Chapter 4

Experimental Investigation of Spanish Liquid Production

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

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

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

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

4.1 Investigating the Goals of Consonant Production using Coarticulation

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

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

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

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

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

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

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

4.2 Method

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

4.2.1 Subjects

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

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

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

4.2.2 Lingual Imaging

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

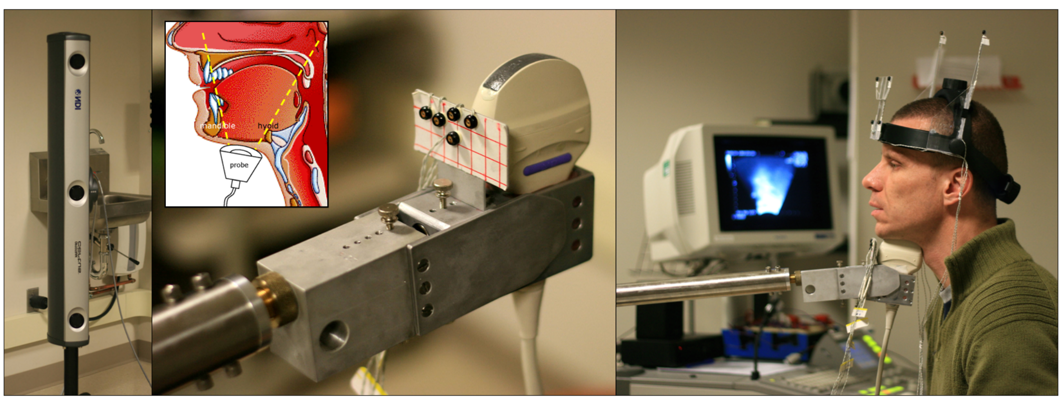

FIGURE 4.1: **Dynamic imaging of midsagittal lingual articulation using HOCUS**. Left: OptoTrak camera; Center: pivoting ultrasound probe holder; Inset: typical field of view of ultrasound probe, from alveolar ridge to tongue root. Right: Subject positioned on probe, wearing optically-tracked tiara used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

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

4.2.3 Audio Acquisition

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

4.2.4 Articulatory Analysis

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

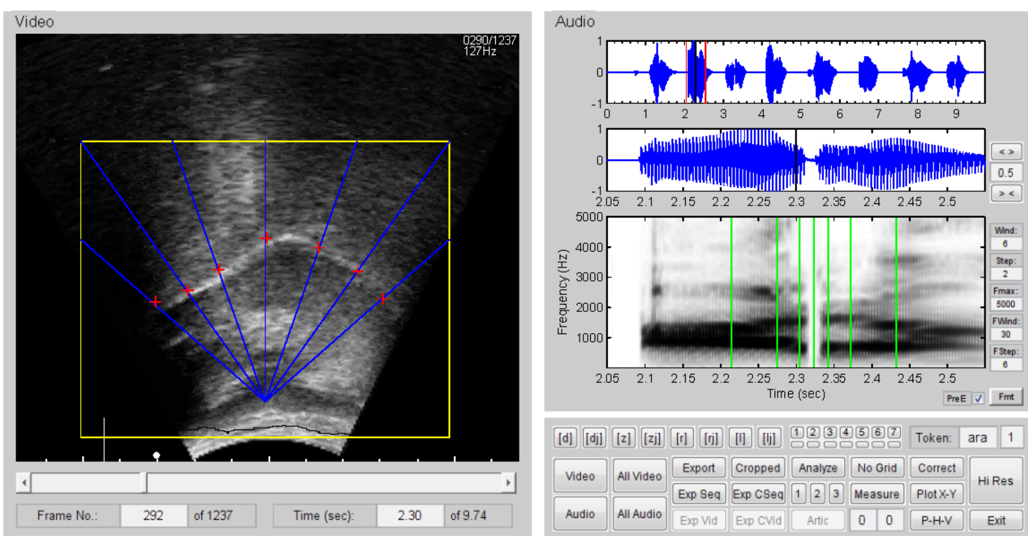

FIGURE 4.2: Matlab GUI used to review synchronized ultrasound and audio data

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

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

4.2.5 Acoustic Analysis

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

4.3 Phonetic Characterization of Intervocalic Liquids

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

4.3.1 Stimuli

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

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

4.3.2 Results: Acoustics of Intervocalic Coronal Consonants

Acoustic Characterization of Intervocalic Stops

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

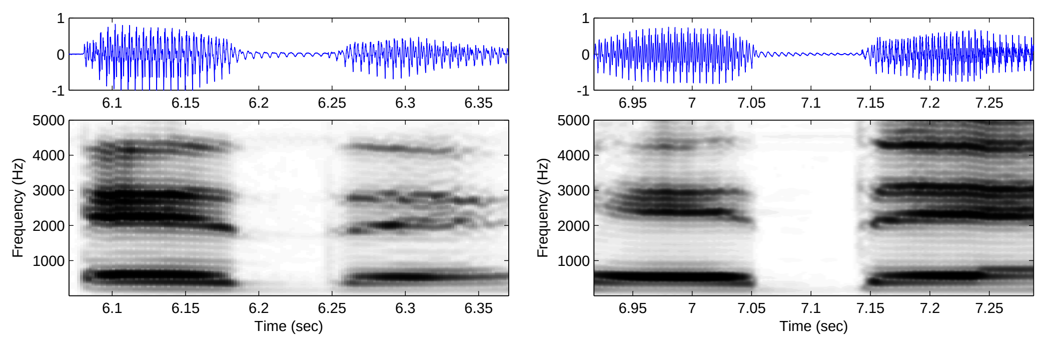

FIGURE 4.3: Acoustic waveforms and spectra of **Spanish intervocalic stop [ede]** showing distinct acoustic stop intervals. Left: subject W1; right: subject W2.

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

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

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

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

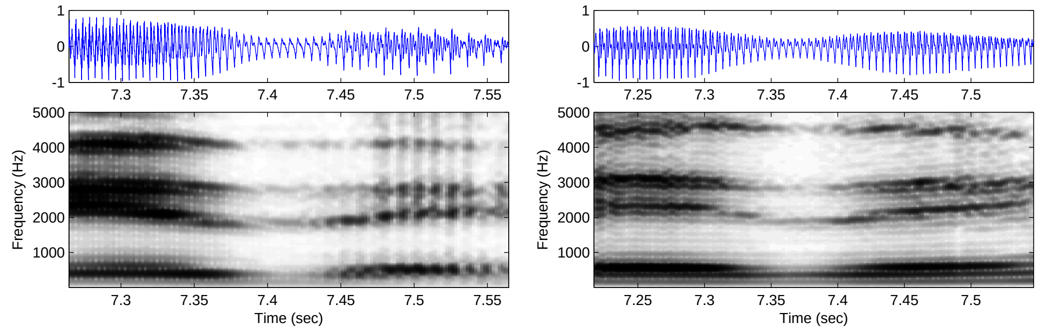

FIGURE 4.4: **Sprirantized intervocalic stop [eðe]** – subjects W3 (left) and W4 (right).

