Towards a gestural characterization of liquids: Evidence from Spanish and Russian

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Abstract

The production of intervocalic liquid consonants by five speakers of Spanish and four speakers of Russian was examined using ultrasound. Liquids in both languages were found to be united by a lower susceptibility to vocalic coarticulation than coronal obstruents produced in the same environments. Tongue body articulation in the Spanish lateral resembled that of a mid-front vowel; dorsal posture in the Spanish trill resembled that of a mid-back vowel. Tongue body articulation in Russian non-palatalized laterals resembled that of a mid-back vowel, and Russian non-palatalized trills were produced with a dorsal posture resembling that of a mid-central vowel.

These results are consistent with the hypothesis that coronal liquid consonants consist of a consonant-like coronal component and an intrinsic vowel-like dorsal component (Delattre and Freeman 1968; Sproat and Fujimura 1993). Liquid segments are modeled as recurrent stable constellations in which a tongue-tip gesture is coordinated with a tongue-body gesture (Browman and Goldstein 1995). Differences between 'clear' and 'pharyngealized' liquids are attributed to differences in dorsal target locations. Rhotic allophony is argued to result from the interaction of articulatory and aerodynamic factors. Spanish liquid vocalization is modeled as lenition of tongue tip gestures, and Slavic liquid metathesis as a change in intergestural coupling relationships.

1. Introduction

Rhotics and laterals share several important phonotactic and phonological properties. In languages which license complex onsets and codas, liquid consonants often facilitate clusters, and typically distribute adjacent to the syllable nucleus. Cross-linguistically, both synchronically and diachronically, rhotics and lateral sonorants participate in many of the same phonological processes, including vocalization, neutralization, metathesis, and dissimilation (Walsh Dickey 1997). Liquid

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consonants are also acquired late, sometimes imperfectly, and in similar ways, by first- and second-language learners (Dinnsen 1992; Yavaş 1998).

Because of the many different types of segments which pattern together in these ways, it is difficult to define a basis for a universal class of liquids. Different sets of trills, taps, approximants, fricatives and nasals function as liquids in different languages, and unlike more canonical major classes, no single phonetic property is universally shared by all members (Lindau 1985). Capturing the relevant set of consonants and describing the behavior of its members has proven especially difficult under feature-based phonological theory (Wiese 2001; Proctor 2009). This study aims to provide more insights into the commonalities of liquids by addressing the following question: *why does such a diverse set of segments pattern together within and across phonologies?*

1.1. *Gestural commonalities among liquids*

Although the quest for a unifying set of acoustic properties has proven elusive (Ladefoged and Maddieson 1996), a considerable body of evidence suggests that liquid consonants in some languages might share more in common in the articulatory domain. Despite the great diversity in tongue shaping observed among rhotics (Westbury et al. 1998), Delattre and Freeman (1968) demonstrated that the many allophones of American English /ɹ/ are unified in that they all employ a coronal and a pharyngeal constriction. Cineradiographic studies by Zawadzki and 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, an anterior lingual, and a tongue root gesture.

Giles and Moll (1975) found lingual dorsum shape to be constant across allophones of American English /l/, with dorsal contours similar to those observed in vowels. In an EPG study on the vocalization of syllable-final /l/ in Southern British English, Hardcastle and Barry (1989) concluded that dark /l/ is defined by two articulatory components, each with a corresponding acoustic correlate. Sproat and Fujimura (1993) found that American English /l/ behaves as a complex segment consisting of two coordinated gestures: a vocalic dorsal gesture and a consonantal coronal gesture; clear/dark allophony in English /l/ is argued to result from gestural timing differences, as well as the "greater retraction and lowering of the tongue dorsum" observed in darker variants of /l/.

1.2. *Articulatory characterization of liquids*

While numerous studies have addressed the individual phonetics of laterals and rhotics, relatively little investigation has been conducted into the common phonetic properties of liquids. An MRI study of American English (Gick et al. 2002) revealed that [ɹ] and [ɫ] are both produced with coronal and dorsal components, and that the dorsal constriction in these liquids strongly resembles those of vowels ([ʌ] and [ɔ], respectively). Gick et al. (2006) identified some common tendencies in Salish, Serbo-Croatian, Korean, Mandarin and English, where post-vocalic liquids were found to have a measurable dorsal constriction, and multiple simultaneous gestures were observed during the production of liquids in intervocalic positions.

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 55% of languages which use at least one rhotic. English also uses a smaller set of liquids than many languages: 18% have at least two rhotics, and 31% contrast more than one lateral phoneme (Maddieson 1984). Because of the tremendous cross-linguistic variety in the number and type of segments which function as liquids, a better understanding of the phonetic similarities and differences between these consonants is critical to a proper understanding of the nature of the class. To begin to address this deficit, this study presents articulatory data obtained from speakers of two languages with diverse liquid inventories: Spanish and Russian.

1.3. *Investigating consonant production using coarticulation*

It has long been observed that the phonetic properties of consonants are influenced by the surrounding vowels (Liberman et al. 1954; Menzerath and de Lacerda 1933). This phenomenon of vocalic coarticulation can be exploited experimentally to provide insights into the phonetic characterization of consonants. 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 (Öhman 1966; Recasens and Pallarès 1999).

The central hypothesis being examined in this study is that *coronal liquid consonants are characterized by more global constraints on tongue shaping than coronal obstruents*. If liquid consonants, like other coronals, are 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 among coronal obstruents. Alternatively, if 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.

2. Investigation of Spanish liquid articulation

Spanish has a system of three liquid consonants /r-ɾ-l/ which share many phonological properties. The two rhotics are contrastive intervocalically, but neutralize in other environments, where they exhibit varying degrees of allophony (Hualde

2005). Phonotactically, rhotics and laterals occur in codas with greater frequency than most segments (Proctor 2009), and uniquely facilitate complex onsets in Spanish. Diachronically, synchronically, and during acquisition, laterals and rhotics together participate in a variety of phonological processes, including substitution, dissimilation, and metathesis (Lipski 1994; Quilis 1999). Liquids are especially susceptible to phonological processes in coda environments, where they tend to vocalize, spirantize, neutralize with each other, and assimilate with adjacent consonants (Jiménez Sabater 1975; Hualde 2005). The aim of this study is to investigate whether the class-like behavior of Spanish liquids might arise from common phonetic properties, consistent with the articulatory characterization of liquids in English and other languages.

Although the mechanics of trill production have been described in detail (Catford 1977; McGowan 1992; Solé 2002), the way in which the trill is differentiated from the tap in Spanish is unclear. Static palatographic tracings by Navarro Tomás (1970) show remarkably similar patterns of lingual contact for /ɾ/ and /r/. Investigating a similar contrast in Catalan, Recasens and Pallarès (1999) concluded that "the tongue body is subject to a higher degree of constraint during the production of the trill than the tap". Recasens (1987) concluded that trills and dark laterals were more resistant to coarticulation because these consonants involve "a velarization gesture", unlike [ɾ] and clear [l]. Spanish [l] is characterized by a relatively high second formant frequency (Quilis 1963), which has been shown to be inversely correlated with degree of velarization or pharyngealization (Fant 1960; Recasens 2004). X-ray studies of Castilian Spanish laterals (Quilis 1963; Martínez Celdrán 1984) show that the back of the tongue assumes a lower posture than that observed during lateral production in English and Russian, consistent with the characterization of Spanish [l] as a clear lateral (Lipski 1994; Recasens 2004).

If trills, but not taps, are produced with a dorsal gesture, this raises the question of how taps differ phonetically from coronal obstruents. Likewise, if the clear laterals of Spanish differ from English, Russian and Catalan [ɫ] in that they 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. In the experiments described below, dorsal articulation of Spanish liquids will be examined in detail to provide further insights into these issues.

2.1. *Method*

A high-speed ultrasound study was conducted to compare liquid and coronal obstruent articulation by speakers of Latin American Spanish. The voiced Spanish 'stop' /d/ is realized with varying degrees of spirantization in intervocalic position by different speakers of different varieties of Spanish – allophony which has variously been analyzed as yielding fricatives (Harris 1969; Mascaró 1984) or approximants (Romero 1995; Ladefoged 2001). Nevertheless, the consonant /d/ serves as a suitable control segment for this study in that we can assume its goals

Table 1. *Spanish-speaking study participants.*

Subject	Age	Hometown	Spanish Variety	Time in US
W1	21	Guaynabo	Puerto Rican	3.5 years
W2	20	Quito	Ecuadoran	19 years
W3	20	Miami, USA	Cuban	20 years
W4	19	Santo Domingo	Dominican	15 years
M1	25	Managua	Nicaraguan	15 years

of production to be purely coronal, regardless of constriction degree. Because we can expect the tongue body to be maximally coarticulated with context vowels during the production of /d/, a comparison of dorsal articulation during the production of liquid consonants will provide important insights into their intrinsic articulatory properties.

2.1.1. *Subjects.* Five native speakers of Latin American Spanish – four female (W1–W4) and one male (M1) – participated in the experiment (Table 1). Speakers of different Spanish varieties were recruited so that a range of dialectal variation in the rhotics could be examined. 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 dominated by speakers of their variety. All participants were first screened for fluency through interviews with a native speaker of Spanish, and for Spanish literacy by practicing the experimental task described below. Subjects were paid for their participation, and naïve as to the purpose of the experiment.

2.1.2. *Stimuli.* Spanish coronal consonants were elicited in three antagonistic intervocalic environments using the words listed in Table 2. Stimuli were spoken as isolated words, presented in ten-word blocks. The entire corpus was elicited three times from each subject, and the two utterances which imaged most clearly were selected for analysis.

2.1.3. *Data acquisition.* The Haskins Optically-Corrected Ultrasound System (HOCUS) was used to image the tongue in the midsagittal plane at a frame rate of 127 Hz and correct the lingual images for head movement (Whalen et al. 2005). Synchronous 22,000 Hz acoustic recordings were made using a headset-mounted Sennheiser microphone. Every third ultrasound frame within each speech segment of interest 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 frames per second.

