production. In the development of Slavic, for example, palatalized rhotics have proven to be more diachronically unstable than non-palatalized rhotics (Carlton 1991), which may be due to the perturbation of the tongue body introduced by the palatalization gesture (Iskarous & Kavitskaya, submitted).

If it is the case that rhotic tongue body gestures are more intrinsically stable over a longer period of time than the tongue body gestures of some types of lateral approximants, this might account for some of the phonological asymmetries observed above: the more 'vocalic' qualities of rhotics could stem from their greater capacity to couple with other gestures in the syllable in a manner which faciliates gestural recovery by the listener.

In the articulatory models of coronal liquids proposed in Sections 5.1 and 8.1, tongue tip damping (and stiffness) was found to be a critical parameter which differentiated the rhotics from the lateral. Although all three liquids in Spanish, for example, share vowel-like dorsal constrictions (TBCD = wide), the lateral was modeled with the same tongue-tip gesture specified for other consonants (damping ratio = 1), while the rhotics were modeled using lightly-damped tongue tip gestures. Because of this difference in gestural constituency, we can consider the lateral – which uses a more rigidly controlled coronal gesture – to be more 'consonantal' than the rhotics. Given that many languages avoid homorganic obstruent-obstruent sequences, presumably because of difficulties in producing or recovering adjacent similar consonantal gestures, this might account for the typological preference for #Cr- over #Cl- clusters, as well as the diachronic instability of #Cl- onsets in Romance (Table 2.22).

While the observations made here are consistent with the articulatory data obtained from these ultrasound studies, they remain speculative. More detailed investigation into patterns of gestural coordination in rhotics and laterals in a greater range of languages will be required in order to examine the possible gestural bases of phonological asymmetries between liquids.

## 9.5 Uvular Rhotics

It was shown in Chapter 2 that uvular rhotics are problematic for feature-based accounts of liquids, if the canonical form of the rhotic is a fricative, rather than a trill. A sonorant class of liquids can be defined in varieties of French, German, Dutch and Portuguese in which this rhotic is considered to be /ʀ/, but not for varieties in which the canonical form of this phoneme is [ʁ] or [χ], because these segments are [-sonorant].

The fundamental problem is that phonetic relationships between the various allophones of uvular segments are gradient, while the units of representation in feature-based phonological theory are binary. Both sonorant and non-sonorant allophones pattern as rhotics in all of these languages, and the trill /ʀ/ devoices or spirantizes in a wide variety of environments. Uvular phonemes considered to be underlyingly approximant, such as that of oriental Hebrew, are transcribed with the fricative symbol [ʁ] (Laufer 1999): the fact that the IPA does not provide an independent symbol for an uvular approximant suggests that categorical distinctions between trills, fricatives and approximants are not straightforward for consonantal constrictions formed in this region of the mouth.

In an articulatory phonological model, we are better able to model the behavior of uvular consonants because the phonological primitives are neither binary not privative. Tract variable constriction degree targets are categorical, but the linguistic task might be achieved in a variety of ways. The tract variable specification TBCD{crit}, for example, refers to the narrow range of constriction apertures which, given the right aerodynamic conditions in the region of the tract specified by the constriction location, will result in frication. The same constriction, under different conditions, might also produce a trilled or approximant allophone. Despite differences in phonetic realization, the phonological primitives remain the same, and we can define a class of consonants over the group of consonants which share a common set of gestural specifications for constriction degree, constriction location, or both.

### 9.5.1 Historical Development of Uvular Rhotics

The development of uvular rhotics in languages which previously used coronal trills is not well understood. The development may have been a borrowing in Western European communities which regarded French as a prestige language (Trautman 1880); however, the genesis of uvular rhotics in French rhotics remains to be explained. Regardless of the origins, it is difficult to account for the fact that uvular rhotics coexist with, substitute for, and alternate with coronal rhotics in many languages which use them (Portuguese, Swedish, Hebrew). The innovation can be rapid: (Sankoff et al. 2007) describe a transformation from /r/ to /ʀ/ usage in some Montreál French-speaking communities in the last thirty years.

A gestural model of coronal rhotics can provide some insights into potential mechanisms of change in these langugaes. The articulation of trills in both Spanish (Ch. 4) and Russian (Ch. 7) was shown to involve stable, prolonged tongue body gestures with posterior constriction targets. In the case of Spanish, the dorsal gesture of the trill was the most retracted of all liquids; in both languages, the tongue body raised towards the soft palate during the production of trills in low vowel contexts. If the tongue body gesture in this region became more constricted (through overshoot, for example), frication or trilling of an undercontrolled uvular could result, under the appropriate aerodynamic conditions. With an accompanying lenition and eventual loss of the tongue tip gesture, the transformation to an uvular rhotic would be complete.

## 9.6 Nasalized Liquids

Nasalized rhotics are found in several Niger-Congo languages including Igbo (/r̃/) and Ghotuo (/ɾ̃/), as well as the Trans-New Guinea language Waffa (/ɾ̃/); nasalized laterals are also attested in Wamey and Umbundu (/l̃/). The segments in these languages – which pattern phonologically with non-nasalized laterals and rhotics (Zec 1995, Newman 2000) – are problematic for the classification of liquids as non-nasal sonorants. In response to this dilemma, Walsh Dickey (1997) proposed the existence of the feature [liquid] to account for minimal pairs such as *ịrị́* 'to creep' / *ịr̃ị́* 'to climb' (Igbo, Dunstan 1969).

No such dilemma exists under an articulary model, where nasalization is controlled by a velic aperture tract variable which can combine with any combination of oral and glottal gestures to create additional phonological contrasts. Assuming that the trill in Igbo, like Russian and Spanish, is produced by the coordination of tongue tip and tongue body gestures, then the nasal trill would involve the coupling of the same two gestures with an additional velic openning gesture. The class of coronal liquids in all of these languages can be characterized in the same way – those segments produced through the coordination of vowel-like dorsal and consonant-like coronal gestures – whether they contain nasalized liquids or not.

## 9.7 Outstanding Issues

While an articulatory characterization of liquid consonants is capable of accounting for many aspects of their phonology, it also raises some important issues which are yet to be resolved.

### 9.7.1 Modeling Laterality

The issue of how to deal with all types of lateral segments remains unresolved in the framework of articulatory phonology. While the dark laterals found in Russian, and in English codas can be adequately represented using a purely midsagittal model, it remains to be seen how clear laterals might be properly represented. As the models of Spanish liquids presented in Chapter 5 demonstrate, the relative proximity of the dorsal and tongue tip gestures mean that the tongue is less elongated than in a dark lateral – an difference most obviously revealed in the anomalous trajectories of the higher formants in the speech synthesized from the articulatory model.

More work is required to investigate the phonetic realization of clear laterals in languages such as Spanish and German to determine their goals of production. Further experimentation may reveal additional ways in which the lingual articulation of lateral appoximants differs from that of obstruents, allowing us to better model both clear and dark laterals using the existing set of tract variables. Failing that, it may be the case that laterality must be actively controlled through an additional tract variable.