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

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

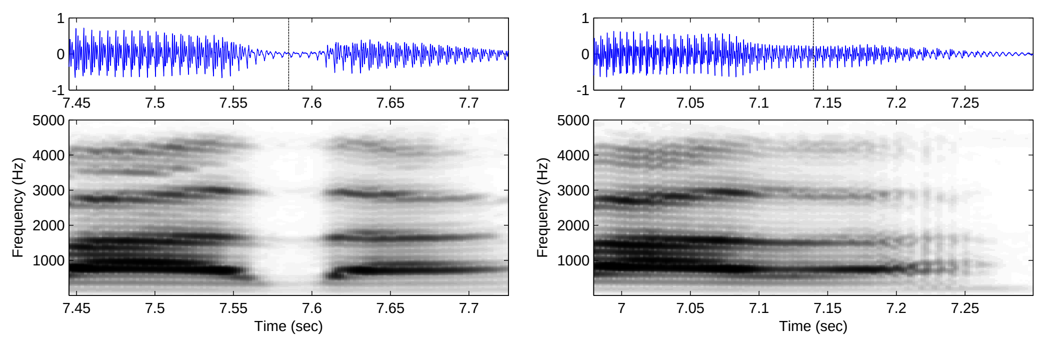

FIGURE 4.5: **Varying degrees of sprirantization in intervocalic stop production**: two utterances of token /ada/ – subject W1.

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

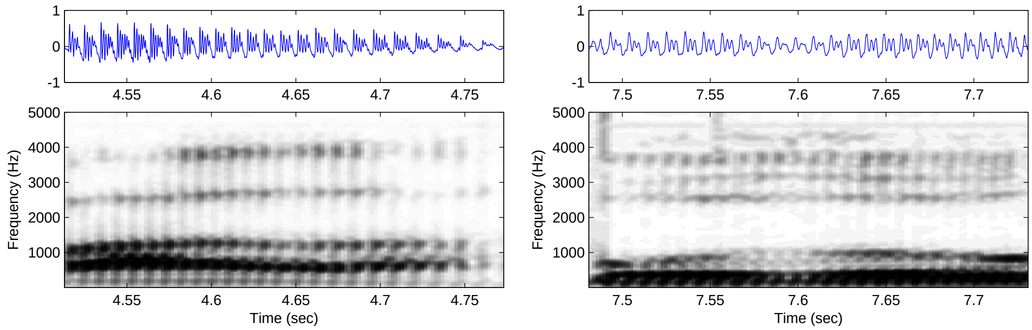

FIGURE 4.6: **Heavily sprirantized intervocalic stops** showing little or no movement in formant trajectories – subject M1. Tokens [aða] (left) and [uðu] (right).

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

Acoustic Characterization of Intervocalic Laterals

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

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

Acoustic Characterization of Intervocalic Taps

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

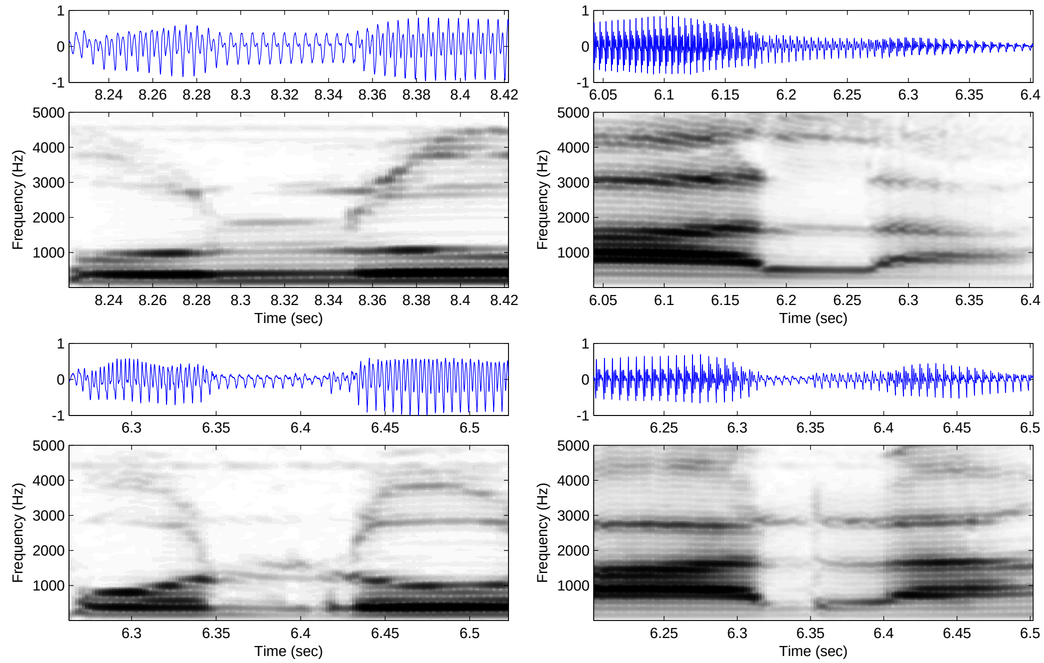

FIGURE 4.7: Acoustic waveforms and spectra of **Spanish intervocalic laterals**: left column: [ulu]; right column: [ala]. Top row: subject W3; bottom row: subject W4. Second formant trajectories in all utterances convergent on range 1450 Hz < F2 < 1900 Hz.

(Table 4.2).

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

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

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

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

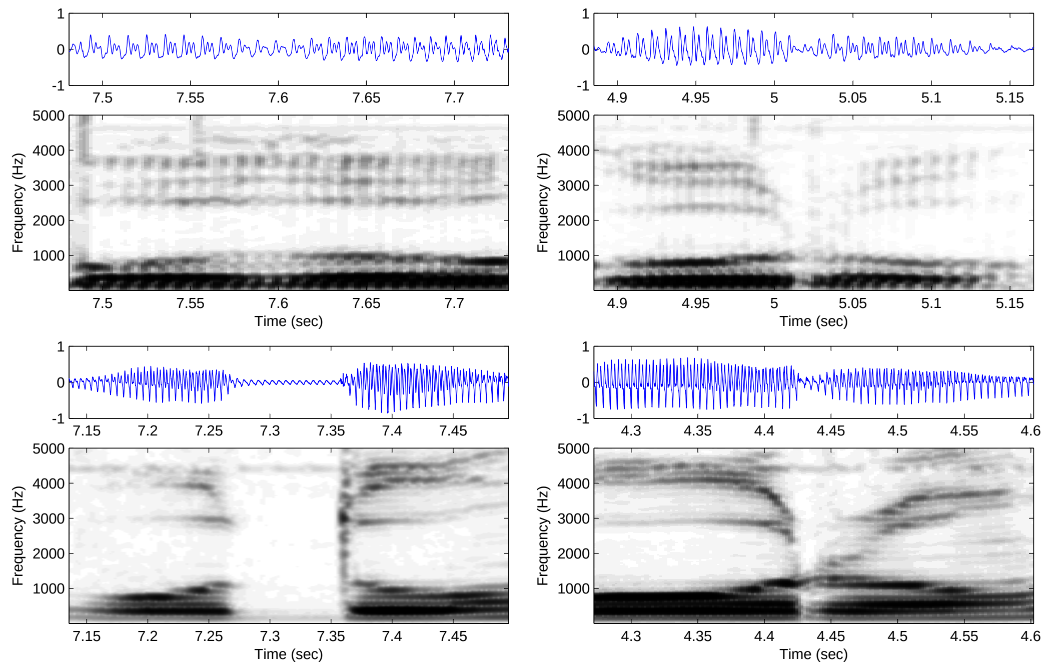

FIGURE 4.8: Comparison of **Spanish intervocalic coronal stops and taps**. Left column: [udu]; right column: [uɾu]. Top row: subject M1; Bottom row: subject W4.