For most tokens, a clear image extending from the mandible shadow to the hyoid shadow was obtained, providing a dynamic profile of the midsagittal tongue

Table 2. *Elicitation items: Spanish coronal consonants.*

Prompt	Gloss	IPA	Target	Environment
ere	*'the letter r'*	[ˈeɾe]	/ɾ/	[e_e]
erre	*'the letter rr'*	[ˈere]	/r/	[e_e]
ele	*'the letter l'*	[ˈele]	/l/	[e_e]
hede	*'it stinks'*	[ˈeðe]	/d/	[e_e]
para	*'for'*	[ˈpaɾa]	/ɾ/	[a_a]
parra	*'vine'*	[ˈpara]	/r/	[a_a]
pala	*'spade'*	[ˈpala]	/l/	[a_a]
capada	*'castrated (f.)'*	[kaˈpaða]	/d/	[a_a]
guru	*'guru'*	[guˈɾu]	/ɾ/	[u_u]
acurruca	*'he curls up'*	[akuˈruka]	/r/	[u_u]
pulula	*'it swarms around'*	[puˈlula]	/l/	[u_u]
vudú	*'voodoo'*	[buˈðu]	/d/	[u_u]

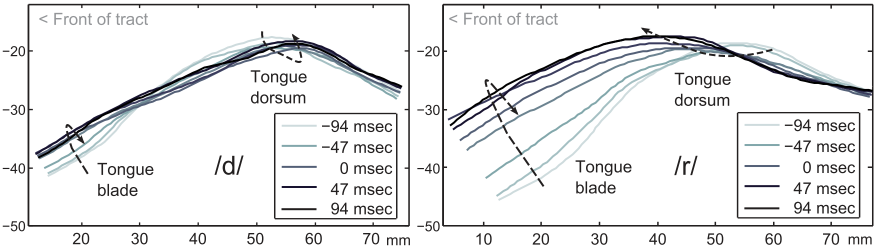

Figure 1. *Midsagittal lingual articulation of Spanish coronal obstruent and trill in low intervocalic context by subject M1. Left panel: token [aða]; Right panel: token [ara]. Each curve shows the location of the midsagittal tongue edge at one point in time. Temporal origin corresponds to the midpoint of consonantal articulation. Axes indicate distance (mm) from an arbitrary origin located near the base of the nose. Arrows indicate broad trajectories of tongue blade and dorsum.*

edge from the alveolar ridge to the mid oropharynx. 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 (The MathWorks Inc. 2007).

2.2. *Results and analysis*

2.2.1. *Dynamic articulation of coronal consonants.* Articulation of the tokens [aða] and [ara] by subject M1 is illustrated in Figure 1. Sequences of tongue edges extracted at 23.62 millisecond intervals are superimposed to depict lingual move-

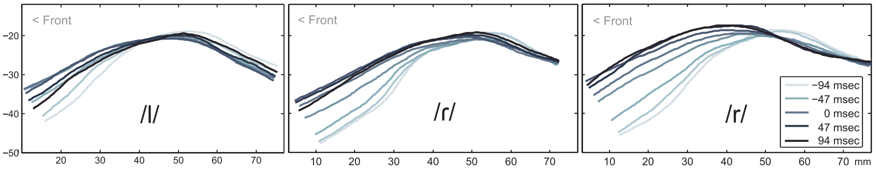

Figure 2. *Midsagittal articulation of the three Spanish liquids in a low intervocalic context – subject M1. Left: [ala]; Center: [aɾa]; Right: [ara].*

ment, beginning at the acoustic midpoint of the pre-consonantal vowel, and ending at the acoustic midpoint of the post-consonantal vowel. In all figures showing midsagittal articulatory data, the left of the figure corresponds to the front of the vocal tract (alveolar ridge), and the right of the figure corresponds to the back of the vocal tract (back of the tongue and upper pharynx). All axis values indicate displacement in millimeters from an arbitrary origin defined for each experimental session.

While the direction and orientation of tongue blade movement is similar for both consonants, movement of the tongue body differs between /d/ and /r/. During the production of the trill, in contrast to the obstruent, the tongue body moves up and forward – away from the articulatory target of the context vowel – which suggests that this movement is intrinsic to the consonant. Dorsal advancement can also be observed during the production of tokens [ala] and [aɾa]. The similarity of the dynamic lingual activity 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 (Figure 2).

Articulation of /d/ in a front vowel context is illustrated in Figure 3 (top left). Throughout the production of the obstruent, the back of the tongue remains more advanced than was observed in the [a_a] context. 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. Articulation of a trill in the same environment (Figure 3, top right) involves dorsal raising and retraction – activity which differs from that observed during obstruent production because the movement is away from the mid-front vocalic constriction target.

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 production in the [e_e] context (Figure 3, bottom). No tongue body lowering was observed during the production of any of the liquids. In each case, dorsal behavior is counter to that which would be expected if the tongue body was *uncontrolled* (lowering as a result of coronal extension, as observed in the obstruents).

The same *characteristic* patterns of tongue movement described above for Subjects M1 and W1 were observed in coronals produced by all five subjects, despite their diverse realizations of some of these consonants. /d/, for example was produced with varying degrees of lenition and frication (W1, W2: most prototypically

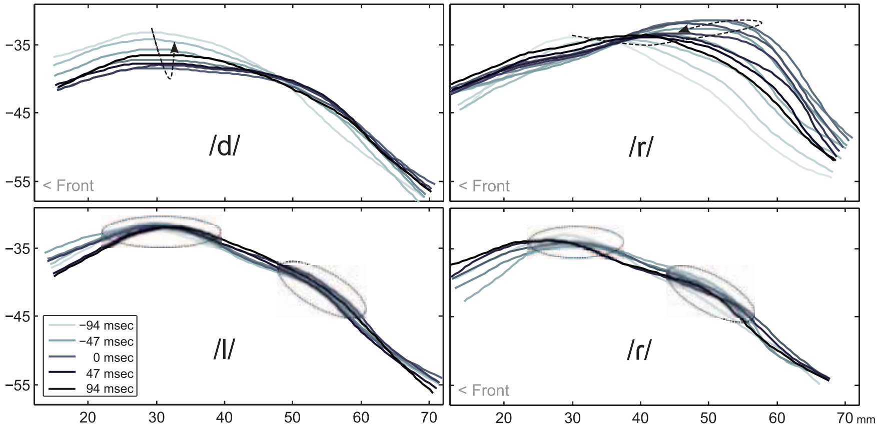

Figure 3. *Midsagittal articulation of the three Spanish liquids in a low intervocalic context – subject M1. Left: [ala]; Center: [aɾa]; Right: [ara].*

stop-like, M1 more approximant-like; W3, W4: heavily spirantized), while the rhotics were produced with variable tongue tip oscillation and degree of assibilation (W1 showed no rhotic frication; W2, W3 & M1 assibilated some trills; all intervocalic trills produced by W4 were heavily fricated).

2.2.2. *Dorsal articulation of Spanish consonants.* To examine their articulatory goals, 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: (i) the acoustic midpoint of the pre-consonantal vowel; (ii) the midpoint of the consonantal interval; and (iii) the acoustic midpoint of the post-consonantal vowel. Acoustic landmarks were located manually by inspecting the spectrograms of each utterance (Figure 4). 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 (Figure 5).

2.2.3. *Quantifying vowel-consonant coarticulation.* The behavior of the tongue dorsum was examined by finding the apex (maximum vertical displacement) of each curve defining a tongue edge. Three such points were identified across tokens, corresponding to dorsal postures in the [e_e] context, [a_a] context and [u_u] context, at equivalent points in time. The area of a triangle constructed between the three points was calculated using the equation shown in (1) as a means of quantifying gross dorsal positional differences between vocalic contexts for each consonant, at each point of time.

$$A_{e\text{-}a\text{-}u} = \tfrac{1}{2}\left|x_e.y_u - x_e.y_a + x_a.y_e - x_a.y_u + x_u.y_a - x_u.y_e\right| \tag{1}$$

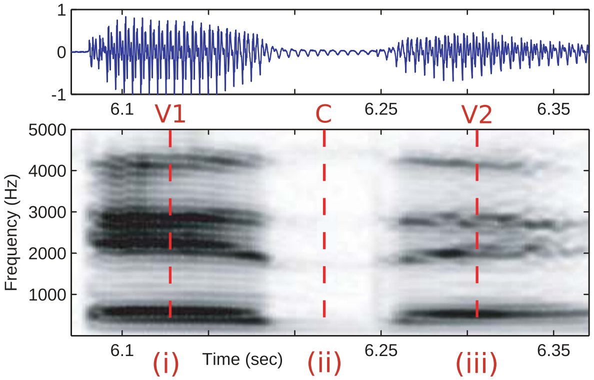

Figure 4. *Location of acoustic landmarks in spectra of Spanish intervocalic consonants: (i) pre-consonantal vowel; (ii) mid-consonant; (iii) post-consonantal vowel. (Depicted: [eðe], Subject W1).*

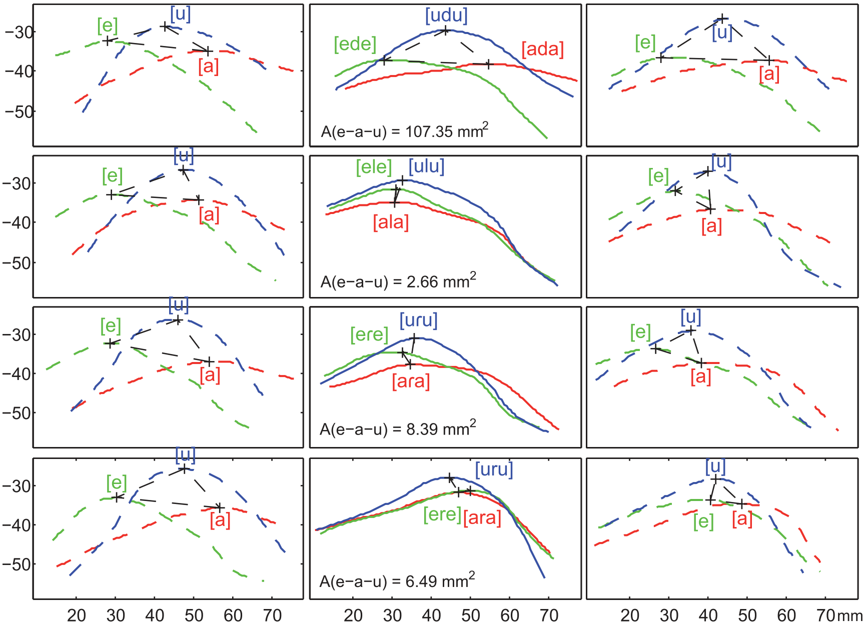

Figure 5. *Midsagittal lingual articulation of Spanish coronal consonants in three intervocalic contexts – subject W1. Top row: obstruent; 2nd row: lateral; 3rd row: tap; 4th row: trill; Left: pre-consonantal vowel; Center: mid consonant; Right: post-consonantal vowel.*