### 9.7.2 Uvular Rhotics

More work needs to be done on uvular rhotics. While the analysis presented earlier goes some way towards accounting for their historical origins, and representing them in a way which can be better reconciled with other types of rhotics, they remain a problem for phonological theory. In particular, it remains to be seen exactly how uvular liquids differ phonetically, if at all, from voiced obstruents produced at the same place or articulation. Articulatory investigation of Western Germanic and Slavic languages which contrast uvular fricative and rhotic segments will provide important insights into the phonetic basis of the class of liquids, and will provide an important test case for the model of liquid consonants being developed here.

### 9.7.3 Modeling Retroflexion

Retroflex consonants present additional challenges to the model of liquid consonants proposed here. Given that all types of retroflex consonant require more global control of lingual articulation than their apical equivalents, it is unclear exactly how retroflex liquids might differ from retroflex obstruents, and how these distinctions might be reconciled with the proposed characterization of liquids as a class. Pilot data is currently being used to examine liquid articulation in Tamil – an ideal language to pursue these issues because of its rich set of liquids and retroflex consonants.

# Chapter 10

# Conclusion

## 10.1 Summary of Findings

The most important findings of this dissertation are the following:

i. the three liquids of Spanish are characterized by a greater degree of dorsal resistance to vocalic coarticulation than the coronal stop
ii. the Spanish lateral is produced with a coronal approximation and a tongue body gesture resembling that of a mid front vowel
iii. the Spanish trill is produced with a coronal approximation and a tongue body gesture resembling that of a mid back vowel
iv. the Spanish tap is produced with a coronal approximation and a tongue body gesture resembling that of a mid central vowel
v. Russian non-palatalized liquids are characterized by a greater degree of dorsal resistance to vocalic coarticulation than the non-palatalized coronal stop
vi. of the Russian non-palatalized consonants /r/, /l/ and /d/, only the lateral is produced as a 'velarized' (pharyngealized) segment
vii. the Russian non-palatalized lateral is produced with a coronal approximation and a dorsal gesture resembling that of a mid back vowel
viii. the Russian non-palatalized trill is produced with a coronal approximation and a dorsal gesture resembling that of a mid central vowel
ix. the Russian palatalized liquids are produced with additional constraints on the posterior tongue body, not observed in the production of the palatalized Russian coronal stop

## 10.2 Summary of Claims

The most important claims of this dissertation are the following:

i. coronal liquids in Spanish and Russian are characterized by the coordinative production of tongue tip and tongue body gestures
ii. clear/dark lateral allophony results not from the absence of a dorsal gesture in the clear lateral, but from differences in tongue body constriction location
iii. liquid vocalization results from the lenition or loss of the tongue tip gesture in a liquid segment
iv. coda liquid neutralization results from the loss of distinction between tongue body constriction locations and tongue tip gestural control
v. VL metathesis may be explained as a change in the syllabic coupling relationships between the constituent gestures of adjacent liquids and vocalic nuclei
vi. vocalically-conditioned liquid allophony results from the blending of adjacent tongue body gestures associated with the liquid and the context vowels

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# Appendix A

# Language References

Primary sources of language data, and references for languages cited by name only, are listed below. Complete references may be found in the bibliography. Where the original source was not consulted, secondary references are given. Classifications are taken from Ethnologue (Lewis 2009). 'Location' refers only to the variety of the language relevant to the phonological examples cited, and is not intended to be a comprehensive description of the geographical spread of the language.

| LANGUAGE | CLASSIFICATION | LOCATION | REFERENCE |
|---|---|---|---|
| Acehnese | Austronesian | Sumatra, Indonesia | Thurgood (1999) |
| Apache | Athapaskan | New Mexico, USA | Gafos (1999) |
| Arabana | Karnic | Central Australia | Bowern (2001) |
| Aramaic | Semitic | Middle East | Hume (2004) |
| Aramaic, Mandaic | Semitic | Iran, Iraq | Ultan (1978) |
| Armenian | Indo-European | Armenia | Hayes et al. (2004) |
| Avok | Austronesian | Malekula, Vanuatu | Lynch (2009) |
| Bardi | Pama-Nyungan | WA, Australia | Bowern (p.c.) |
| Bagnères-de-Luchon | Romance | Pyrennes, France | Ultan (1978) |
| Basque | Isolate | Spain; France | Trask (1997) |
| Bella Coola | Salishan | BC, Canada | Bagemihl (1991) |
| Berber, Tashlhiyt | Afro-Asiatic | Morocco | Dell et al. (2003) |
| Boro | Tibeto-Burman | Assam, India | Basumatārī (2005) |
| Breton | Celtic | Brittany, France | Ultan (1978) |
| Bukusu | Bantoid | Kenya | Odden (2004) |
| Bulgarian | South Slavic | Bulgaria | Blevins et al. (1998) |
| Camsá | Isolate | Colombia | Howard (1967) |
| Catalan | Romance | Spain; France | Wheeler (1979) |
| Chamic | Austronesian | Vietnam | Thurgood (1999) |
| Chamorro | Austronesian | Guam | Topping (1973) |
| Chinese, Hakka | Sino-Tibetan | Guangdong, China | Lee & Zee (2009) |
| Chinese, Mandarin | Sino-Tibetan | China | van Dam (2004) |
| Croatian | South Slavic | Croatia | Crosswhite (2001) |
| Czech | West Slavic | Czech Republic | Scheer (2004) |