Acoustic Characterization of Intervocalic Trills

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

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

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

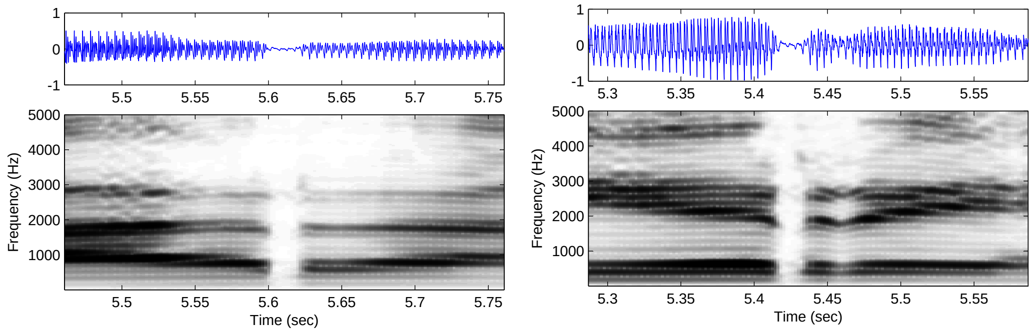

FIGURE 4.9: Spanish intervocalic trill production: **variation in number of closure intervals** – subject W2. Left: single closure ([ara]); right: double closure ([ere]).

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

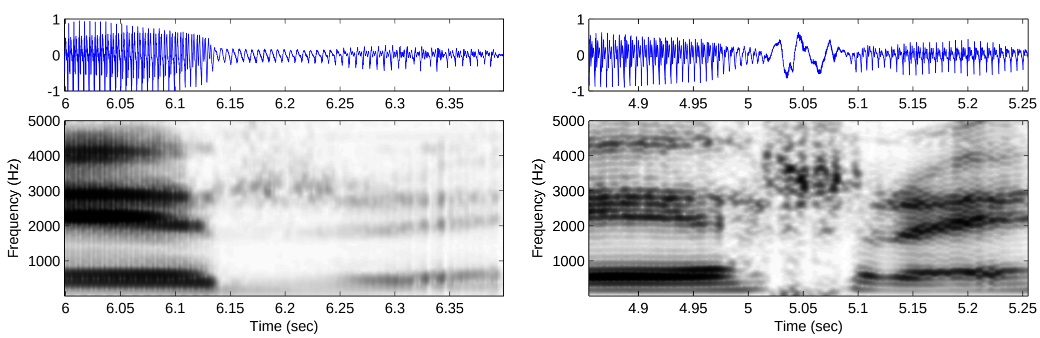

FIGURE 4.10: **Spirantization in Spanish trills** in a mid-front intervocalic context: [ere]. Left: subject W3; right: W4.

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

Acoustic Characterization of Spanish Rhotics

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

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

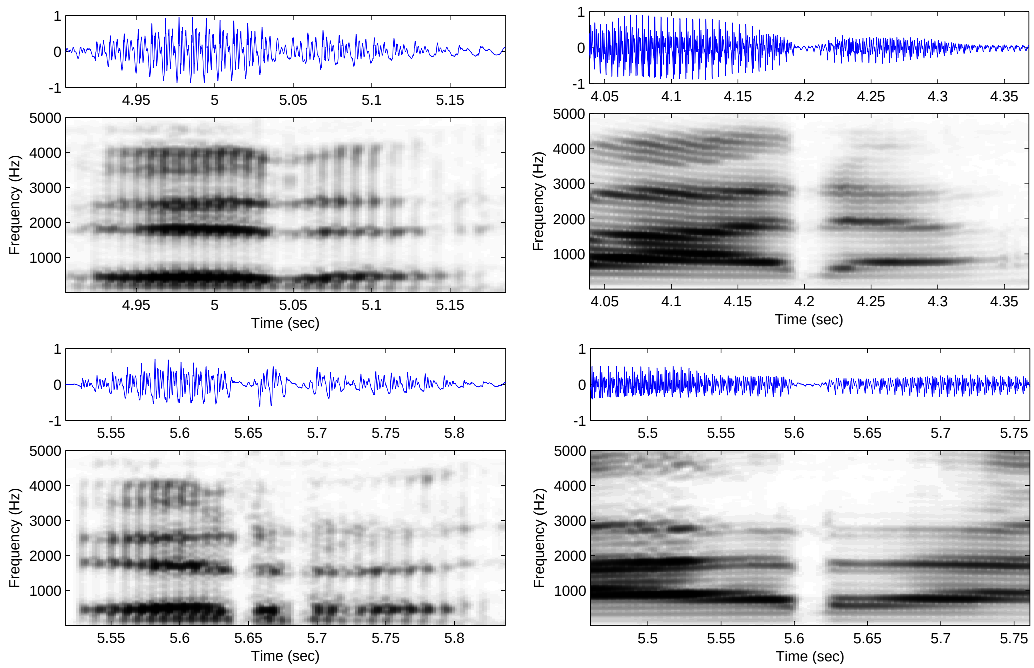

FIGURE 4.11: **Non-lowered third formants** in Spanish intervocalic rhotics. Top left: [ere] (subject M1); top right: [ara] (W1). Bottom left: [ere] (M1); bottom right: [ara] (W2).

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

4.3.3 Formant Analysis of Intervocalic Liquids

Method

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

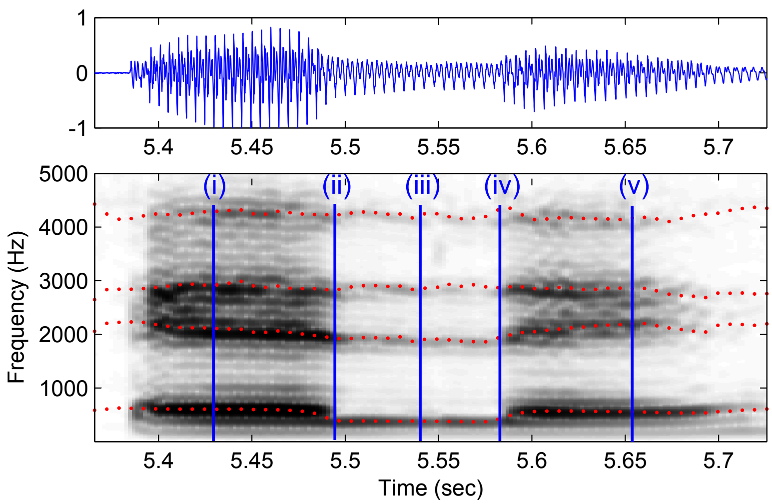

FIGURE 4.12: **Acoustic landmarks used for analysis of intervocalic consonants**: (i) pre-consonantal vowel; (ii) beginning of consonantal interval; (iii) center of consonant; (iv) end of consonantal interval; (v) center of post-consonantal vowel. (Sequence illustrated: [ele], subject W1).

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

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

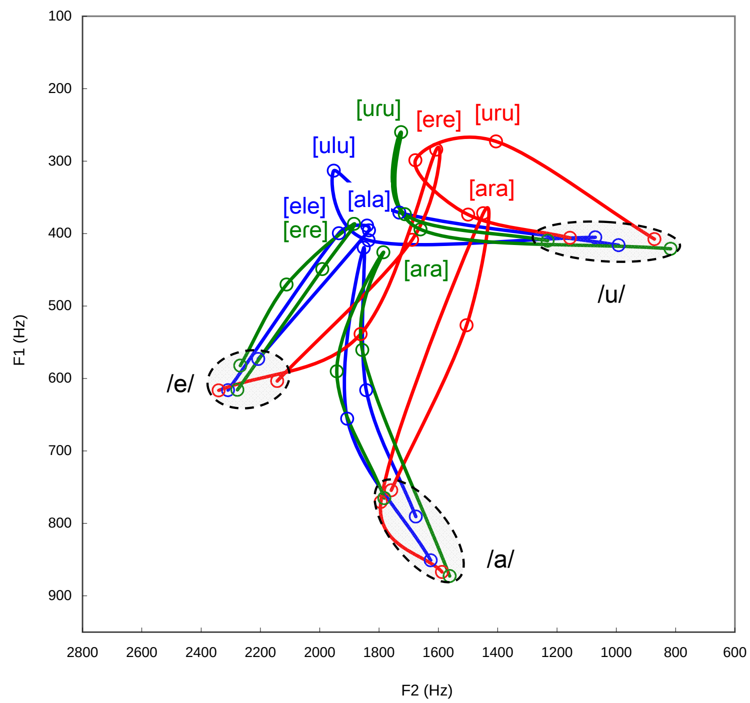

FIGURE 4.13: **Formant trajectories of Spanish intervocalic liquids – subject W1**. Horizontal axis: first formant frequency (Hz); Vertical axis: second formant frequency (Hz). Circled: landmarks on acoustic trajectories of each intervocalic liquid VLV, calculated at points indicated in Fig. 4.12.