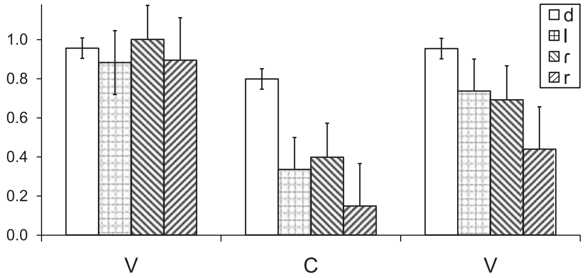

Figure 6. *Mean normalized coarticulatory dorsal spread: intervocalic Spanish coronal consonants (VCV sequences), all subjects. Left: mean dorsal spread across pre-consonantal vowels; Centre: mean dorsal spread, mid consonant; Right: mean dorsal spread in post-consonantal vowel.*

The small area of the triangle constructed between the lingual apices of the trill (A_{VrV} = 6.49 mm^2: Figure 5, bottom center) demonstrates that it is produced with a more consistently controlled dorsum which is less susceptible to coarticulatory effects. In contrast, the much larger area of the lingual apex triangle in the coronal obstruent ($A_{V\eth V}$ = 107.35 mm^2: Figure 5, top center) indicates that it is produced with a greater variety of dorsal postures, depending on the context vowel.

Cross-vocalic dorsal spreads for Spanish coronal consonants, calculated using this method for all five subjects, are given in the Appendix. In order to be able to compare susceptance to vocalic coarticulation across subjects, area metrics were normalized by dividing by the maximum dorsal spread for each subject. Mean normalized dorsal spreads for each coronal consonant are plotted in Figure 6. Two main effects can be observed:

i. the effect of vocalic coarticulation (as measured by dorsal spread) is greater during the production of obstruents than liquids
ii. the effect of consonantal coarticulation on the post-consonantal vowel is greater for liquids than obstruents

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 obstruents and liquids
ii. a *two-sided Wilcoxon rank sum test* of the null hypothesis that the differential dorsal displacement data for obstruents 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 3. Both tests reject the null hypothesis ($p < 0.05$) that coarticulatory differences in dorsal articulation do not differ for obstruents and liquids during mid- and post-consonant production (second and

Table 3. *Effect of dorsal spread by consonant class – Spanish obstruents vs. liquids. 1st column: dorsal coarticulatory effects do not differ among pre-consonantal vowels; 2nd column: coarticulation differs mid-consonantally; 3rd column: coarticulation differs among post-consonantal vowels.*

Test	V1-obs = V1-liq	C-obs = C-liq	V2-obs = 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)

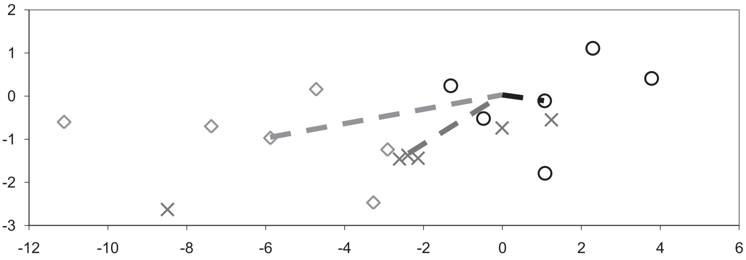

Figure 7. *Mean locations of Spanish liquid dorsal targets with respect to estimated schwa. Diamonds: intervocalic laterals; Crosses: intervocalic taps; Circles: intervocalic trills. Dashed lines indicate mean dorsal displacement (mm) from pre-consonantal vocalic center (origin).*

third columns). The same tests also accept the null hypothesis that coarticulation does not differ between obstruents and liquids during the production of the pre-consonantal vowel (first column), which suggests that anticipatory coarticulation of consonants was minimal. 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 obstruent and the liquids, and that this difference persists into the post-consonantal vowel.

2.2.4. *Location of liquid dorsal gestures.* We can estimate the relative locations of the gestural targets for Spanish liquid consonants by calculating mean dorsal displacement across a range of phonological environments. For each superimposed set of tongue edges, the center of gravity of the triangle connecting dorsal apices in different vowel contexts was calculated to provide an estimate of the dorsal target for each of the liquids. For subject W1, for example, the center of dorsal convergence for the lateral ($x = 32$, $y = -32$ mm: Figure 5, center row 2) is located 16 mm anterior to that of the trill ($x = 47$, $y = -30$ mm: Figure 5, center row 4).

Centers of gravity were also calculated for triangles connecting lingual apices of the pre-consonantal vowels, to locate a point in the center of the articulatory space roughly corresponding to the location of a schwa. Mean displacements to intervocalic liquid dorsal targets from this vocalic center (Table 12) are plotted in Figure 7. The data are consistent with the conclusion drawn from the tongue movement data that the dorsal targets of the Spanish lateral and tap are anterior to that of the trill, but also reveal variation in dorsal articulation among tokens and speakers, especially for the tap.

2.3. *Conclusion – Spanish coronal consonants*

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

i. the trill, lateral and tap are all produced with significantly less variation in dorsal articulation than /d/
ii. the trill, lateral and tap all have a significantly greater coarticulatory effect on the post-consonantal vowel than /d/
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 study is that Spanish liquid consonants share the common property that their production involves a dorsal component – a characteristic which differentiates them from the coronal obstruent /d/, which is produced with a coronal gesture only. It is important to note that these data do not provide any information about articulation away from the midsagittal plane – information which is obviously important to our understanding of differences between laterals and rhotics. Furthermore, the dorsal stability detected using this method might result from different phonetic factors in different consonants – vowel-like gestural targets in some cases, or dorsal bracing for aerodynamic goals in others, for example (Spajić et al. 1996; Solé 2002). These issues will be addressed further in §4; the critical observation to be made here is that for all five Spanish speakers examined in this study, the dorsum is more stable and convergent during liquid production than during coronal obstruent production.

These findings are consistent with earlier studies showing that Spanish laterals are produced with an advanced dorsum (Quilis 1963; Straka 1965; Martínez Celdrán 1984); however, the ultrasound data suggest that this is the result of an intrinsic lingual target, rather than the absence of a dorsal gesture – a characterization which would not be observable from palatographic data, which provides no information about regions of the tongue which do not come into contact with the roof of the mouth. The results of this experiment offer further support for the hypothesis that liquids are characterized by the global coordination of lingual gestures.

3. Investigation of Russian liquid articulation

Russian is a language of particular interest in the study of liquids because its consonantal phonology is distinguished by typologically unusual phonotactics, and contrastive palatalization. Because the distinction between palatalized and non-palatalized phonemes affects all types of consonants in Russian, it represents an important test for the hypothesis that liquids differ from obstruents in terms of their gestural constituency.

3.1. *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). The two trills, for example, are contrasted word-medially in парад [pa'rat] *'parade'* and наряд [na'r^{j}at] *'costume'*, and the two laterals word-initially in лук [luk] *'onion'* and люк [l^{j}uk] *'hatch'*. The difference between these 'mutable pairs' of consonants is typically described as one of secondary articulation (Jones and Ward 1969; Catford 1988); however, 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), or pharyngealized (Bolla 1981).

Although the acoustic manifestation (Halle 1959; Purcell 1979) and perceptual salience (Kochetov 2006; Kavitskaya 2006) of the Russian palatalization contrast has been well documented, the articulatory basis of this distinction is unclear. Fant (1960) 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. Yet midsagittal x-ray data (Bolla 1981) show different patterns of dorsal articulation among non-palatalized consonants, and Kochetov (2005) demonstrated "substantial articulatory asymmetries between the Russian (hard/soft) lateral and rhotic contrasts," using EMA. In an MRI study of Russian consonant pairs, Kedrova et al. (2008) concluded that soft consonants are produced with a similar articulatory pattern, but "position and form of the tongue shape and body characteristic for every hard consonant highly depend on its role in the entire sound system." Reviewing spectral and x-ray evidence, Ladefoged and Maddieson (1996) suggest that only the non-palatalized lateral should be classified as velarized in Russian.

In summary, it is not well understood whether Russian non-palatalized consonants are consistently and contrastively velarized, and if so, what the precise dorsal gestural target is. A major limitation of the existing literature is that dynamic articulation of Russian hard/soft consonant contrasts has not been systematically examined in multiple vowel contexts by multiple speakers (although see Iskarous and Kavitskaya 2010). Since we cannot describe the goals of liquid production

Table 4. *Russian-speaking study participants.*

Subject	Age	Hometown	Time in US
M1	24	Kadamjay, Kyrgyzstan	2 years
W1	32	Kiev, Ukraine	7 years
W2	23	Bishkek, Kyrgyzstan	6 months
W3	24	Zelenograd, Russia	16 years

without also understanding the ways in which similar pairs of consonants are contrastively articulated, the articulation of two types of Russian coronal segments – liquids and stops – will be compared. If Russian non-palatalized consonants are intrinsically velarized or pharyngealized, we would expect to find evidence for a dorsal gestural component in all non-palatalized consonants, including obstruents.

3.2. *Method*

An ultrasound study was conducted to examine the articulation of Russian liquids /r/-/r^j/-/l/-/l^j/ and coronal stops /d/-/d^j/. Data were acquired using the same method described in Section 2.1.

3.2.1. *Subjects.* Four native speakers of Russian – three female and one male – participated in the experiment (Table 4). 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. All participants were initially screened for fluency in Standard Russian by interviewing with a native speaker, and for Russian literacy by practicing the experimental task described below. Subjects were paid for their participation, and naïve as to the purpose of the experiment.

3.2.2. *Corpora.* Because no maximally-balanced word set could be found in which the targeted coronal consonants were minimally contrastive, Russian coronal consonants were elicited using pseudo-words presented in Cyrillic orthography. Each consonant was elicited in three different intervocalic environments: front [e_e], back [u_u] and low [a_a] (Table 5).

