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’
/fsplʲ-/	всплеск	‘splash’
/fspr-/	вспрыснуть	‘to spray’
/vzbr-/	взброс	‘upthrust’
/vzdr-/	вздрогнуть	‘to shudder’
/vzdrʲ-/	вздремнуть	‘to snooze’
/fstrʲ-/	встреча	‘meeting’
/fskr-/	вскрыть	‘to open’
/fskrʲ-/	вскритнуть	‘to cry out’
/vzglʲ-/	взгляд	‘glance’
/vzgrʲ-/	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	*pat̠.r̠os, ep̠.l̠e.to, reg̠.m̠i.ni, tek̠.n̠on*	—
Attic Greek	*pa.t̠r̠os, e.p̠l̠e.to, re.g̠m̠i.ni, te.k̠n̠on*	{/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] [k‖], [ŋ‖]; Hadza [ᵏ‖], [ᵑ‖]), 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 cooccur. 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).

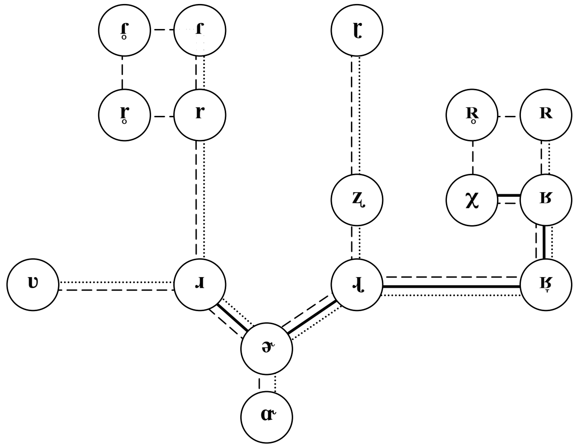

FIGURE 1.1: **Consonants which function as rhotics**, organized according to the phonetic associations between them (Magnuson 2007, after Lindau 1978).

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).

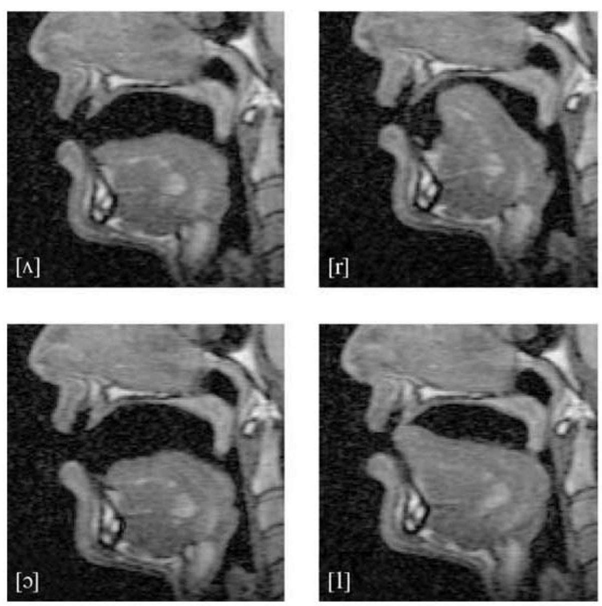

FIGURE 1.2: **Articulatory commonalities between English liquids and vowels**. Midsagittal MRI of male speaker of American English showing [ɹ] and [ɫ] to be produced with coronal and vowel-like dorsal constrictions (Gick, Kang & Whalen 2002).

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.

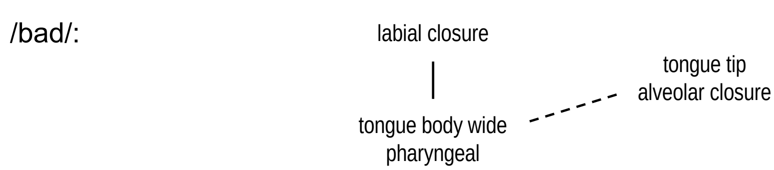

FIGURE 1.3: **Coupling Graph illustrating the phonological structure of the word /bad/**

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

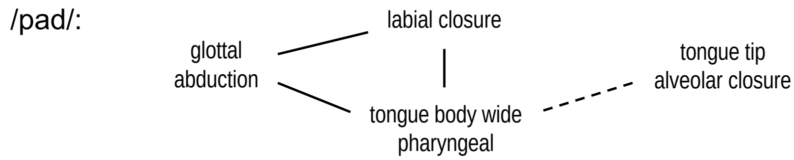

FIGURE 1.4: **Coupling Graph of the word /pad/**

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 (/pʰ/). 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-

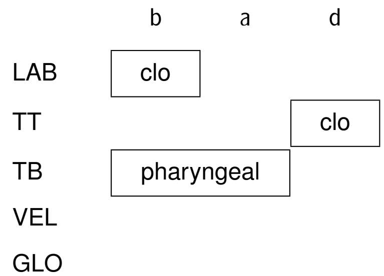

TABLE 1.4: **Gestural score of the word /bad/**, illustrating the temporal organization of the constituent tract variables.

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).

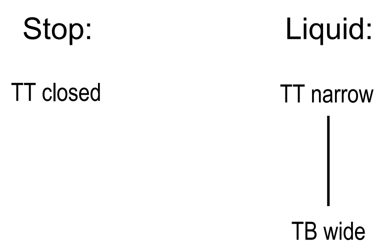

FIGURE 1.5: **Contrasting phonological representations of coronal stops and liquids**.

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.

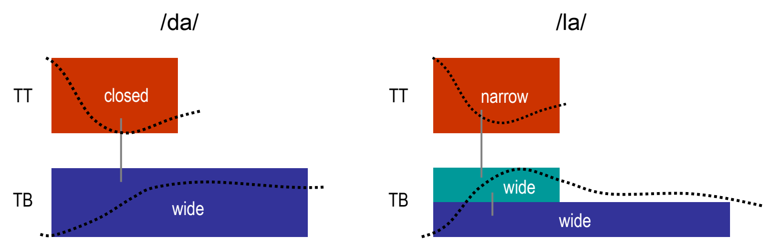

FIGURE 1.6: **Gestural timing and lingual trajectories in coronal stop and liquid onsets**.

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.