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

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

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

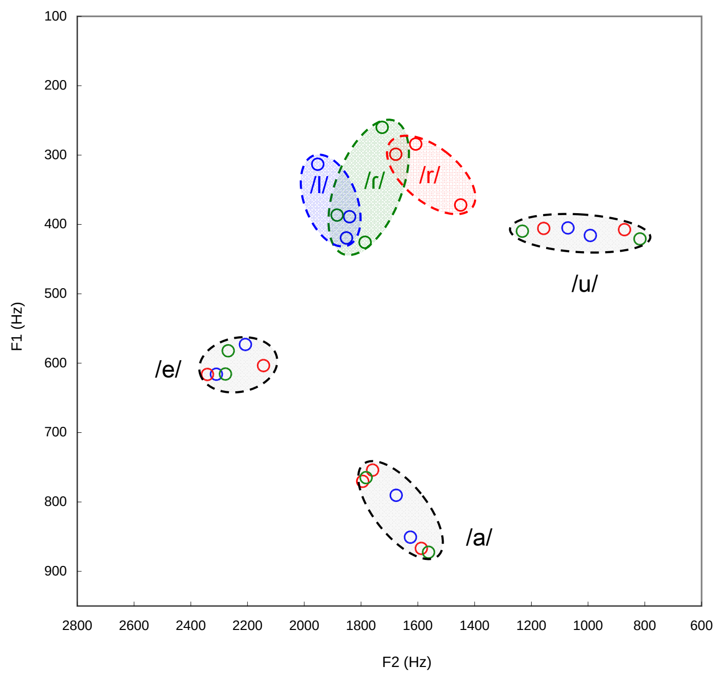

FIGURE 4.14: **Acoustic targets of Spanish intervocalic liquids: subject W1**. Horizontal axis: first formant frequency (Hz); Veritical axis: second formant frequency (Hz). Ellipses enclose acoustic center frequencies of liquids produced in all vowel contexts.

lateral characterized by a higher mean F2 than the rhotics.

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

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

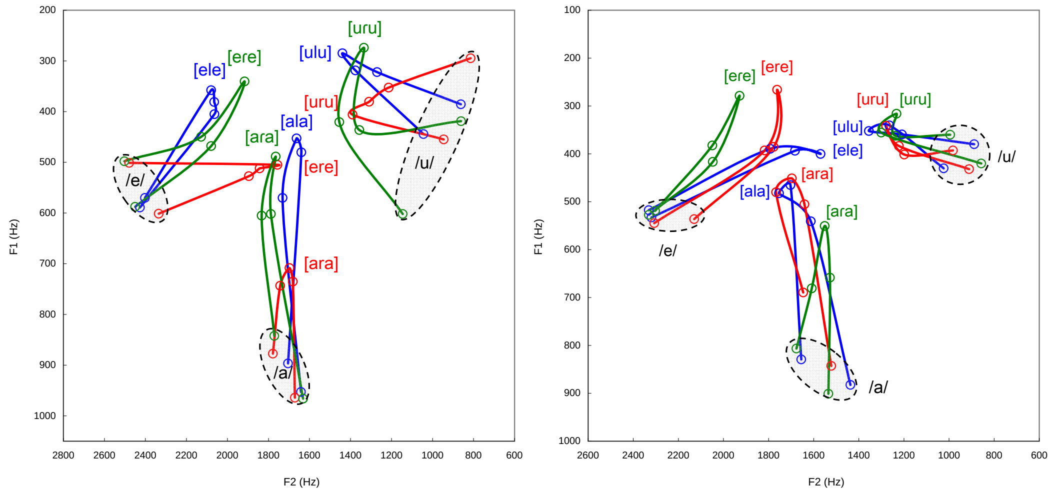

FIGURE 4.15: **Formant trajectories of Spanish intervocalic liquids**: subjects W2 (left); W3 (right).

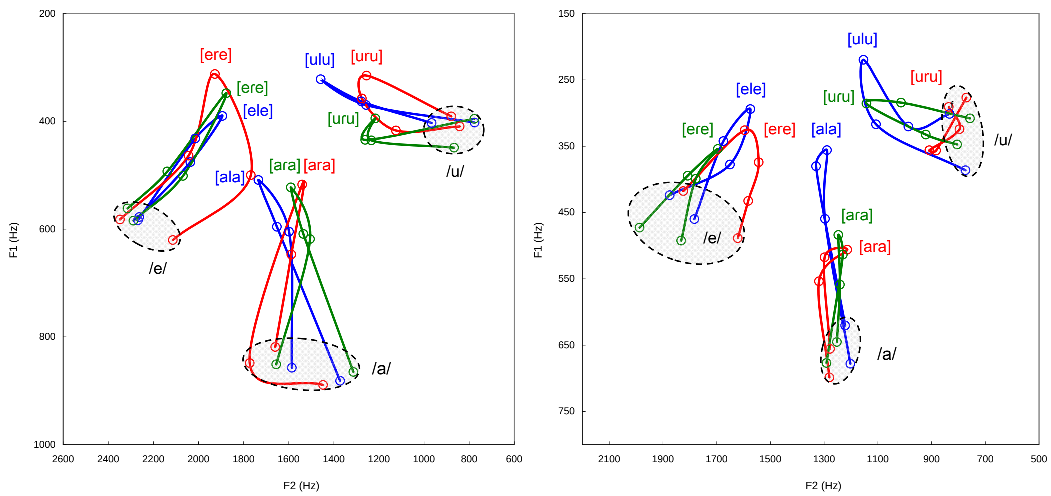

FIGURE 4.16: **Formant trajectories of Spanish intervocalic liquids**: subjects W4 (left); M1 (right).

quencies across all vowel contexts than for the other subjects.

4.3.4 Summary: Acoustic Properties of Spanish Intervocalic Liquids

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

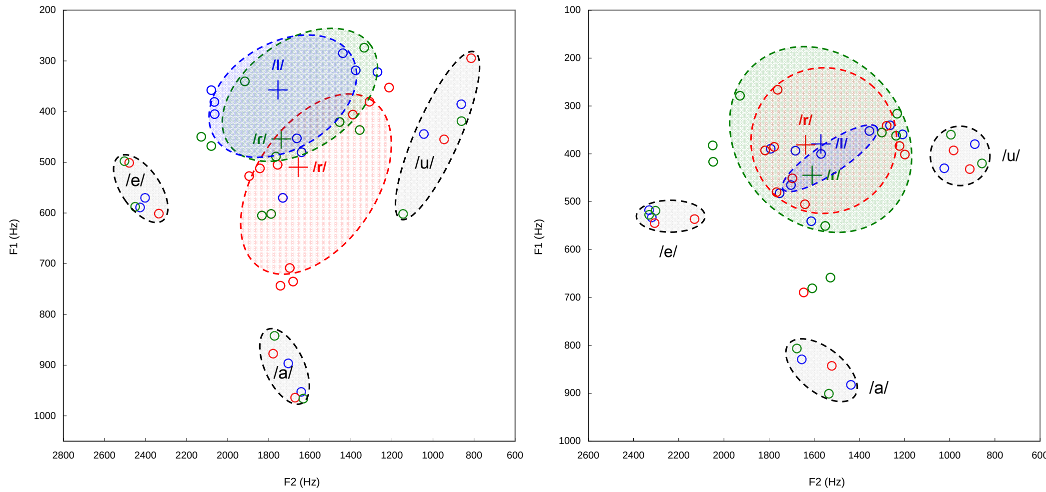

FIGURE 4.17: **Acoustic targets of Spanish intervocalic liquids**: subjects W2 (left) and W3 (right).