Stimuli were presented in six-word blocks organized by consonant. Subjects independently and spontaneously produced each word as a spondaic foot. The entire corpus was elicited three times from each subject, and the two utterances which imaged most clearly were selected for analysis.

Table 5. *Russian coronal consonants: Elicitation items, phonological forms, and target segments.*

Token	IPA	Target	Token	IPA	Target	Token	IPA	Target
эрэ	[ere]	/r/	элэ	[ele]	/l/	эдэ	[ede]	/d/
ара	[ara]	/r/	ала	[ala]	/l/	ада	[ada]	/d/
уру	[uru]	/r/	улу	[ulu]	/l/	уду	[udu]	/d/
эре	[erʲe]	/r/	эле	[elʲe]	/l/	эде	[edʲe]	/d/
аря	[arʲa]	/r/	аля	[alʲa]	/l/	адя	[adʲa]	/d/
урю	[urʲu]	/r/	улю	[ulʲu]	/l/	удю	[udʲu]	/d/

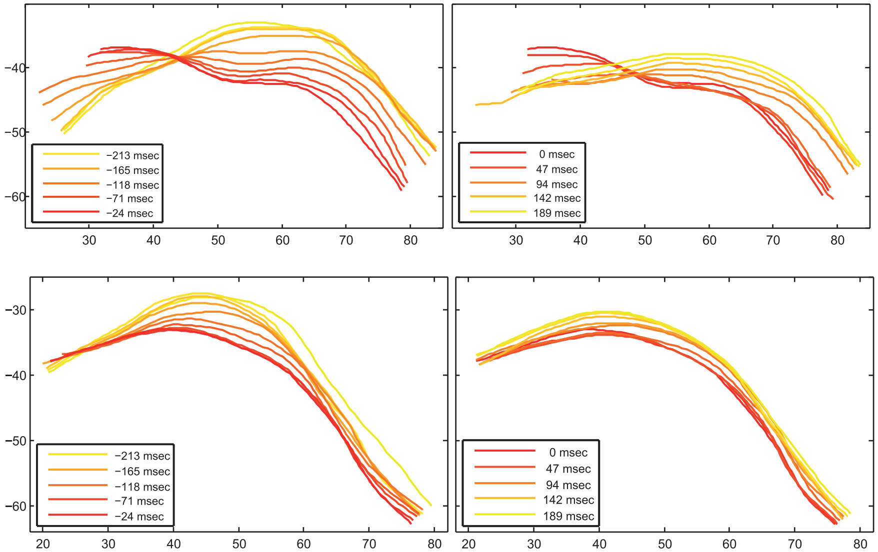

Figure 8. *Midsagittal articulation of Russian non-palatalized coronal stop – subject W3. Top row: [ada]; Bottom row: [ede]; Left: formation; Right: release.*

3.3. *Results and analysis*

3.3.1. *Articulation of non-palatalized stops.* Articulation of the token [ada] by a female speaker of Russian is illustrated in Figure 8 (top row). The closure sequence – ten frames beginning at the mid-point of the pre-consonantal vowel (−213 ms) and ending at the point of coronal contact (0 ms) – is illustrated in the left panel. Consonantal release into the post-consonantal vowel (0 to 189 ms) is shown on the right. The tongue dorsum begins and ends in a retracted position corresponding to the pharyngeal articulation of the context vowel /a/. During coronal closure, the dorsum is pulled forward and allowed to drop, but the back of the tongue retains a lowered, retracted posture throughout.

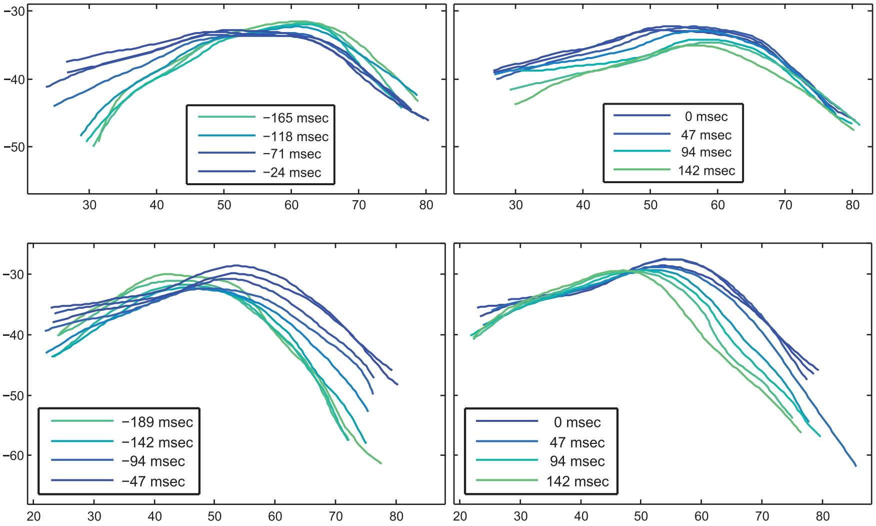

Figure 9. *Midsagittal articulation of Russian non-palatalized trill – subject W3. Top row: [ara]; Bottom row: [ere]; Left: formation; Right: release.*

Articulation of the coronal stop by the same speaker in a front vowel context [ede] is illustrated in Figure 8 (bottom row). Throughout the whole sequence, the tongue dorsum remains in an advanced position corresponding to the wide palatal target of the context vowel. As observed in the back vowel context, the dorsum lowers and fronts during stop formation – 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 vowel contexts, and for all four subjects. In summary, all tongue body movement observed during the production of intervocalic Russian voiced coronal stops was consistent with one of two articulatory goals: maintaining the dorsal posture associated with the context vowel, and achieving coronal closure.[1]

3.3.2. *Articulation of non-palatalized rhotics.* During formation of the non-palatalized trill (Figure 9, top left), 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 subsequent stage of the production 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 (Figure 9, top right). Trill articulation in a front vowel context (Figure 9, bottom row) exhibits dorsal motion in the opposite direction to that observed during the production of the stop in the same environment. The apex of the tongue dorsum retracts (and

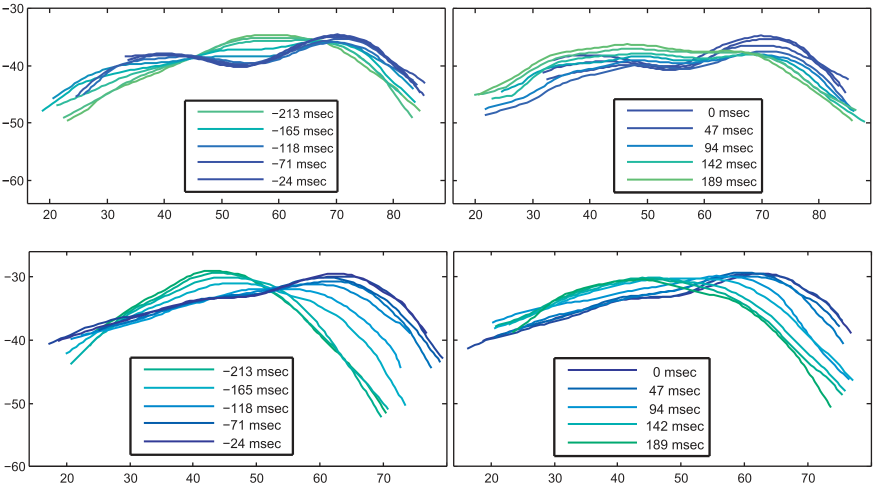

Figure 10. *Midsagittal articulation of Russian non-palatalized lateral – subject W3. Top row: [ala]; Bottom row: [ele]; Left: formation; Right: release.*

raises) 10 mm during trill formation by subject W3, and similar patterns of lingual movement were observed for the other four subjects. Since this movement is counter to that required for context vowel articulation or coronal closure, it suggests that the tongue dorsum is being actively recruited in the production of the trill.

3.3.3. *Articulation of non-palatalized laterals.* Even greater dorsal independence can be observed in the production of the Russian /l/. Articulation of the posterior lateral constriction involves dorsal raising and retraction in a low vowel context (Figure 10, top), and dorsal retraction (21 mm) towards an uvular-pharyngeal target can be observed when the lateral is produced in a front vowel context (Figure 10, bottom row). Similar patterns of production were observed for laterals produced by all four subjects.

3.3.4. *Mid-consonantal dorsal articulation.* Using the technique described in Section 2.2.2, tongue shapes of Russian non-palatalized consonants produced in different vocalic contexts were compared, to provide further insights into the nature of the dorsal constriction intrinsic to the consonant. Midsagittal lingual profiles extracted at three points in time during two productions of /d/-/l/-/r/ by subject W3 in vowel contexts [e_e], [a_a] and [u_u] are superimposed in Figure 11.

Midconsonantal dorsal articulation of both liquids, but not the stop, converges towards a central location. Centers of gravity were calculated using the same method described in Section 2.2.3, and used to provide an estimate of the mean dorsal target for each of the liquids (Table 16). Mean displacements of intervocalic

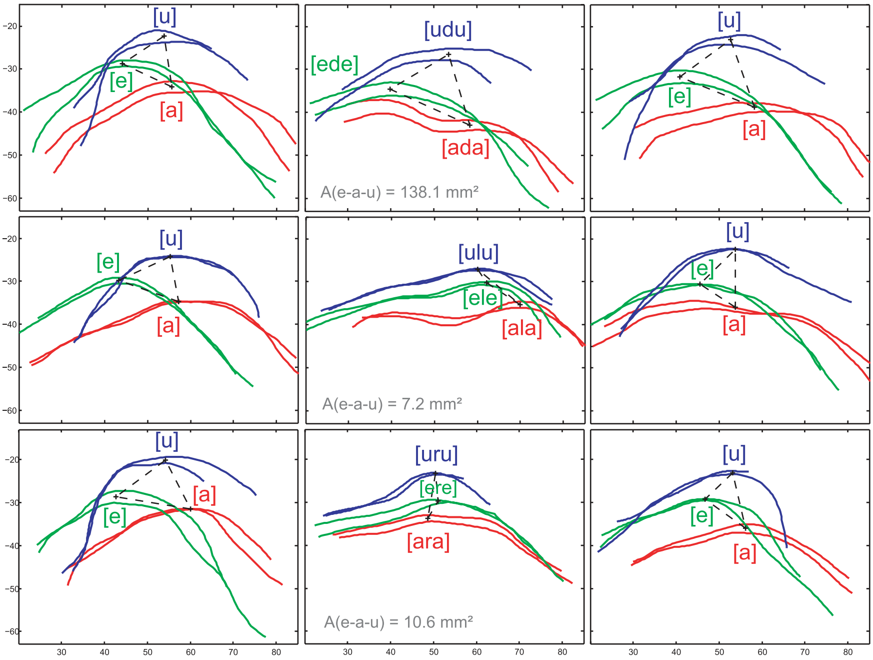

Figure 11. *Midsagittal lingual articulation of Russian non-palatalized consonants in three intervocalic contexts – subject W3. Top row: stop; 2nd row: lateral; 3rd row: trill; Left: pre-consonantal vowel; Center: mid consonant; Right: post-consonantal vowel. Tongue edges extracted from two utterances of each token are plotted in each panel.*