| Language | Classification | Location | Reference |
|---|---|---|---|
| Dairi | Malayo-Polynesian | Sumatra, Indonesia | van der Tuuk (1971) |
| Diyari | Pama-Nyungan | SA, Australia | Austin (1981) |
| Dizin | Omotic | Ethiopia | Beachy (2005) |
| Djabugay | Pama-Nyungan | Qld, Australia | Patz (1991) |
| Dschang | Niger-Congo | Cameroon | Bird (1997) |
| Dutch | West Germanic | Netherlands; Belgium | Booij (1995) |
| Dutch, S.Netherlands | West Germanic | S.Netherlands | Verstraeten et al. (2001) |
| Dyirbal, Nganjan | Pama-Nyungan | SA, Australia | Kavitskaya (2002) |
| Ega | Kwa | Côte d'Ivoire | Connell et al. (2002) |
| Endo | Eastern Sudanic | Kenya | Larsen (1991) |
| English, AAV | West Germanic | USA | Green (2002) |
| English, Australian | West Germanic | Australia | Proctor |
| English, Liberian | West Germanic | Liberia | Hancock (1974) |
| English, UK | West Germanic | UK | Hardcastle et al. (1989) |
| Eskimo | Eskimo-Aleut | Canada; USA | Ultan (1978) |
| Fante | Niger-Congo | Ghana | Abakah (2005) |
| Flemish, Brabant | West Germanic | Brabant, Belgium | Verstraeten et al. (2001) |
| French | Romance | France; Belgium | Carton (1974) |
| French, Agde | Romance | Agde, France | Ultan (1978) |
| French, Montreal | Romance | QC, Canada | Sankoff (2007) |
| Gadsup | Trans-New Guinea | E.Highlands, PNG | Frantz (1976) |
| Gayo | Malayo-Polynesian | Sumatra, Indonesia | Hume (2004) |
| German | West Germanic | Central Europe | Wiese (2001) |
| German, Berlin | West Germanic | Berlin, Germany | Wiese (2001) |
| Georgian | South Caucasian | Georgia | Fallon (1993) |
| Greek, Attic | Indo-European | Eastern Europe | Allen (1973) |
| Greek, Homeric | Indo-European | Eastern Europe | Allen (1973) |
| Greek, Modern | Indo-European | Greece | Newton (1972) |
| Greek, Sphakiá | Indo-European | Crete, Greece | Trudgill (1989) |
| Gbeya | Niger-Congo | C.African Republic | Samarin (1966) |
| Gonja | Niger-Congo | Ghana | Zec (1995) |
| Gooniyandi | Bunaban | WA, Australia | McGregor (1990) |
| Gothic | East Germanic | Ukraine | Chomsky et al. (1968) |
| Ghotuo | Niger-Congo | Nigeria | Elugbe (1989) |
| Guugu Yimidhirr | Pama-Nyungan | Qld, Australia | Dixon (1980) |
| Hadza | Khoisan | Tanzania | Sands et al. (1993) |
| Hausa | Chadic | Nigeria | Newman (2000) |
| Hatam | Isolate | Papua, Indonesia | Reesink (1998) |
| Hawaiian | Polynesian | Hawaii | Pukui et al. (1979) |
| Hebrew, Modern | Semitic | Israel | Laufer (1999) |
| Hindi | Indo-Aryan | India | Ohala (1994) |
| Iban | Malayo-Polynesian | Sarawak, Malaysia | Blust (1996) |
| Icelandic | North Germanic | Iceland | van de Torre (2003) |
| Igbo | Niger-Congo | Nigeria | Dunstan (1969) |
| Irish | Celtic | Ireland | Ní Chiosáin (1999) |
| Italian | Romance | Italy | Maiden (2000) |
| Italian, Florentine | Romance | Florence, Italy | Holton (1994) |
| Jamsay | Niger-Congo | Mali | Heath (2008) |
| Japanese | Japonic | Japan | Itô (1995) |
| Javanese | Malayo-Polynesian | Java, Indonesia | Blust (1996) |
| Jibbali | Semitic | Oman | Johnstone (1981) |
| Jita | Bantoid | Tanzania | Downing (2001) |

| LANGUAGE | CLASSIFICATION | LOCATION | REFERENCE |
|---|---|---|---|
| Kaititj | Arandic | NT. Australia | Ladefoged et al. (1996) |
| Kanuri | Nilo-Saharan | Niger; Chad | Hutchison (1981) |
| Kammu | Mon-Khmer | Burma | Thurgood (1999) |
| Karnic | Pama Nyungan | Central Australia | Bowern (2001) |
| Kayah Li, Eastern | Tibeto-Burman | Burma | Solnit (1997) |
| Kazakh | Turkic | Kazakhstan | Johanson et al. (1998) |
| Keliko | Central Sudanic | Sudan | Tucker (1940) |
| Kikongo Kituba | Creole (Kongo) | Congo | Mufwene (2001) |
| Komi | Uralic | Russian Federation | Kavitskaya (2002) |
| Korean | Isolate | Korea | Iverson et al. (1994) |
| Korean, 5th C. | Isolate | Korea | Cho (2001) |
| Koyra Chiini | Nilo-Saharan | Mali | Heath (2008) |
| Kuman | Trans-New Guinea | Simbu, PNG | Trefry (1969) |
| Lardil | Tangkic | NT, Australia | Round (p.c.) |
| Latin | Italic | Southern Europe | Allen (1973) |
| Lezgi | North Caucasian | Dagestan, Russ. Fed. | Haspelmath (1993) |
| Lithuanian | Baltic | Lithuania | Levin (2001) |
| Logo | Central Sudanic | D.R. Congo | Tucker (1940) |
| Macedonian | South Slavic | Dihovo, Macedonia | Crosswhite (2001) |
| Malay | Malayo-Polynesian | Malaysia | van der Tuuk (1971) |
| Manam | North New Guinea | Madang , PNG | Turner (1986) |
| Maori | Polynesian | New Zealand | Tregear (1969) |
| Marathi | Indo-Aryan | Maharashtra, India | Ultan (1978) |
| Maskelynes | Austronesian | Vanuatu | Lynch (2009) |
| Mayi | Pama-Nyungan | Qld, Australia | Breen (1981) |
| Mbabaram | Pama-Nyungan | Qld, Australia | Dixon (1991) |
| Menangkabau | Malayo-Polynesian | Sumatra, Indonesia | van der Tuuk (1971) |
| Michif | Mixed: French-Cree | Manitoba, USA | Rosen (2007) |
| Mokilese | Far Oceanic | Micronesia | Harrison et al. (1976) |
| Mongolian | Mongolic | Mongolia | Ramsey (1987) |
| Moru-Madi | Central Sudanic | Uganda, Sudan | Tucker (1940) |
| Nahuatl | Uto-Aztecan | Mexico | Langacker (1979) |
| Nasioi | South Bougainville | Bougainville, PNG | Hurd et al. (1966) |
| Navajo | Athapaskan | Ar, NM, Ut, USA | Hoijer (1974) |
| Nii | Trans-New Guinea | W. Highlands, PNG | Stucky et al. (1973) |
| Onondaga | Iroquoian | ON, Canada | Kavitskaya (2002) |
| Oromo | Cushitic | Ethiopia | Fallon (2002) |
| Panyjima | Pama-Nyungan | WA, Australia | Dench (1991) |
| Persian | Indo-Aryan | Iran | Ultan (1978) |
| Pirahã | Mura | Brazil | Everett (1982) |
| Pitta-Pitta | Pama-Nyungan | Qld, Australia | Blake (1979) |
| Polish | West Slavic | Poland | Blevins et al. (1998) |
| Polynesian, Eastern | Austronesian | Oceanea | Blust (1996) |
| Portuguese | Romance | Portugal; Brazil | Azevedo (2005) |
| Portuguese, Caipira | Romance | São Paulo, Brazil | Azevedo (1981) |
| Portuguese, European | Romance | Portugal | Cruz Ferreira (2004) |
| Proto-Polynesian | Austronesian | Oceania | Tregear (1969) |
| Proto-Slavic | Indo-European | Eastern Europe | Blevins et al. (1998) |
| Rade | Austronesian | Vietnam | Thurgood (1999) |
| Romanian | Romance | Romania | Chitoran (2002) |
| Romansch | Romance | Switzerland | Montreuil (1999) |
| Rotokas | North Bougainville | Bougainville, PNG | Firchow et al. (1969) |