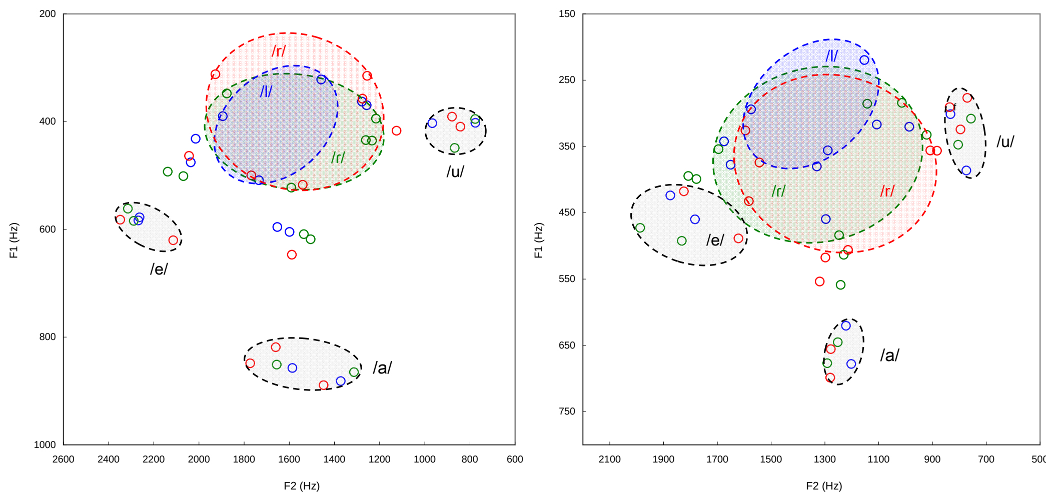

FIGURE 4.18: **Acoustic targets of Spanish intervocalic liquids**: subjects W4 (left) and M1 (right).

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

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

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

4.3.5 Results: Dynamic Analysis of Midsagittal Lingual Articulation

Articulation of Spanish Coronal Consonants in a Low Vowel Context

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

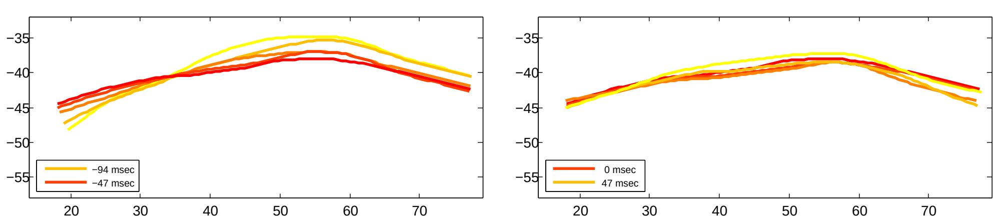

FIGURE 4.19: Dynamic midsagittal lingual **articulation of Spanish intervocalic coronal stop [ada]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

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

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

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

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

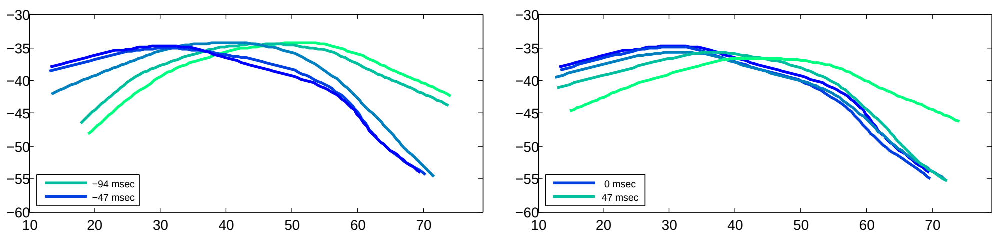

FIGURE 4.20: Midsagittal lingual **articulation of Spanish intervocalic lateral [ala]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

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

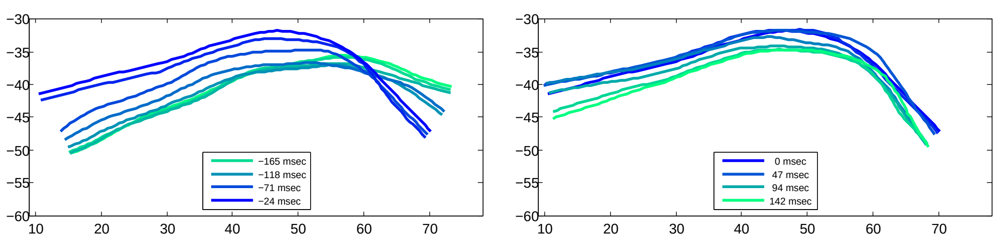

FIGURE 4.21: Midsagittal lingual **articulation of Spanish intervocalic trill [arra]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

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

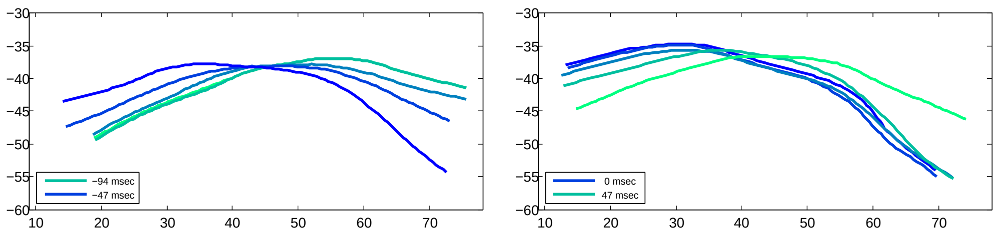

FIGURE 4.22: Midsagittal lingual **articulation of Spanish intervocalic tap [ara]** – subject W1. Left panel: consonant formation; Right panel: consonantal release.

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

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

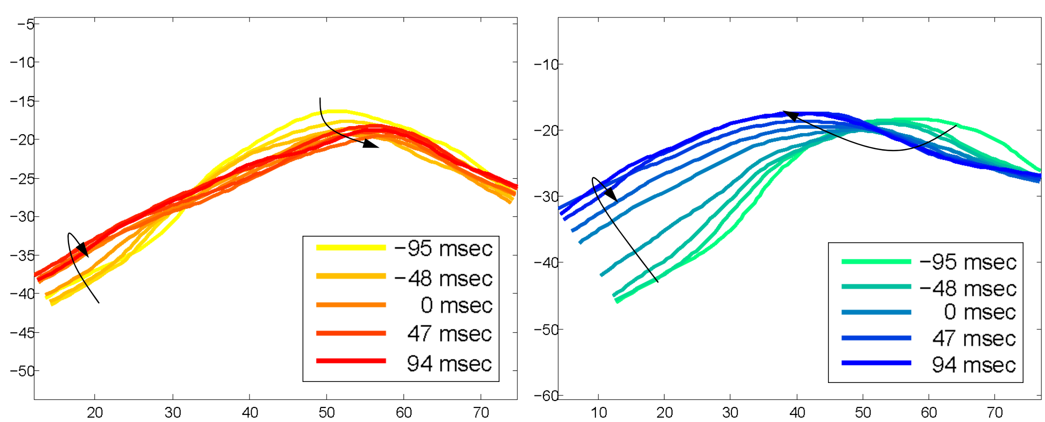

FIGURE 4.23: **Comparison of articulation of Spanish stop and trill** in low intervocalic context – subject M1. Left panel: token [ada]; Right panel: token [ara].