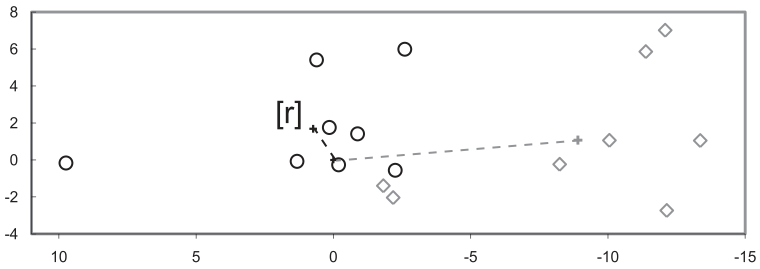

Figure 12. *Mean locations of Russian non-palatalized liquid dorsal targets with respect to estimated 'schwa'. Diamonds: intervocalic laterals; Circles: intervocalic trills. Dashed lines indicate mean dorsal displacement (mm) from pre-consonantal vocalic center (origin).*

liquid dorsal targets from the estimated vocalic center are plotted in Figure 12. The data show that the mean dorsal target of the trill is located in the vicinity of a mid-central vowel, anterior to that of the lateral, which is located in the vicinity of a mid-back vowel.[2]

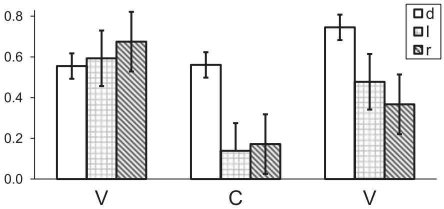

Figure 13. *Mean normalized coarticulatory dorsal spread: Russian non-palatalized coronal consonants – all subjects. Left: mean dorsal spread across pre-consonantal vowels in VCV sequence; Center: mean dorsal spread, mid consonant; Right: mean dorsal spread in post-consonantal vowel.*

Table 6. *Effect of dorsal spread by consonant class – Russian non-palatalized stops vs. liquids. 1st column: dorsal coarticulatory effects do not differ among pre-consonantal vowels; 2nd column: coarticulation differs mid-consonantally; 3rd column: coarticulation differs among post-consonantal vowels.*

Test	V1-obs = V1-liq	C-obs = C-liq	V2-obs = 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)

3.3.5. *Quantifying vowel-consonant coarticulation.* The effect of vocalic coarticulation on Russian non-palatalized consonantal production was estimated using the method described in Section 2.2.2. Cross-context dorsal spread for Russian non-palatalized coronal stops and liquids is given in Appendix A. To compare susceptance to vocalic coarticulation across subjects, area metrics were normalized with respect to the maximum dorsal spread for each subject. Mean normalized dorsal spreads for each coronal consonant are plotted in Figure 13.

As with the Spanish intervocalic coronal consonants, two main effects can be observed in these data: (i) the effect of vocalic coarticulation is greater during the production of stops than liquids; and (ii) the effect of consonantal coarticulation on the post-consonantal vowel appears to be 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 6. 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 ($p < 0.01$) 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 ($p < 0.05$) 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:

i. dorsal articulation in coronal stops is a function of the context vowels
ii. dorsal articulation during liquid production is primarily due to components intrinsic to the consonant
iii. there is no significant coarticulatory effect of the stops on the following vowel
iv. there is a significant coarticulatory effect of the liquids on the following vowel

3.3.6. *Articulation of palatalized stops.* During articulation of the Russian palatalized stop in a front vowel context (Figure 14, bottom row), the dorsum is advanced and allowed to drop as coronal closure is achieved (left panel), consistent with the behavior of an uncontrolled tongue body. Immediately after coronal closure (0 to 94 msec: right panel), 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. In a back vowel context (Figure 14,

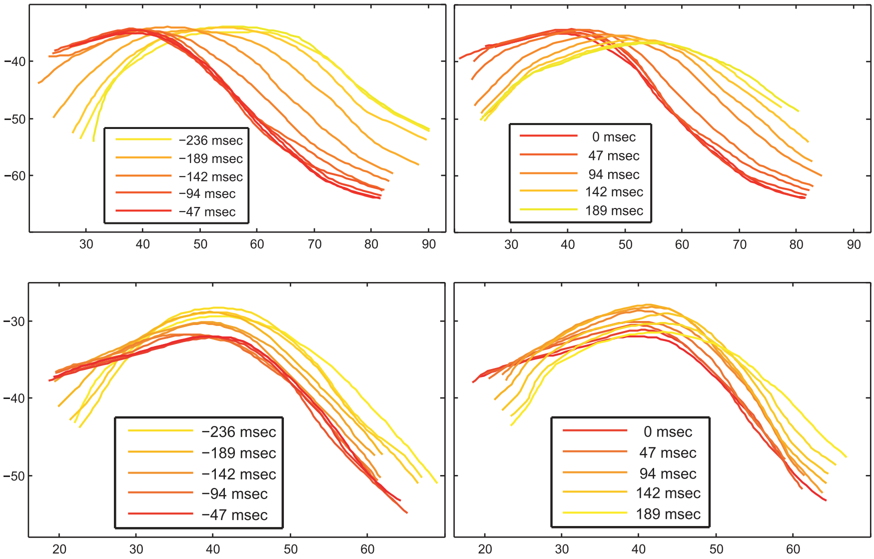

Figure 14. *Midsagittal articulation of Russian palatalized stops – subject W3. Top row: [adʲa]; Bottom row: [edʲe]. Left: formation; Right: consonantal release.*

top row) extensive advancement of the back of the tongue can be observed at the same time that the coronal closure and palatalization gestures are achieved, before the tongue body recovers towards the back target of the context vowel. 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.

3.3.7. *Articulation of palatalized rhotics.* The production of the Russian palatalized trill (Figure 15) 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. Most importantly, tongue movement during the production of

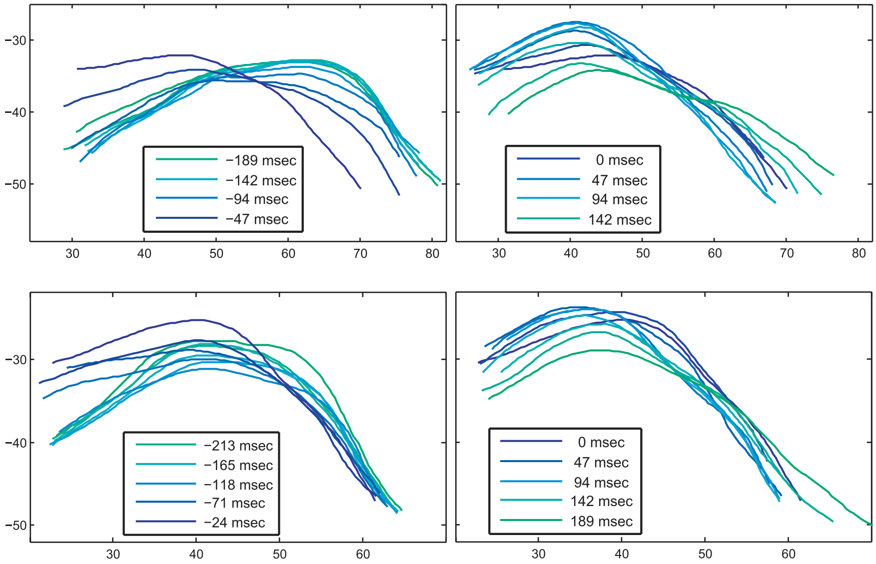

Figure 15. *Midsagittal articulation of Russian palatalized trills – subject W3. Top row: [arʲa]; Bottom row: [erʲe]. Left: formation; Right: consonantal release.*

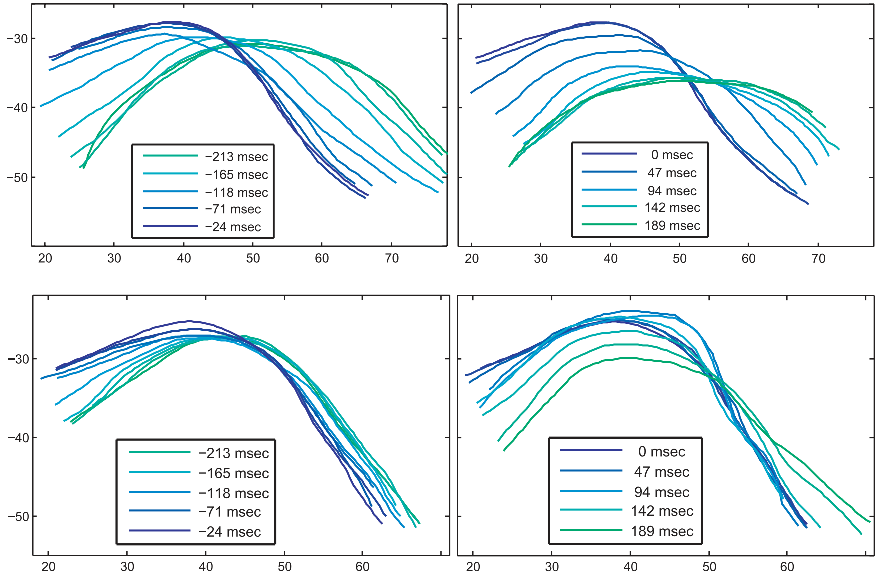

Figure 16. *Midsagittal articulation of Russian palatalized laterals – subject W3. Top row: [alʲa]; Bottom row: [elʲe]. Left: formation; Right: consonantal release.*

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 (Figure 15, top: x = 54, y = −37 mm; Figure 15, bottom: x = 52, y = −36 mm). Stationary regions of this nature have been described as ‘pivot’ points (Harshman et al. 1977; Iskarous 2005).