| LANGUAGE | CLASSIFICATION | LOCATION | REFERENCE |
|---|---|---|---|
| Russian | East Slavic | Eastern Europe | Timberlake (2004) |
| Sabaot | Eastern Sudanic | Kenya | Larsen (1991) |
| Salar | Turkic | China | Johanson et al. (1998) |
| Samoan | Polynesian | Samoa | Tregear (1969) |
| Sanskrit, Vedic | Indo-European | India | Watkins (1992) |
| Sardinian, Campadinian | Romance | South Sardinia | Frigeni (2005) |
| Sardinian, Sestu | Romance | Sestu, Sardinia | Smith (2005) |
| Serbian | South Slavic | Serbia, Montenegro | Crosswhite (2001) |
| Serbo-Croatian | South Slavic | Yugoslavia | Gick et al. (2006) |
| Spanish | Romance | Spain | Hualde (2005) |
| Spanish, Andalusian | Romance | Spain | Holton (1994) |
| Spanish, Carribean | Romance | Carribean | Willis (2006) |
| Spanish, Cuban | Romance | Cuba | Quilis (1999) |
| Sentani | East Bird's Head | Papua, Indonesia | Cowan (1965) |
| Shan | Tai | Burma | Matisoff (2003) |
| Slovak | West Slavic | Slovakia | Rubach (1993) |
| Songhay, Humburi Senni | Nilo-Saharan | Mali | Heath (2008) |
| Squamish | Salish | BC, Canada | Gick et al. (2006) |
| Sranan | Creole (English) | Surinam | Parkvall (2007) |
| Sundanese | Malayo-Polynesian | Java, Indonesia | Cohn (1992) |
| Swedish | North Germanic | Scandinavia | Engstrand (2001) |
| Tagalog | Malayo-Polynesian | Philippines | Ultan (1978) |
| Tahltan | Athapaskan | BC, Canada | Gafos (1999) |
| Tamil, Literary | Dravidian | India; Sri Lanka | Krishnamurti (2003) |
| Tamil, Sri Lankan | Dravidian | Jaffna, Sri Lanka | Kuno (1958) |
| Tamil, Standard | Dravidian | Tamil Nadu, India | Schiffman (1999) |
| Tarao | Tibeto-Burman | Manipur, India | Thurgood (1999) |
| Thai | Tai | Thailand | Iwaski et al. (2005) |
| Telegu | Dravidian | A. Pradesh, India | Hume (2004) |
| Tiwi | Australian | NT, Australia | Osborne (1974) |
| Toaripi | Trans-New Guinea | Gulf Province, PNG | Brown (1973) |
| Toba Batak | Malayo-Polynesian | Sumatra, Indonesia | van der Tuuk (1971) |
| Tongan | Polynesian | Tonga | Tregear (1969) |
| Tukang Besi | Austronesian | Sulawesi, Indonesia | Donohue (1999) |
| Turkic | Altaic | Eurasia | Johanson et al. (1998) |
| Turkish | Turkic | Turkey | Johanson et al. (1998) |
| Tswana | Bantoid | Botswana | Nurse et al. (2003) |
| Twi | Niger-Congo | Ghana | Michaelis (2008) |
| Tzeltal | Mayan | Mexico | Gafos (1999) |
| Umbundu | Bantoid | Angola | Schadeberg (1990) |
| Unua | Austronesian | Vanuatu | Lynch (2009) |
| Uyghur | Turkic | China | Johanson et al. (1998) |
| Waffa | Trans-New Guinea | Morobe, PNG | Stringer et al. (1971) |
| Wangkangurru | Karnic | Central Australia | Bowern (2001) |
| Wangkayutyuru | Karnic | Central Australia | Bowern (2001) |
| Warray | Pama-Nyungan | NT, Australia | Borowsky et al. (1997) |
| Warrgamay | Pama-Nyungan | Qld, Australia | Dixon (1980) |
| Welsh | Celtic | Wales, UK | Ladefoged et al. (1996) |
| Xhosa | Bantoid | South Africa | Ladefoged et al. (1996) |
| Yaygir | Pama-Nyungan | NSW, Australia | Crowley (1979) |
| Yidiɲ | Pama-Nyungan | Qld, Australia | Dixon (1977) |
| Yoruba | Niger-Congo | Nigeria | Akinbiyi (2001) |

| Language | Classification | Location | Reference |
|---|---|---|---|
| Zoque | Mixe-Zoque | Chiapas, Mexico | Ultan (1978) |
| Zulu | Bantoid | South Africa | Nurse et al. (2003) |

# Appendix B

# Spanish Elicitation Items

| PROMPT | GLOSS | IPA | TARGET | ENVIRON |
|---|---|---|---|---|
| lime | *'he files'* | ['lime] | /l/ | # _ /i/ |
| rime | *'he rhymes'* | ['rime] | /r/ | # _ /i/ |
| dime | *'give me'* | ['dime] | /d/ | # _ /i/ |
| lema | *'motto'* | ['lema] | /l/ | # _ /e/ |
| rema | *'he rows'* | ['rema] | /r/ | # _ /e/ |
| tema | *'topic'* | ['tema] | /t/ | # _ /e/ |
| lama | *'moss'* | ['lama] | /l/ | # _ /a/ |
| rama | *'branch'* | ['rama] | /r/ | # _ /a/ |
| dama | *'lady'* | ['dama] | /d/ | # _ /a/ |
| loma | *'hillock'* | ['loma] | /l/ | # _ /o/ |
| Roma | *'Rome'* | ['roma] | /r/ | # _ /o/ |
| doma | *'he tames'* | ['doma] | /d/ | # _ /o/ |
| lumbre | *'fire'* | ['lumbre] | /l/ | # _ /u/ |
| rumba | *'rumba'* | ['rumba] | /r/ | # _ /u/ |
| tumba | *'he knocks over'* | ['tumba] | /t/ | # _ /u/ |