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

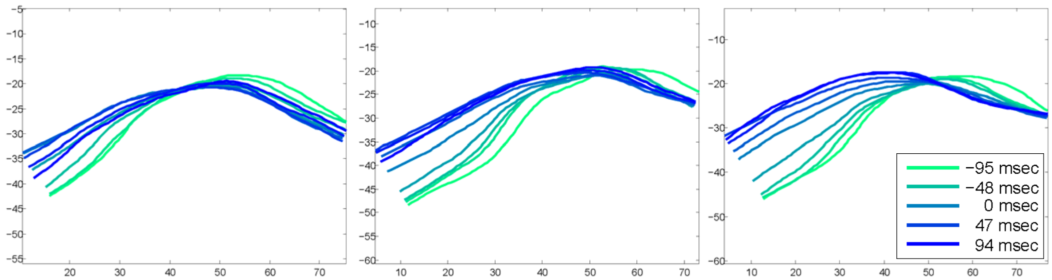

FIGURE 4.24: **Comparison of articulation of the three Spanish liquids** in a low intervocalic context – subject M1. Left: [ala]; Center: [aɾa]; Right: [ara].

Articulation of Spanish Coronal Consonants in a Front Vowel Context

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

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

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

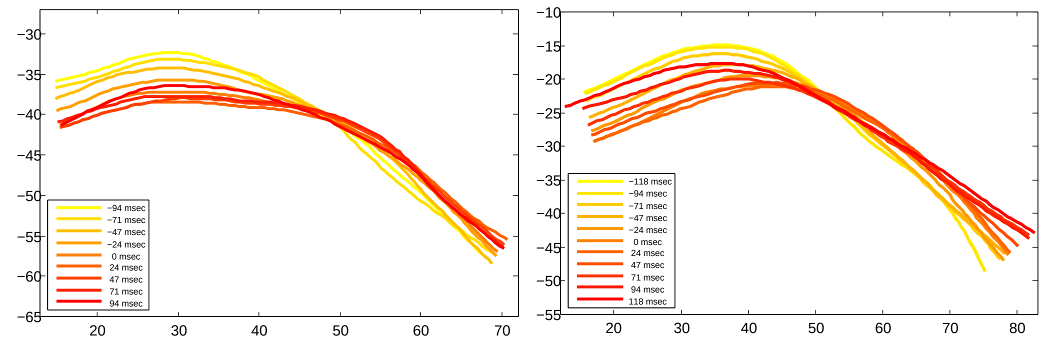

FIGURE 4.25: Dynamic midsagittal lingual **articulation of Spanish coronal stops in a front intervocalic context**. Left panel: [ede] (subject W1); Right panel: [ede] (subject M1).

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

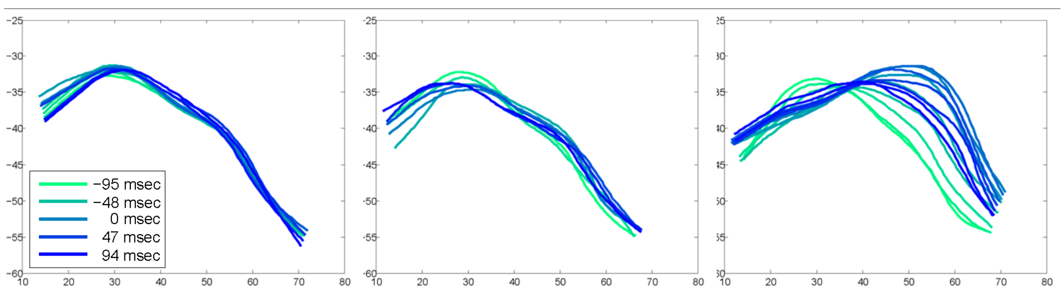

FIGURE 4.26: Midsagittal lingual **articulation of Spanish liquids in a front intervocalic context** – subject W1. Left: [ele]; Center: [ere]; Right: [ere].

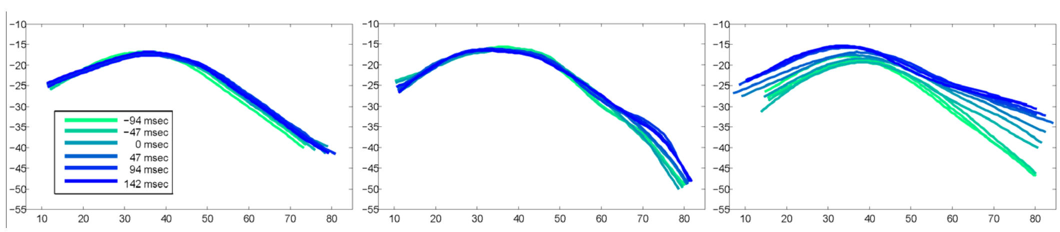

FIGURE 4.27: Midsagittal lingual **articulation of Spanish liquids in a front intervocalic context** – subject M1. Left: [ele]; Center: [ere]; Right: [ere].

4.3.6 Comparison of Mid-consonantal Dorsal Articulation

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

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

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

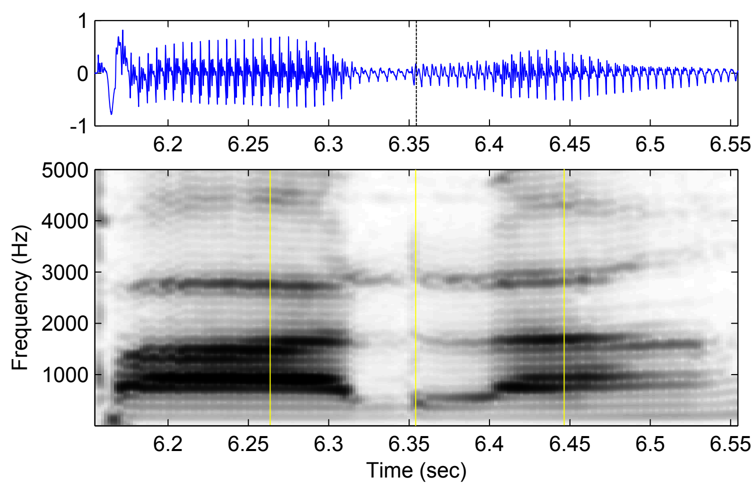

FIGURE 4.28: **Analysis landmarks for Spanish intervocalic consonants**: (i) pre-consonantal vowel; (ii) mid consonant; (iii) post-consonantal vowel. (Token illustrated: [para], subject W1).