3.3.8. *Articulation of palatalized laterals.* Articulation of the Russian palatalized lateral is shown in Figure 16. 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 ([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.

These data suggest that palatalized liquids are articulated with two different intrinsic tongue body gestures: the palatalization approximation, and an anterior dorsal gesture equivalent to that identified in the non-palatalized liquid. The methodology used to identify the constriction location of dorsal gestures in Spanish and Russian non-palatalized liquid consonants (Section 2.2.3) is not applicable here because lingual apices are located at regions corresponding to the palatalization gesture. 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 can be explained as the result of competition on the tongue body to articulate both the palatalization and posterior dorsal gestures intrinsic to /l^j/ and /r^j/.

3.4. *Conclusion – Russian coronal consonants*

Analysis of Russian intervocalic coronal consonant production has revealed that, for the four speakers examined in this study:

i. liquid consonants exhibit greater resistance to vocalic coarticulation than stops
ii. the tongue dorsum is not recruited during the production of the voiced coronal stop, suggesting that /d/ is neither intrinsically velarized nor pharyngealized
iii. /r/ is produced with a dorsal gesture with a mid-central vocalic target
iv. /l/ is produced with a dorsal gesture with an uvular-pharyngeal target
v. /d^j/-/r^j/-/l^j/ were all produced with an anterior dorsal approximation gesture
vi. the tongue body was more highly constrained during the production of liquids /r^j/-/l^j/ than for the stop /d^j/

The results of this study are consistent with the hypothesis 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 is also applicable in consonant systems which exploit additional articulatory contrasts such as palatalization gestures.

4. Discussion

If liquid consonants in Spanish and Russian share a phonetic characterization with rhotics and laterals in other languages, as the results of these experiments suggest, it remains to consider whether some of the phonological behavior associated with the class of liquids might be grounded in their common articulatory properties. Phonological representations of liquids in Spanish and Russian informed by the ultrasound data will first be outlined, before some phonological processes involving liquids in these languages are examined using these models.

The conclusion drawn from these experiments is that liquid consonants are characterized by the presence of a dorsal articulatory component, unlike coronal obstruents, which are produced with a tongue-tip gesture alone. In the framework of Articulatory Phonology (Saltzman and Munhall 1989; Browman and Goldstein 1989, 1992), 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. In a liquid onset, there are three gestures which need to be coordinated: the liquid tongue tip

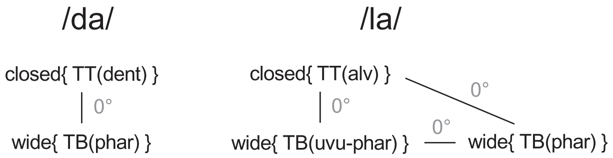

Figure 17. *Hypothesized Spanish syllable structures: coronal obstruent (left) vs. liquid onset (right). Coupling graphs illustrate gestural constituency – target constriction location (dental/alveolar/uvular-pharyngeal/pharyngeal) and target constriction degree (closed/wide) for the tongue tip (TT) and tongue body (TB) – along with inter-gestural coupling relationships (0° = in-phase coordination).*

Table 7. *Proposed tract variable specifications for Spanish coronal consonants.*

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

gesture, the liquid tongue body gesture, and the vocalic tongue body gesture. Assuming that all onset gestures are coupled in-phase with the nucleus (Browman and Goldstein 1985; Gafos 2002), the two onset structures are contrasted in the phonological representations of the Spanish words *da* ‘he gives’ and *la* ‘her’ (Figure 17).

4.1. *Gestural characterization of Spanish liquids*

The difference in gestural constituency contrasted in Figure 17 captures the essential articulatory difference between Spanish coronal obstruents 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 this and previous articulatory studies, is proposed in Table 7. Because ultrasound does not provide sufficient detail about articulation anterior to the alveolar ridge, specifications for tongue tip gestures are informed by data from x-ray and palatographic studies (Navarro Tomás 1970; Martínez Celdrán 1984).

A limitation of the current model is that gestural specifications are restricted to a midsagittal system of reference. This has proven adequate for modeling dark laterals in languages like English and Russian, where side channels are created through lingual elongation between advanced coronal and retracted dorsal gestures. It remains to be seen if additional specifications are needed for languages with clear laterals in order to describe the active lateralization which might be required to create side channels when the tongue dorsum is advanced. If this is the case, additional tract variables such as *Constriction Shape* (Browman and Goldstein 1989), or *Tongue Body Lateralization Degree* might be able to model this behavior.

It also remains to be seen whether the components of multi-gestural segments in Spanish and Russian onsets are best modeled in a synchronous coupling relationship, as has been proposed for English initial laterals (Browman and Goldstein 1995), and whether there are asymmetries in the organization of these gestures with respect to syllable position (Krakow 1999; Marin and Pouplier 2010).

4.2. *Modeling liquid variation*

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, 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 (see Saltzman and Munhall 1989; Browman and Goldstein 1992) associated with each of the gestures which constitute a liquid, will all result in changes in the realization of the consonant. The data in Figures 7 and 12 provide some insight into the extent of variation in dorsal articulation among the participants in these studies.

4.2.1. *Rhotic allophony.* Spanish rhotics – even in intervocalic position – are realized with a wide range of allophony, as trills of different lengths, taps, fricatives and approximants (Lipski 1994; Quilis 1999; Hualde 2005). Although this variation is difficult to motivate and describe in terms of feature-based phonological primitives (see Harris 1969), it follows readily from a gestural model. Because both taps and trills involve the coordination of a stabilizing tongue body gesture with a coronal approximation gesture, different rhotic allophones can result from small differences in airstream properties, tongue-tip stiffness, coronal aperture, tongue body placement, and inter-gestural timing.

A wide range of rhotic allophony was observed among the Spanish speakers in this study (§2.2.1), who all produced trills with the same underlying characteristic patterns of articulation: dorsal stabilization in a mid-back posture, coordinated with coronal approximation to the alveolar ridge. This suggests that aerodynamic factors play an important role in Spanish liquid variation: depending on how airflow is controlled and/or impeded, a wide range of trills, taps, fricatives and approximants can result, given the same, or similar articulatory configuration. Widdison (1998) and Recasens (2002) examine the mechanisms which might underlie some of these speech processes, and their implications for sound change.

4.2.2. *Rhotacism, lambdacism, and liquid neutralization.* Rhoticization of coda laterals is a feature of the Spanish spoken in the Bahía Honda, Havana and Cárdenas regions of Cuba, e.g., *delantal* → [delantaɾ] 'apron'; *multa* → [muɾta] 'fine'; *pulso* → [puɾso] 'I press' (Quilis 1999). Under a gestural model, such rhoticization could result from a reduction in the degree of damping of the tongue tip, or retraction of the tongue body gesture. The intermediate liquid allophones attested in Puerto Rican Spanish codas – *puerta* [ˈpue^{ɾ}l.ta] 'door'; *por favor* [po^{ɾ}l.fa.ˈβol] 'please' (Hualde 2005) – might correspond to realizations in which the coronal gesture is adopting an articulatory configuration intermediate to that prototypically associated with the lateral and the tap.

4.2.3. *Liquid vocalization.* In some Spanish varieties, including that of the Cibao region of the Dominican Republic, coda liquids are prone to vocalization preconsonantally, and word-finally in words with final stress. The segment which results from this process is typically described as a high front vowel or a palatal glide: *algo* [ˈai̯.ɣo] 'something', *mujer* [mu.ˈhei̯] 'woman' (Jiménez Sabater 1975). 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 inherently different structures, and both geometries differ from those of vowels.

Under the articulatory model proposed here, vocalization would result from lenition, deletion or masking of liquid coronal gestures. The phonological organization of the word /algo/, for example, is illustrated in the gestural score in Figure 18. If the tongue tip gesture of the lateral (*closed alveolar*) is deleted or undershot, the intrinsic tongue body gesture – a mid-front vocalic constriction (*wide palatal*) – would be perceived as a palatal vowel /algo/ → [ˈai̯.ɣo]. Similar accounts of vocal-

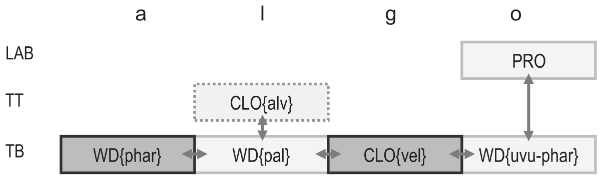

Figure 18. *A gestural account of Spanish coda liquid vocalization: deletion of tongue tip (TT) gesture coordinated with intrinsic vocalic tongue body (TB) gesture. Gestural score illustrated for /algo/, realized as [ai̯.ɣo] as a result of lenition or deletion of (closed alveolar) coronal component of coda lateral.*

Table 8. *Hypothesized tract variable specifications for Russian coronal consonants.*

TV	/d/	/l/	/r/	/d^j/	/l^j/	/r^j/
TTCL	dental	alveolar	alveolar	dental	alveolar	alveolar
TTCD	closed	closed	narrow	closed	closed	narrow
TBCL	–	uvu-phar	velar	–	uvu-phar	velar
TBCD	–	wide	wide	–	wide	wide
TBCL				palatal	palatal	palatal
TBCD				narrow	narrow	narrow

ization have been proposed for dark laterals in Brazilian Portuguese (Leidner 1976: /l/ → [u]), British English (Hardcastle and Barry 1989: /l/ → [ɤ]) and child Dutch (Browman and Goldstein 1995: /l/ → [w]). The fact that coda vocalization affects both laterals and rhotics in Spanish is consistent with the hypotheses that liquids share articulatory commonalities, and that clear laterals are also produced with an intrinsic dorsal gesture.

4.3. *Gestural characterization of Russian liquids*

A preliminary set of gestural specifications for some Russian coronal consonants, consistent with the results of the ultrasound study and informed by the articulatory studies reviewed in §3, are proposed in Table 8. For each palatalized consonant, a gesture corresponding to a high front glide has been added to the constellation corresponding to the non-palatalized member of the mutable pair.