TABLE B.1: Spanish elicitation items – **word-initial** environment

| PROMPT | GLOSS | IPA | TARGET | ENVIRON |
|---|---|---|---|---|
| irina | *'Irina'* | ['irina] | /ɾ/ | /i _ i/ |
| irrita | *'he annoys'* | ['irita] | /r/ | /i _ i/ |
| ilícito | *'ilicit'* | [i'lisito] | /l/ | /i _ i/ |
| idilio | *'idyll'* | [i'dilio] | /d/ | /i _ i/ |
| ere | *'the letter r'* | ['eɾe] | /ɾ/ | /e _ e/ |
| erre | *'the letter rr'* | ['ere] | /r/ | /e _ e/ |
| ele | *'the letter l'* | ['ele] | /l/ | /e _ e/ |
| hede | *'it stinks'* | ['ede] | /d/ | /e _ e/ |
| para | *'for'* | ['paɾa] | /ɾ/ | /a _ a/ |
| parra | *'vine'* | ['para] | /r/ | /a _ a/ |
| pala | *'spade'* | ['pala] | /l/ | /a _ a/ |
| capada | *'castrated (f.)'* | [ka'pada] | /d/ | /a _ a/ |
| poro | *'pore'* | ['poɾo] | /ɾ/ | /o _ o/ |
| porro | *'joint'* | ['poro] | /r/ | /o _ o/ |
| polo | *'pole'* | ['polo] | /l/ | /o _ o/ |
| podo | *'I prune'* | ['podo] | /d/ | /o _ o/ |
| guru | *'guru'* | [gu'ɾu] | /ɾ/ | /u _ u/ |
| acurruca | *'he curls up'* | [aku'ruka] | /r/ | /u _ u/ |
| pulula | *'it swarms around'* | [pu'lula] | /l/ | /u _ u/ |
| vudú | *'voodoo'* | [vu'du] | /d/ | /u _ u/ |

TABLE B.2: Spanish elicitation items – **intervocalic onset** environment.

| PROMPT | GLOSS | IPA | TARGET | ENVIRON |
|---|---|---|---|---|
| sirviente | *'servent'* | [siɾ.vi.'en.te] | /ɾ/ | /i _ vi/ |
| filmina | *'transparency'* | [fil.'mi.na] | /l/ | /i _ mi/ |
| rítmico | *'rhythmic'* | ['rit.mi.co] | /t/ | /i _ mi/ |
| intermedia | *'intermediate'* | [in.teɾ.'me.di.a] | /ɾ/ | /e _ me/ |
| fielmente | *'faithfully'* | [fi.el.'men.te] | /l/ | /e _ me/ |
| vedme! | *'look at me! (Vds.)'* | ['ved.me] | /d/ | /e _ me/ |
| arma | *'he arms'* | ['aɾ.ma] | /ɾ/ | /a _ ma/ |
| alma | *'soul'* | ['al.ma] | /l/ | /a _ ma/ |
| amad mar | *'love the sea'* | [a.'mad.maɾ] | /d/ | /a _ ma/ |
| deformo | *'I distort'* | [de.'foɾ.mo] | /ɾ/ | /o _ mo/ |
| devolvo | *'I return'* | [de.'vol.vo] | /l/ | /o _ vo/ |
| argot monja | *'nun slang'* | [aɾ.ɣot.'mon.xa] | /t/ | /o _ mo/ |
| murmura | *'He whispers'* | ['muɾ.mu.ɾa] | /ɾ/ | /u _ mu/ |
| sulfura | *'He infuriates'* | ['sul.fu.ɾa] | /l/ | /u _ fu/ |
| salud muchacho | *'Hey dude!'* | [sa.'lud.mu.tʃa.tʃo] | /d/ | /u _ mu/ |

TABLE B.3: Spanish elicitation items – **intervocalic coda** environment

| PROMPT | GLOSS | IPA | TARGET | ENVIRON |
|---|---|---|---|---|
| mil | *'1000'* | [mil] | /l/ | /i/ _ # |
| gemir | *'to moan'* | [ge'mir] | /r/ | /i/ _ # |
| gemid | *'moan! (Vds.)'* | [ge'mid] | /d/ | /i/ _ # |
| miel | *'honey'* | ['miel] | /l/ | /e/ _ # |
| ver | *'to see'* | [ver] | /r/ | /e/ _ # |
| ved | *'see! (Vds.)'* | [ved] | /d/ | /e/ _ # |
| mal | *'bad'* | [mal] | /l/ | /a/ _ # |
| mar | *'sea'* | [mar] | /r/ | /a/ _ # |
| amad | *'love! (Vds.)'* | [a'mad] | /d/ | /a/ _ # |
| bol | *'ball'* | [bol] | /l/ | /o/ _ # |
| por | *'for'* | [por] | /r/ | /o/ _ # |
| mod | *''* | [mod] | /d/ | /o/ _ # |
| azul | *'blue'* | [a'zul] | /l/ | /u/ _ # |
| sur | *'south'* | [sur] | /r/ | /u/ _ # |
| sud | *'south'* | [sud] | /d/ | /u/ _ # |

TABLE B.4: Spanish elicitation items – **word-final** environment

# Appendix C

# Spanish Acoustic Data

| | LATERAL | | | | TRILL | | | | TAP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | C | F1 | F2 | F3 | | F1 | F2 | F3 |
| e | 616 | 2309 | 2984 | e | 616 | 2341 | 2958 | e | 616 | 2277 | 2932 |
| l | 400 | 1935 | 2871 | r | 539 | 1862 | 2580 | ɾ | 449 | 1991 | 2818 |
| l | 389 | 1840 | 2865 | r | 284 | 1607 | 2767 | ɾ | 387 | 1884 | 2808 |
| l | 396 | 1834 | 2860 | r | 409 | 1688 | 2858 | ɾ | 470 | 2112 | 2946 |
| e | 573 | 2207 | 2871 | e | 604 | 2143 | 2754 | e | 582 | 2268 | 2874 |
| a | 851 | 1626 | 2723 | a | 867 | 1588 | 2765 | a | 873 | 1562 | 2811 |
| l | 655 | 1907 | 2975 | r | 770 | 1794 | 2728 | ɾ | 561 | 1857 | 2883 |
| l | 419 | 1851 | 2959 | r | 372 | 1449 | 2453 | ɾ | 426 | 1786 | 2790 |
| l | 616 | 1843 | 2959 | r | 527 | 1505 | 2512 | ɾ | 590 | 1942 | 2847 |
| a | 791 | 1676 | 2731 | a | 754 | 1759 | 2716 | a | 765 | 1782 | 2738 |
| u | 416 | 992 | 2804 | u | 408 | 871 | 2828 | u | 421 | 817 | 2648 |
| l | 371 | 1732 | 2603 | r | 273 | 1405 | 2789 | ɾ | 394 | 1660 | 2522 |
| l | 313 | 1952 | 2546 | r | 299 | 1677 | 2476 | ɾ | 260 | 1725 | 2657 |
| l | 409 | 1835 | 2732 | r | 374 | 1500 | 2261 | ɾ | 373 | 1713 | 2614 |
| u | 405 | 1071 | 2689 | u | 406 | 1156 | 2728 | u | 410 | 1232 | 2700 |

TABLE C.1: **Mean Formant Frequencies – Spanish Medial Onset Consonants – Subject W1**. All values in Hz, averaged over two utterances of each token.