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

Quantification of Vowel-Consonant Coarticulation

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

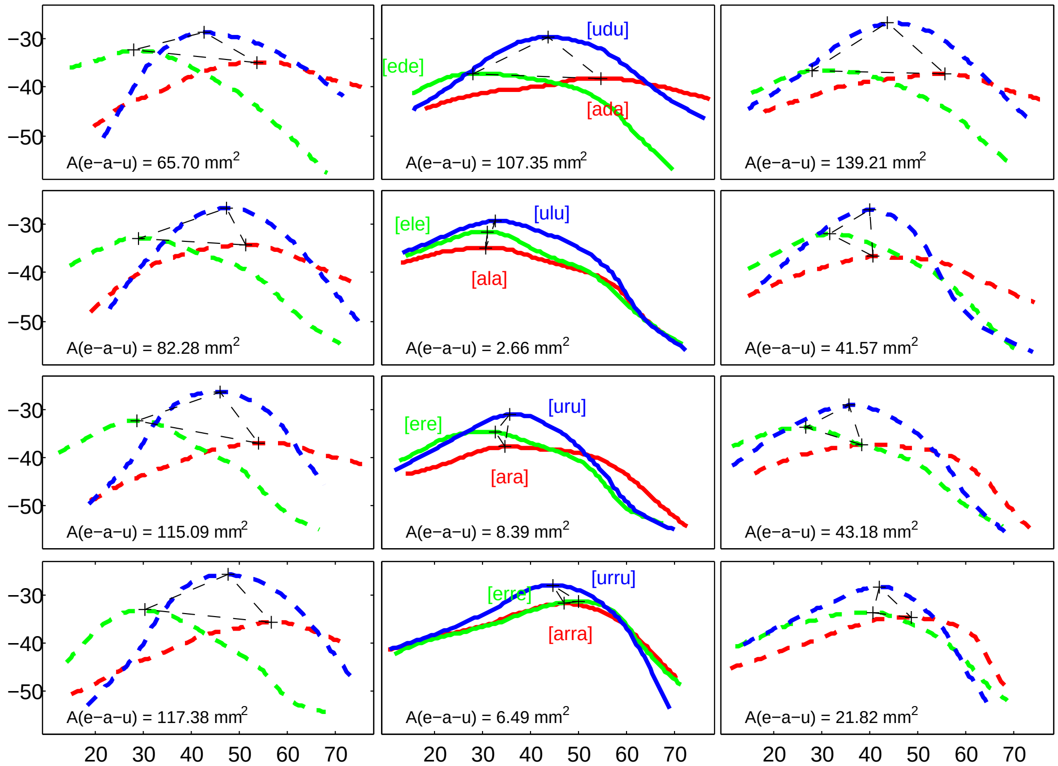

FIGURE 4.29: **Midsagittal lingual articulation of Spanish coronal consonants in three intervocalic contexts** – subject W1. Top row: stop; 2nd row: lateral; 3rd row: tap; 4th row: trill; Left column: pre-consonantal vowel; Center column: mid consonant; Right column: post-consonantal vowel.

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

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

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

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

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

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

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

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

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

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

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

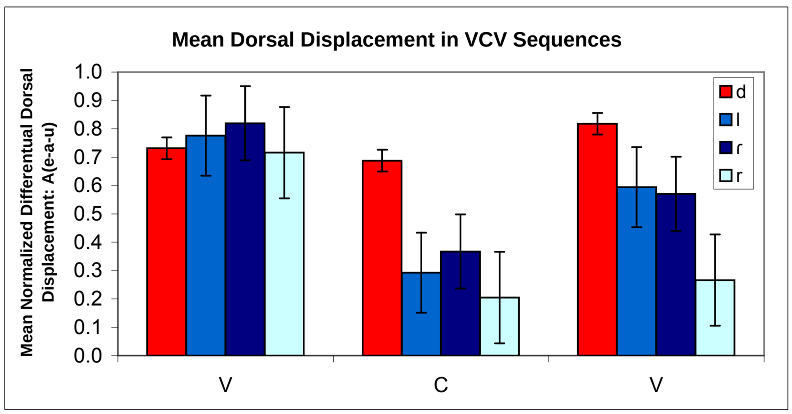

FIGURE 4.31: **Mean normalized differential dorsal displacement** for Spanish coronal consonants – all subjects.

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

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

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

i. a *one-way analysis of variance test* of the null hypothesis that dorsal coarticulatory effects (as measured by the differential dorsal displacement data) are the same for Spanish coronal stops and liquids
ii. a *two-sided Wilcoxon rank sum test* of the null hypothesis that the differential dorsal displacement data for stops and liquids are independent samples from

identical continuous distributions with equal medians, against the alternative that they do not have equal medians

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

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

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

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

Location of Liquid Dorsal Gestures

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

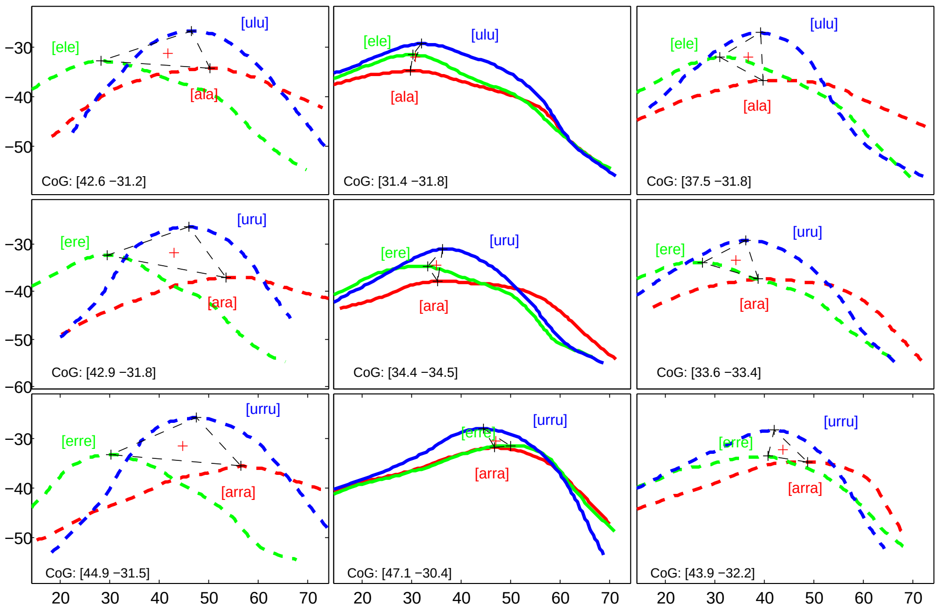

FIGURE 4.32: **Location of Spanish liquid dorsal gestures**, estimated using centers of gravity of dorsal apexes across three vowel contexts [e_e]-[a_a]-[u_u] – subject W1.

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

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

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

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

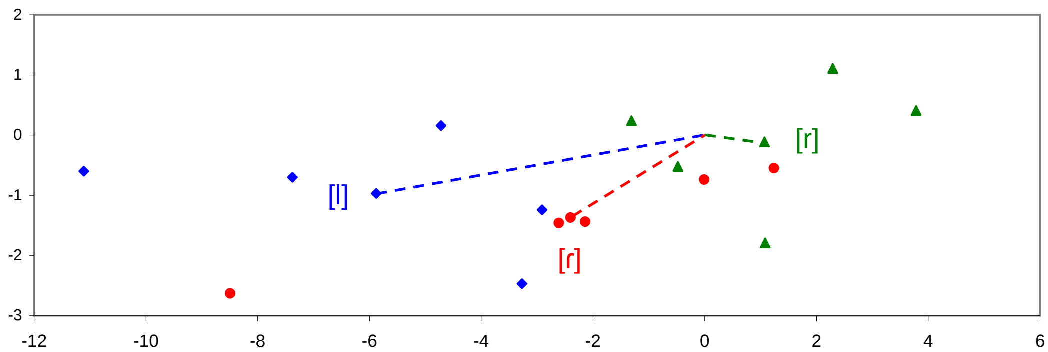

FIGURE 4.33: **Mean locations of Spanish liquid dorsal targets with respect to 'schwa'.** Blue: intervocalic laterals; Red: intervocalic taps; Green: intervocalic trills. Dashed lines indicate mean dorsal displacement from pre-consonantal vocalic center.