4.3.1. *Slavic liquid metathesis.* Historically, liquids have been involved in a disproportionate number of metathesis phenomena in Russian, the most common of which involved the interchange of coda liquids with their preceding nuclear vowels in the development of Proto-Slavic: e.g. */orv-ınʊ/ *'even'* → /rov(e)n/-, */ordlo/ *'plough'* → /ralo/ (Cubberley 2002). It is noteworthy that the vowel which participated in this process was /o/, as it was shown in Section 3.2 that the dorsal components of the Russian (non-palatalized) liquids have constriction locations resembling those of the mid-back and mid-central vowels. 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 */olkotı/ *'elbow'* developing into Modern Russian /lok(o)t^j/. A comparison of the gestural organization at the beginning of the two words 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 (Figure 19). 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

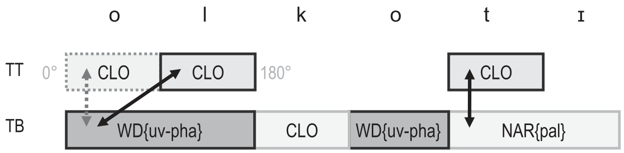

Figure 19. *Slavic liquid metathesis modeled as a change in gestural phasing. Hypothesized gestural score illustrated for Proto-Slavic */olkotɪ/* 'elbow'*, in which the tongue tip (TT) gesture of the coda lateral is coupled anti-phase (180°) to the tongue body (TB) gesture of the tautosyllabic vowel /o/. Broken lines indicate the in-phase (0°) relationship between the same gestures in the onset lateral of the Modern Russian word /lok(o)t^j/.*

in the onset /lo/, and delayed with respect to the start of the dorsal constriction when the lateral appears in the coda /ol/.

Under this model, diachronic CV metathesis results from a change in the phasing relationships between the constellations 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 with the historical evidence from Slavic, where metathesis of coda liquids was one of several sound changes which "had the effect of converting closed syllables to open ones" in Common Slavic (Bethin 1998). Other patterns of metathesis might be expected in other languages, as rhotics and laterals with different gestural constituencies may enter into different types of coordinative relationships with tautosyllabic segments which would make coda or onset structures more or less stable.

5. Conclusions

The midsagittal production of liquid consonants in Spanish and Russian has been examined using ultrasound data. Liquids in both languages were found to be characterized by a greater degree of dorsal resistance to vocalic coarticulation than coronal obstruents, consistent with the hypothesis that coronal liquids are characterized by the coordinative production of tongue tip and tongue body gestures. The data suggest that 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.

Gestural representations of Spanish and Russian liquid consonants have been proposed, based on results of this study, which offer insights into a number of phonological phenomena associated with liquid consonants in these languages. Under an Articulatory Phonology framework, liquid vocalization can be modeled as the result of lenition of the tongue tip gesture in a liquid segment. Coda liquid neutralization can be explained as the result of the loss of distinction between tongue body constriction locations and tongue tip gestural control, and VL metathesis may be explained as a change in the syllabic coupling relationships between the constituent gestures of adjacent liquids and vocalic nuclei.

Appendix. Lingual measurement data

Table 9. *Total dorsal spread of Spanish pre-consonantal vowels (mm^2) measured across three vocalic postures [e]-[a]-[u] (see Figure 5, left column). Each cell corresponds to the area of a triangle constructed between tongue edges extracted from three utterances.*

	W1	W2	W3	W4	M1
/d/	65.7	52.0	79.1	108.1	76.2
/d/	94.4	72.5	73.1	89.0	77.2
/l/	82.3	48.3	78.7	108.8	94.7
/l/	67.9	59.5	76.2	51.1	47.7
/ɾ/	115.1	59.7	82.7	80.7	99.1
/ɾ/	104.6	59.9	80.5	92.5	54.2
/r/	117.4	27.8	45.9	94.6	119.3
/r/	108.6	47.1	55.2	52.2	61.7
Obstruent	80.0	62.2	76.1	98.6	77.5
Liquid	99.3	50.4	69.9	80.0	82.4

Table 10. *Mean susceptance to vocalic coarticulation of Spanish intervocalic coronal consonants: total dorsal spread (mm^2) measured across three vowel contexts [e_e]-[a_a]-[u_u] (Figure 5, center column). Each cell corresponds to the area of a triangle constructed between tongue edges extracted from three utterances.*

	W1	W2	W3	W4	M1
/d/	107.3	52.5	96.9	51.1	55.4
/d/	67.0	66.6	63.5	61.1	34.1
/l/	2.7	35.2	25.0	33.0	40.1
/l/	26.9	30.0	28.0	39.0	16.9
/ɾ/	8.4	22.6	37.1	40.9	70.8
/ɾ/	14.9	22.9	44.0	35.3	38.0
/r/	6.5	6.7	2.7	2.9	76.3
/r/	6.4	11.3	13.6	0.5	14.0
Obstruent	87.2	59.6	80.2	56.1	46.3
Liquid	11.0	21.4	25.1	25.3	38.5

Table 11. *Total dorsal spread of Spanish post-consonantal vowels (mm^2) measured across three vocalic postures [e]-[a]-[u] (see Figure 5, right column). Each cell corresponds to the area of a triangle constructed between tongue edges extracted from three utterances.*

	W1	W2	W3	W4	M1
/d/	139.2	66.3	76.2	53.7	91.6
/d/	89.4	81.9	65.1	66.7	56.8
/l/	41.6	70.7	79.5	64.3	36.9
/l/	47.0	72.4	70.2	55.2	67.5
/ɾ/	43.2	39.0	56.9	68.5	81.8
/ɾ/	75.8	46.5	74.1	37.4	47.2
/r/	21.8	19.2	29.2	35.0	31.3
/r/	54.9	42.6	56.7	27.1	42.1
Obstruent	114.3	74.1	70.7	60.2	74.2
Liquid	47.4	48.4	61.1	47.9	51.9

Table 12. *Mean displacements (mm) of dorsal targets from pre-consonantal vocalic center: Spanish intervocalic liquids – all subjects. Dorsal targets estimated from centers of gravity of triangles constructed between dorsal apices (Figure 5).*

	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 13. *Total dorsal spread of Russian pre-consonantal vowels (mm^2) measured across three vocalic postures [e]-[a]-[u] (see Figure 11, left column). Each cell corresponds to the area of a triangle constructed between tongue edges extracted from three utterances.*

	W1	W2	W3	M1
/d/	88.2	72.6	84.7	19.4
/d/	57.8	57.0	53.4	50.8
/l/	98.5	43.8	73.1	72.3
/l/	80.6	42.3	87.5	87.6
/r/	93.8	61.5	88.2	20.1
/r/	71.7	41.1	81.7	125.1
Stop	73.0	64.8	69.0	35.1
Liquid	86.1	47.2	82.6	76.3

Table 14. *Mean susceptance to vocalic coarticulation of Russian intervocalic coronal consonants: total dorsal spread (mm^2) measured across three vowel contexts [e_e]-[a_a]-[u_u] (Figure 11, center column). Each cell corresponds to the area of a triangle constructed between tongue edges extracted from three utterances.*

	W1	W2	W3	M1
/d/	37.4	73.8	129.1	22.1
/d/	47.5	40.6	147.4	24.5
/l/	20.3	27.9	3.6	2.6
/l/	22.0	26.8	10.8	12.1
/r/	6.9	56.1	8.4	10.4
/r/	31.2	31.2	12.9	10.6
Stop	42.5	57.2	138.2	23.3
Liquid	20.1	35.5	8.9	8.9

Table 15. *Total dorsal spread of Russian post-consonantal vowels (mm^2) measured across three vocalic postures [e]-[a]-[u] (see Figure 11, right column). Each cell corresponds to the area of a triangle constructed between tongue edges extracted from three utterances.*

	W1	W2	W3	M1
/d/	79.0	94.3	126.5	46.0
/d/	51.3	69.2	116.3	88.8
/l/	43.8	72.4	44.4	55.3
/l/	36.6	78.6	4.9	143.8
/r/	44.8	72.0	49.3	2.0
/r/	69.3	44.1	46.2	8.3
Stop	65.1	81.8	121.4	67.4
Liquid	48.6	66.8	36.2	52.3

Table 16. *Mean displacements (mm) of dorsal targets from pre-consonantal vocalic center: Russian intervocalic non-palatalized liquids – all subjects. Dorsal targets estimated from centers of gravity of triangles constructed between dorsal apices (Figure. 11).*

	/l/		/r/	
	dx	dy	w3	w4
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

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Notes

1. As noted in §2.1, ultrasound images the back of the tongue into the mid oropharynx, but typically no lower, which limits our capacity to examine pharyngeal articulation. While these data suggest that the dorsum is uncontrolled by Russian non-palatalized coronal stops, it may be the case that there is unobserved articulatory activity in the lower pharyngeal region.
2. Thanks to an anonymous reviewer for observing that these results are consistent with Jones & Ward's (1969) characterization of Russian /l/ as having "the vowel-resonance . . . of cardinal [o]."

References

Bethin, Christina Y. 1998. *Slavic prosody: language change and phonological theory* (Cambridge Studies in Linguistics 86). Cambridge: Cambridge University Press.

Bolla, Kálmán. 1981. *A conspectus of Russian speech sounds* (Slavistische Forschungen 32). Köln: Böhlau.

Browman, Catherine P. & Louis M. Goldstein. 1985. Dynamic modeling of phonetic structure. In Victoria A. Fromkin (ed.), *Phonetic linguistics. Essays in honor of Peter Ladefoged*, 35–53. Orlando: Academic Press.

Browman, Catherine P. & Louis M. Goldstein. 1989. Articulatory gestures as phonological units. *Phonology* 6(2). 201–251.

Browman, Catherine P. & Louis M. Goldstein. 1992. Articulatory phonology: an overview. *Phonetica* 49(3–4). 155–180.

Browman, Catherine P. & Louis M. Goldstein. 1995. Gestural syllable position effects in American English. In Fredericka Bell-Berti & Lawrence J. Raphael (eds.), *Producing speech: Contemporary issues (for Katherine Safford Harris)*, 19–34. New York: AIP Press.

Catford, John C. 1977. *Fundamental problems in phonetics*. Bloomington: Indiana University Press.

Catford, John C. 1988. *A practical introduction to phonetics*. Oxford; New York: Clarendon.