| | LATERAL | | | | TRILL | | | | TAP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | C | F1 | F2 | F3 | | F1 | F2 | F3 |
| e | 570 | 2402 | 2830 | e | 501 | 2479 | 2892 | e | 498 | 2502 | 2862 |
| l | 358 | 2080 | 3045 | r | 505 | 1756 | 2657 | ɾ | 450 | 2129 | 2878 |
| l | 381 | 2065 | 3503 | r | 512 | 1843 | 2695 | ɾ | 340 | 1916 | 2751 |
| l | 405 | 2063 | 3396 | r | 527 | 1895 | 2683 | ɾ | 468 | 2080 | 2897 |
| e | 589 | 2427 | 3040 | e | 601 | 2335 | 2819 | e | 588 | 2450 | 2986 |
| a | 953 | 1642 | 2965 | a | 964 | 1671 | 2894 | a | 966 | 1631 | 2932 |
| l | 570 | 1731 | 3025 | r | 735 | 1681 | 2684 | ɾ | 602 | 1788 | 2888 |
| l | 453 | 1663 | 3736 | r | 709 | 1698 | 2654 | ɾ | 489 | 1765 | 2889 |
| l | 480 | 1640 | 3000 | r | 743 | 1743 | 2743 | ɾ | 605 | 1833 | 2890 |
| a | 897 | 1705 | 2949 | a | 877 | 1778 | 2755 | a | 842 | 1771 | 2875 |
| u | 386 | 862 | 3016 | u | 295 | 814 | 2862 | u | 419 | 861 | 3035 |
| l | 322 | 1270 | 2170 | r | 353 | 1214 | 2437 | ɾ | 436 | 1357 | 2555 |
| l | 285 | 1439 | 2913 | r | 381 | 1309 | 2398 | ɾ | 274 | 1335 | 3020 |
| l | 319 | 1376 | 2851 | r | 406 | 1390 | 2460 | ɾ | 421 | 1455 | 2752 |
| u | 444 | 1044 | 2949 | u | 455 | 945 | 2936 | u | 602 | 1146 | 3398 |

TABLE C.2: **Mean Formant Frequencies – Spanish Medial Onset Consonants – Subject W2**. All values in Hz, averaged over two utterances of each token.

| | LATERAL | | | | TRILL | | | | TAP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | C | F1 | F2 | F3 | | F1 | F2 | F3 |
| e | 518 | 2331 | 2978 | e | 545 | 2307 | 2959 | e | 527 | 2331 | 2979 |
| l | 389 | 1793 | 2802 | r | 393 | 1817 | 2737 | ɾ | 417 | 2047 | 2937 |
| l | 400 | 1570 | 2516 | r | 266 | 1762 | 2767 | ɾ | 279 | 1929 | 2786 |
| l | 393 | 1683 | 2617 | r | 385 | 1778 | 2705 | ɾ | 383 | 2049 | 2900 |
| e | 533 | 2319 | 2882 | e | 536 | 2130 | 2802 | e | 519 | 2303 | 2888 |
| a | 883 | 1437 | 2916 | a | 843 | 1522 | 2995 | a | 901 | 1535 | 2968 |
| l | 541 | 1613 | 2948 | r | 505 | 1641 | 2727 | ɾ | 658 | 1528 | 2700 |
| l | 482 | 1753 | 2897 | r | 451 | 1697 | 2553 | ɾ | 550 | 1551 | 2648 |
| l | 465 | 1703 | 2849 | r | 480 | 1767 | 2696 | ɾ | 681 | 1609 | 2734 |
| a | 829 | 1655 | 2870 | a | 690 | 1647 | 2731 | a | 807 | 1677 | 2810 |
| u | 380 | 889 | 2941 | u | 393 | 983 | 2983 | u | 420 | 857 | 3120 |
| l | 359 | 1209 | 2168 | r | 401 | 1199 | 2288 | ɾ | 356 | 1301 | 2371 |
| l | 352 | 1355 | 2269 | r | 341 | 1279 | 2125 | ɾ | 316 | 1233 | 2046 |
| l | 340 | 1265 | 2320 | r | 384 | 1222 | 1794 | ɾ | 362 | 1237 | 2068 |
| u | 430 | 1024 | 2809 | u | 432 | 911 | 2953 | u | 360 | 995 | 2629 |

TABLE C.3: **Mean Formant Frequencies – Spanish Medial Onset Consonants – Subject W3**. All values in Hz, averaged over two utterances of each token.

| | Lateral F1 | F2 | F3 | C | Trill F1 | F2 | F3 | | Tap F1 | F2 | F3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| e | 584 | 2268 | 3036 | e | 582 | 2348 | 2978 | e | 562 | 2315 | 2986 |
| l | 432 | 2014 | 2797 | r | 464 | 2044 | 2771 | ɾ | 493 | 2138 | 2882 |
| l | 390 | 1894 | 2880 | r | 312 | 1927 | 2572 | ɾ | 348 | 1877 | 2719 |
| l | 476 | 2036 | 2947 | r | 500 | 1768 | 2689 | ɾ | 501 | 2069 | 2934 |
| e | 578 | 2263 | 2966 | e | 620 | 2114 | 2788 | e | 584 | 2288 | 2837 |
| a | 882 | 1372 | 2819 | a | 889 | 1448 | 2733 | a | 865 | 1313 | 2782 |
| l | 596 | 1653 | 2687 | r | 849 | 1773 | 2775 | ɾ | 609 | 1535 | 2754 |
| l | 509 | 1734 | 2905 | r | 517 | 1540 | 2562 | ɾ | 523 | 1591 | 2460 |
| l | 605 | 1599 | 2869 | r | 647 | 1588 | 2492 | ɾ | 619 | 1505 | 2547 |
| a | 857 | 1586 | 2919 | a | 819 | 1660 | 2764 | a | 851 | 1656 | 2779 |
| u | 402 | 776 | 3025 | u | 391 | 879 | 2722 | u | 395 | 777 | 3115 |
| l | 370 | 1257 | 2617 | r | 315 | 1255 | 2396 | ɾ | 434 | 1261 | 2465 |
| l | 322 | 1458 | 2847 | r | 357 | 1276 | 1948 | ɾ | 395 | 1216 | 1809 |
| l | 363 | 1278 | 2377 | r | 417 | 1125 | 2160 | ɾ | 435 | 1234 | 2268 |
| u | 403 | 967 | 2924 | u | 409 | 842 | 2937 | u | 449 | 867 | 3303 |

Table C.4: **Mean Formant Frequencies – Spanish Medial Onset Consonants – Subject W4**. All values in Hz, averaged over two utterances of each token.

| | Lateral F1 | F2 | F3 | C | Trill F1 | F2 | F3 | | Tap F1 | F2 | F3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| e | 424 | 1875 | 2792 | e | 418 | 1824 | 2537 | e | 473 | 1987 | 2953 |
| l | 378 | 1651 | 3051 | r | 326 | 1596 | 2561 | ɾ | 395 | 1808 | 2687 |
| l | 294 | 1575 | 2909 | r | 374 | 1544 | 2626 | ɾ | 354 | 1696 | 2580 |
| l | 342 | 1675 | 3275 | r | 433 | 1583 | 2662 | ɾ | 399 | 1778 | 2676 |
| e | 460 | 1783 | 2756 | e | 489 | 1622 | 2615 | e | 492 | 1832 | 2722 |
| a | 678 | 1202 | 2654 | a | 699 | 1280 | 2610 | a | 677 | 1291 | 2737 |
| l | 460 | 1297 | 2698 | r | 554 | 1319 | 2191 | ɾ | 513 | 1230 | 2510 |
| l | 356 | 1289 | 2707 | r | 506 | 1214 | 2132 | ɾ | 484 | 1247 | 2477 |
| l | 380 | 1330 | 2675 | r | 517 | 1298 | 2175 | ɾ | 559 | 1241 | 2561 |
| a | 620 | 1222 | 3216 | a | 656 | 1278 | 1995 | a | 645 | 1252 | 3057 |
| u | 386 | 774 | 2754 | u | 291 | 836 | 2580 | u | 308 | 757 | 2512 |
| l | 317 | 1107 | 2241 | r | 324 | 796 | 2151 | ɾ | 284 | 1014 | 2222 |
| l | 220 | 1153 | 1826 | r | 356 | 908 | 2157 | ɾ | 286 | 1142 | 2323 |
| l | 320 | 986 | 2275 | r | 356 | 883 | 1795 | ɾ | 332 | 922 | 2265 |
| u | 301 | 833 | 2484 | u | 277 | 771 | 2565 | u | 347 | 805 | 2532 |

Table C.5: **Mean Formant Frequencies – Spanish Medial Onset Consonants – Subject M1**. All values in Hz, averaged over two utterances of each token.

| | V to V Duration | | | | | Consonant Duration | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| V-V | W1 | W2 | W3 | W4 | M1 | W1 | W2 | W3 | W4 | M1 |
| [ede] | 0.21 | 0.28 | 0.26 | 0.27 | 0.17 | 0.08 | 0.10 | 0.09 | 0.07 | 0.06 |
| [ede] | 0.20 | 0.28 | 0.33 | 0.24 | 0.16 | 0.06 | 0.09 | 0.08 | 0.08 | 0.06 |
| [ada] | 0.20 | 0.30 | 0.22 | 0.15 | 0.19 | 0.05 | 0.07 | 0.08 | 0.05 | 0.10 |
| [ada] | 0.22 | 0.27 | 0.17 | 0.15 | 0.16 | 0.11 | 0.06 | 0.08 | 0.06 | 0.07 |
| [udu] | 0.22 | 0.30 | 0.22 | 0.25 | 0.21 | 0.06 | 0.09 | 0.05 | 0.09 | 0.08 |
| [udu] | 0.24 | 0.29 | 0.20 | 0.25 | 0.17 | 0.07 | 0.08 | 0.04 | 0.09 | 0.07 |
| mean /d/ | 0.215 | 0.287 | 0.230 | 0.218 | 0.177 | 0.072 | 0.082 | 0.070 | 0.073 | 0.073 |
| std.dev /d/ | 0.015 | 0.012 | 0.056 | 0.054 | 0.02 | 0.021 | 0.015 | 0.02 | 0.016 | 0.015 |
| [eɾe] | 0.18 | 0.20 | 0.14 | 0.25 | 0.14 | 0.03 | 0.03 | 0.02 | 0.04 | 0.04 |
| [eɾe] | 0.19 | 0.28 | 0.27 | 0.25 | 0.18 | 0.03 | 0.03 | 0.02 | 0.05 | 0.04 |
| [aɾa] | 0.20 | 0.33 | 0.23 | 0.23 | 0.17 | 0.03 | 0.02 | 0.03 | 0.04 | 0.04 |
| [aɾa] | 0.22 | 0.24 | 0.20 | 0.24 | 0.12 | 0.03 | 0.02 | 0.02 | 0.04 | 0.04 |
| [uɾu] | 0.22 | 0.26 | 0.25 | 0.25 | 0.18 | 0.03 | 0.02 | 0.03 | 0.05 | 0.05 |
| [uɾu] | 0.26 | 0.24 | 0.29 | 0.22 | 0.17 | 0.02 | 0.02 | 0.08 | 0.03 | 0.04 |
| mean /ɾ/ | 0.212 | 0.258 | 0.230 | 0.240 | 0.160 | 0.028 | 0.023 | 0.033 | 0.042 | 0.042 |
| std.dev /ɾ/ | 0.029 | 0.044 | 0.054 | 0.013 | 0.024 | 0.004 | 0.005 | 0.023 | 0.008 | 0.004 |
| [ere] | 0.30 | 0.28 | 0.29 | 0.30 | 0.20 | 0.15 | 0.05 | 0.09 | 0.08 | 0.06 |
| [ere] | 0.31 | 0.34 | 0.36 | 0.34 | 0.23 | 0.13 | 0.05 | 0.12 | 0.12 | 0.09 |
| [ara] | 0.29 | 0.31 | 0.29 | 0.31 | 0.19 | 0.09 | 0.14 | 0.10 | 0.10 | 0.06 |
| [ara] | 0.29 | 0.27 | 0.31 | 0.31 | 0.17 | 0.10 | 0.06 | 0.11 | 0.13 | 0.10 |
| [uru] | 0.24 | 0.20 | 0.20 | 0.26 | 0.13 | 0.09 | 0.04 | 0.04 | 0.10 | 0.12 |
| [uru] | 0.26 | 0.21 | 0.15 | 0.23 | 0.19 | 0.09 | 0.05 | 0.03 | 0.12 | 0.08 |
| mean /r/ | 0.282 | 0.268 | 0.270 | 0.292 | 0.185 | 0.108 | 0.065 | 0.082 | 0.108 | 0.086 |
| std.dev /r/ | 0.026 | 0.055 | 0.077 | 0.040 | 0.033 | 0.026 | 0.037 | 0.038 | 0.018 | 0.023 |
| [ele] | 0.24 | 0.31 | 0.23 | 0.25 | 0.24 | 0.08 | 0.08 | 0.05 | 0.08 | 0.11 |
| [ele] | 0.21 | 0.32 | 0.32 | 0.28 | 0.23 | 0.06 | 0.06 | 0.11 | 0.13 | 0.10 |
| [ala] | 0.23 | 0.30 | 0.28 | 0.25 | 0.17 | 0.09 | 0.08 | 0.08 | 0.09 | 0.07 |
| [ala] | 0.22 | 0.21 | 0.33 | 0.22 | 0.18 | 0.07 | 0.06 | 0.08 | 0.07 | 0.09 |
| [ulu] | 0.19 | 0.21 | 0.21 | 0.21 | 0.22 | 0.08 | 0.09 | 0.06 | 0.09 | 0.08 |
| [ulu] | 0.19 | 0.23 | 0.17 | 0.21 | 0.19 | 0.07 | 0.08 | 0.06 | 0.09 | 0.07 |
| mean /l/ | 0.213 | 0.263 | 0.267 | 0.237 | 0.205 | 0.075 | 0.075 | 0.073 | 0.092 | 0.087 |
| std.dev /l/ | 0.021 | 0.052 | 0.064 | 0.028 | 0.029 | 0.010 | 0.012 | 0.022 | 0.020 | 0.016 |
| mean all C | 0.230 | 0.269 | 0.247 | 0.247 | 0.182 | 0.071 | 0.061 | 0.065 | 0.079 | 0.072 |
| std.dev all C | 0.037 | 0.043 | 0.061 | 0.044 | 0.03 | 0.033 | 0.03 | 0.031 | 0.03 | 0.024 |