Cubberley, Paul V. 2002. *Russian: a linguistic introduction*. Cambridge; New York: Cambridge University Press.

Delattre, Pierre & Donald C. Freeman. 1968. A dialect study of American r's by x-ray motion picture. *Linguistics* 44. 29–68.

Dinnsen, Daniel A. 1992. Variation in developing and fully developed phonetic inventories. In Charles A. Ferguson, Lise Menn & Carol Stoel-Gammon (eds.), *Phonological development: Models, research, implications*, 191–210. Timonium, MD: York.

Fant, Gunnar. 1960. *Acoustic theory of speech production, with calculations based on X-ray studies of Russian articulations*. The Hague: Mouton.

Gafos, Adamantios I. 2002. A grammar of gestural coordination. *Natural Language & Linguistic Theory* 20(2). 269–337.

Gick, Bryan, Fiona Campbell, Sunyoung Oh & Linda Tamburri-Watt. 2006. Toward universals in the gestural organization of syllables: A cross-linguistic study of liquids. *Journal of Phonetics* 34(1). 49–72.

Gick, Bryan, Khalil Iskarous, Douglas H. Whalen & Louis M. Goldstein. 2003. Constraints on variations in the production of English /r/. *6th International Seminar on Speech Production* Sydney, 7th–10th December 2003: 73–78.

Gick, Bryan, A. Min Kang & Douglas H. Whalen. 2002. MRI evidence for commonality in the postoral articulations of English vowels and liquids. *Journal of Phonetics* 30(3). 357–371.

Giles, Stephen B. & Kenneth L. Moll. 1975. Cinefluorographic study of selected allophones of English /l/. *Phonetica* 31(3–4). 206–227.

Halle, Morris. 1959. *The Sound Pattern of Russian*. The Hague: Mouton.

Hardcastle, William J. & William Barry. 1989. Articulatory and perceptual factors in /l/ vocalisations in English. *Journal of the International Phonetic Association* 15(2). 3–17.

Harris, James W. 1969. *Spanish phonology*. Cambridge, MA: MIT Press.

Harshman, Richard, Peter Ladefoged & Louis Goldstein. 1977. Factor analysis of tongue shapes. *The Journal of the Acoustical Society of America* 62(3). 693–707.

Hualde, Jose Ignacio. 2005. *The sounds of Spanish*. Cambridge: Cambridge University Press.

Iskarous, Khalil. 2005. Patterns of tongue movement. *Journal of Phonetics* 33(4). 363–381.

Iskarous, Khalil & Darya Kavitskaya. 2010. The interaction between contrast, prosody, and coarticulation in structuring phonetic variability. *Journal of Phonetics* 38(4). 625–639.

Jiménez Sabater, Max. 1975. *Más datos sobre el español en la República Dominicana*. Santo Domingo: Ediciones Intec.

Jones, Daniel & Dennis Ward. 1969. *The phonetics of Russian*. Cambridge: Cambridge University Press.

Kavitskaya, Darya. 2006. Perceptual salience and palatalization in Russian. In Louis Goldstein, Douglas H. Whalen & Catherine T. Best (eds.), *Laboratory phonology 8: Varieties of phonological competence*, 589–610. Berlin: Mouton de Gruyter.

Kedrova, Galina Y., Nicolay V. Anisimov, Leonid M. Zaharov & Yurij A. Pirogov. 2008. Magnetic Resonance investigation of palatalized stop consonants and spirants in Russian. *The Journal of the Acoustical Society of America* 123. 3325.

Kochetov, Alexei. 2005. Phonetic sources of phonological asymmetries: Russian laterals and rhotics. *Canadian Linguistics Association 2005*.

Kochetov, Alexei. 2006. Testing licensing by cue: A case of Russian palatalized coronals. *Phonetica* 63(2–3). 113–148.

Krakow, Rena A. 1999. Physiological organization of syllables: a review. *Journal of Phonetics* 27(1). 23–54.

Ladefoged, Peter. 2001. *A course in phonetics*. Boston: Heinle & Heinle.

Ladefoged, Peter & Ian Maddieson. 1996. *The sounds of the world's languages*. Oxford; Cambridge, MA: Blackwell.

Leidner, David R. 1976. The articulation of American English /l/: A study of gestural synergy and antagonism. *Journal of Phonetics* 4. 327–335.

Li, Min, Chandra Kambhamettu & Maureen Stone. 2005. Automatic contour tracking in ultra-sound images. *Clinical Linguistics & Phonetics* 19(6–7). 545–554.

Liberman, Alvin M., Pierre C. Delattre, Franklin S. Cooper & Louis J. Gerstman. 1954. The role of consonant-vowel transitions in the perception of the stop and nasal consonants. *Psychological Monographs* 68. 1–13.

Lindau, Mona. 1985. The story of /r/. In Victoria Fromkin (ed.), *Phonetic linguistics: Essays in honor of Peter Ladefoged*, 157–168. Orlando: Academic Press.

Lipski, John M. 1994. *Latin American Spanish*. London: Longman.

Maddieson, Ian. 1984. *Patterns of sounds*. Cambridge: Cambridge University Press.

Marin, Stefania & Marianne Pouplier. 2010. Temporal organization of complex onsets and codas in American English: Testing the predictions of a gestural coupling model. *Motor Control* 14(3). 380–407.

Martínez Celdrán, Eugenio. 1984. *Fonética: con especial referencia a la lengua castellana*. Barcelona: Teide.

Mascaró, Joan. 1984. Continuant spreading in Basque, Catalan, and Spanish. In Mark Arono, Richard Oehrle, Mark Arono & Richard Oehrle (eds.), *Language sound structure*, 287–298. Cambridge, MA: MIT Press.

McGowan, Richard S. 1992. Tongue-tip trills and vocal-tract wall compliance. *The Journal of the Acoustical Society of America* 91(5). 2903–2910.

Menzerath, Paul & Armando de Lacerda. 1933. Koartikulation, Steuerung und Lautabgrenzung: Eine experimentelle Untersuchung (Phonetische Studien 1). Bonn: Ferdinand Dümmler.

Navarro Tomás, Tomás. 1970. *Manual de pronunciación española*. Madrid: Consejo Superior de Investigaciones Científicas.

Öhman, Sven E. G. 1966. Coarticulation in VCV utterances: Spectrographic measurements. *The Journal of the Acoustical Society of America* 39(1). 151–168.

Proctor, Michael. 2009. *Gestural characterization of a phonological class: The liquids*. New Haven: Yale University dissertation.

Purcell, Edward T. 1979. Formant frequency patterns in Russian VCV utterances. *The Journal of the Acoustical Society of America* 66(6). 1691–1702.

Quilis, Antonio. 1963. *Fonética y fonología del español*. Madrid: Consejo Superior de Ivestigacisones Científicas.

Quilis, Antonio. 1999. *Tratado de fonología y fonética españolas*. Madrid: Gredos.

Recasens, Daniel. 1987. An acoustic analysis of V-to-C and V-to-V coarticulatory effects in Catalan and Spanish VCV sequences. *Journal of Phonetics* 15. 299–312.

Recasens, Daniel. 2002. Weakening and strengthening in romance revisited. *Rivista di Linguistica* 14. 327–373.

Recasens, Daniel. 2004. Darkness in [l] as a scalar phonetic property: implications for phonology and articulatory control. *Clinical Linguistics and Phonetics* 18. 593–603.

Recasens, Daniel & Maria Dolors Pallarès. 1999. A study of /ɾ/ and /r/ in the light of the "DAC" coarticulation model. *Journal of Phonetics* 27(2). 143–169.

Reformatskii, Alexander A. 1958. O korrelatsii "Tverdykh" i "Miagkikh" Soglasnykh (v Sovremennom Russkom Literaturnom Iazyke). In Emil Petrovici (ed.), *Mélanges linguistiques offerts à Emil Petrovici par ses amis étrangers a l'occasion de son soixantième anniversaire*, 494–499. Bucarest: Academiei Republicii Populare Romine.

Romero, Joaquín. 1995. *Gestural organization in Spanish: An experimental study of spirantization and aspiration*. Storrs, CT: University of Connecticut dissertation.

Saltzman, Elliot L. & Kevin G. Munhall. 1989. A dynamical approach to gestural patterning in speech production. *Ecological Psychology* 1. 333–382.

Solé, Maria-Josep. 2002. Aerodynamic characteristics of trills and phonological patterning. *Journal of Phonetics* 30(4). 655–688.

Spajić, Siniša, Peter Ladefoged & P. Bhaskararao. 1996. The trills of Toda. *Journal of the International Phonetic Association* 26. 1–21.

Sproat, Richard & Osamu Fujimura. 1993. Allophonic variation in English /l/ and its implications for phonetic implementation. *Journal of Phonetics* 21(3). 291–311.

Straka, Georges. 1965. *Album phonétique*. Québec: Presses de l'Université Laval.

The MathWorks Inc. 2007. Matlab, r2007b. Software package.

Timberlake, Alan. 2004. *A reference grammar of Russian*. Cambridge; New York: Cambridge University Press.

Trubetzkoy, Nikolai S. 1969. *Principles of phonology*. Berkeley: University of California Press.

Walsh Dickey, Laura. 1997. *The phonology of liquids*. Amherst: University of Massachussets dissertation.

Westbury, John R., Michiko Hashi & Mary J. Lindstrom. 1998. Differences among speakers in lingual articulation for American English /ɹ/. *Speech Communication* 26(3). 203–226.

Whalen, Doug, Khalil Iskarous, Mark Tiede, David Ostry, Heike Lehnert-LeHouillier, Eric Vatikiotis-Bateson & Donald Hailey. 2005. The Haskins optically corrected ultrasound system (HOCUS). *Journal of Speech, Language, and Hearing Research* 48(3). 543–553.

Widdison, Kirk A. 1998. Phonetic motivation for variation in Spanish trills. *Orbis* 40. 51–61.

Wiese, Richard. 2001. The phonology of /r/. In T. A. Hall (ed.), *Distinctive feature theory*, 335–368. Berlin: Mouton de Gruyter.

Yavaş, Mehmet S. 1998. *Phonology: Development and disorders*. San Diego: Singular.

Zawadzki, Paul A. & David P. Kuehn. 1980. A cinereadiographic study of static and dynamic aspects of American English /r/. *Phonetica* 37. 253–266.