TABLE C.6: **Durations of Spanish Intervocalic Consonants** Left five columns: duration between acoustic centers of pre- and post-consonantal vowels (sec); Right five columns: duration of consonantal closure interval (sec).

| | Word-Initial Rhotics | | | | | | | Intervocalic Trills | | | | | | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #rV | W1 | W2 | W3 | W4 | M1 | Mean | VrV | W1 | W2 | W3 | W4 | M1 | Mean | Onsets |
| ri | 1 | 3 | 1 | 2 | 3 | | iri | 3 | 2 | 2 | 2 | 2 | | |
| ri | 2 | 2 | 1 | 3 | 3 | 2.10 | iri | 3 | 2 | 1 | 4 | 2 | 2.30 | 2.20 |
| re | 1 | 2 | 1 | 3 | 3 | | ere | 4 | 2 | 1 | 3 | 3 | | |
| re | 1 | 2 | 1 | 3 | 2 | 1.90 | ere | 3 | 2 | 1 | 3 | 3 | 2.50 | 2.20 |
| ra | 1 | 2 | 1 | 2 | 2 | | ara | 2 | 1 | 1 | 2 | 2 | | |
| ra | 1 | 1 | 1 | 3 | 2 | 1.60 | ara | 2 | 2 | 1 | 3 | 2 | 1.80 | 1.70 |
| ro | 2 | 1 | 1 | 3 | 2 | | oro | 2 | 2 | 1 | 3 | 3 | | |
| ro | 1 | 2 | 1 | 3 | 3 | 1.90 | oro | 2 | 2 | 1 | 4 | 3 | 2.30 | 2.10 |
| ru | 2 | 1 | 1 | 2 | 2 | | uru | 3 | 1 | 1 | 3 | 2 | | |
| ru | 2 | 1 | 1 | 1 | 2 | 1.50 | uru | 3 | 1 | 1 | 3 | 2 | 2.00 | 1.75 |
| mean | 1.40 | 1.70 | 1.00 | 2.50 | 2.40 | 1.80 | mean | 2.70 | 1.70 | 1.10 | 3.00 | 2.40 | 2.18 | 1.99 |
| s.d. | 0.52 | 0.67 | 0.00 | 0.71 | 0.52 | 0.28 | s.d. | 0.67 | 0.48 | 0.32 | 0.67 | 0.52 | 0.15 | 0.25 |

Table C.7: **Number of Coronal Closures**: Spanish rhotics in onset positions.

| | Word-Medial Coda Rhotics | | | | | | | Word-Final Rhotics | | | | | | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VrC | W1 | W2 | W3 | W4 | M1 | Mean | Vr# | W1 | W2 | W3 | W4 | M1 | Mean | Codas |
| ir | 2 | 1 | 1 | 1 | 1 | | ir# | 1 | 1 | 1 | 1 | 1 | | |
| ir | 1 | 1 | 1 | 1 | 1 | 1.10 | ir# | 1 | 1 | 1 | 1 | 1 | 1.00 | 1.05 |
| er | 2 | 1 | 1 | 1 | 2 | | er# | 1 | 0 | 1 | 1 | 2 | | |
| er | 2 | 1 | 1 | 1 | 2 | 1.40 | er# | 1 | 2 | 1 | 1 | 2 | 1.20 | 1.30 |
| ar | 2 | 1 | 2 | 1 | 2 | | ar# | 3 | 1 | 1 | 1 | 3 | | |
| ar | 2 | 2 | 1 | 2 | 2 | 1.70 | ar# | 1 | 2 | 1 | 1 | 2 | 1.60 | 1.65 |
| or | 2 | 2 | 1 | 1 | 2 | | or# | 1 | 1 | 1 | 2 | 2 | | |
| or | 2 | 2 | 1 | 1 | 2 | 1.60 | or# | 2 | 1 | 1 | 2 | 2 | 1.50 | 1.55 |
| ur | 2 | 2 | 1 | 1 | 1 | | ur# | 1 | 1 | 1 | 1 | 2 | | |
| ur | 2 | 2 | 1 | 1 | 2 | 1.50 | ur# | 1 | 2 | 1 | 1 | 2 | 1.30 | 1.40 |
| mean | 1.90 | 1.50 | 1.10 | 1.10 | 1.70 | 1.46 | mean | 1.30 | 1.20 | 1.00 | 1.20 | 1.90 | 1.32 | 1.39 |
| s.d. | 0.32 | 0.53 | 0.32 | 0.32 | 0.48 | 0.10 | s.d. | 0.67 | 0.63 | 0.00 | 0.42 | 0.57 | 0.27 | 0.23 |

Table C.8: **Number of Coronal Closures**: Spanish rhotics in coda positions.

# Appendix D

# Russian Elicitation Items

| Token | IPA | Target | Environ | Token | IPA | Target | Environ |
|---|---|---|---|---|---|---|---|
| иры | /irɨ/ | /r/ | [i _ ɨ] | ири | /irʲi/ | /rʲ/ | [i _ i] |
| эрэ | /ere/ | /r/ | [e _ e] | эре | /erʲe/ | /rʲ/ | [e _ e] |
| ара | /ara/ | /r/ | [a _ a] | аря | /arʲa/ | /rʲ/ | [a _ a] |
| уру | /uru/ | /r/ | [u _ u] | урю | /urʲu/ | /rʲ/ | [u _ u] |
| илы | /ilɨ/ | /l/ | [i _ ɨ] | или | /ilʲi/ | /lʲ/ | [i _ i] |
| элэ | /ele/ | /l/ | [e _ e] | эле | /elʲe/ | /lʲ/ | [e _ e] |
| ала | /ala/ | /l/ | [a _ a] | аля | /alʲa/ | /lʲ/ | [a _ a] |
| улу | /ulu/ | /l/ | [u _ u] | улю | /ulʲu/ | /lʲ/ | [u _ u] |
| иды | /idɨ/ | /d/ | [i _ ɨ] | иди | /idʲi/ | /dʲ/ | [i _ i] |
| эдэ | /ede/ | /d/ | [e _ e] | эде | /edʲe/ | /dʲ/ | [e _ e] |
| ада | /ada/ | /d/ | [a _ a] | адя | /adʲa/ | /dʲ/ | [a _ a] |
| уду | /udu/ | /d/ | [u _ u] | удю | /udʲu/ | /dʲ/ | [u _ u] |

TABLE D.1: **Russian elicitation items – intervocalic environments**.