4.3.7 Summary of Results – Spanish Intervocalic Consonants

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

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

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

4.4 Phonetic Characterization of Spanish Coda Liquids

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

4.4.1 Stimuli

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

4.4.2 Results: Acoustic Characterization of Word-Final Rhotics

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

Classification of Word-Final Rhotics

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

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

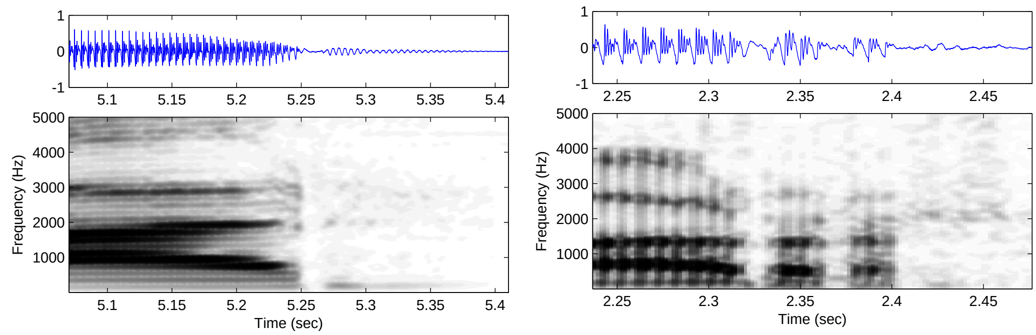

FIGURE 4.34: **Variation in Spanish word-final rhotics – number of coronal closures**: Left: [ar], subject W2; right: [ar], subject M1.

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

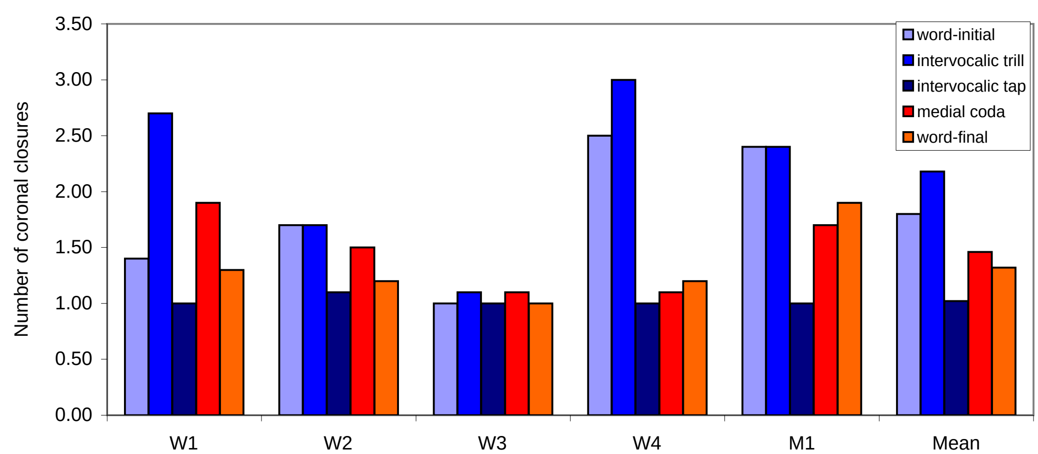

FIGURE 4.35: **Number of Coronal Closures in Spanish rhotics**. Mean numbers of contacts per rhotic for each phonological environment, estimated from numbers of attenuated intervals in acoustic signal.

Acoustic Quality of Word-Final Rhotics

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

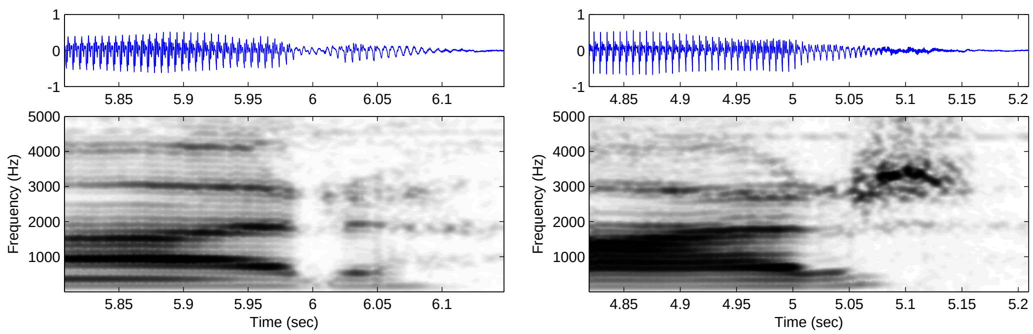

FIGURE 4.36: **Spirantization of Spanish word-final rhotics**: [ar]. Left: subject W3; Right: W4.

Articulation of Word-Final Rhotics

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

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

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

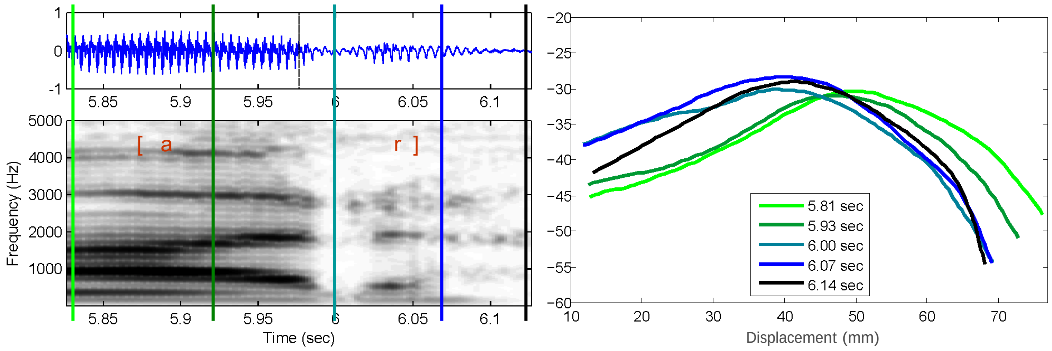

FIGURE 4.37: **Dorsal articulation in tapped word-final rhotic**: [ar˺], subject W3. Left: waveform and spectrum; Right: midsagittal articulation at five points in time.

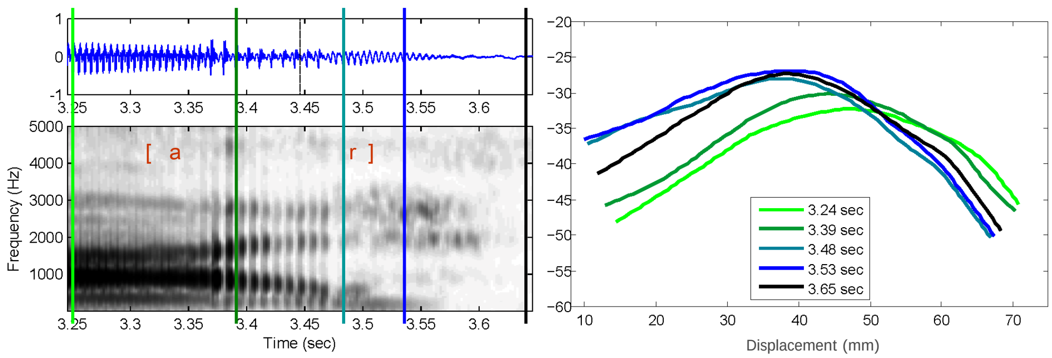

FIGURE 4.38: **Dorsal articulation in spirantized word-final rhotic**: [ar˺], subject W3. Left: waveform and spectrum; Right: midsagittal articulation at five points in time.

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

4.4.3 Svarabhakti in Coda Rhotics

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

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

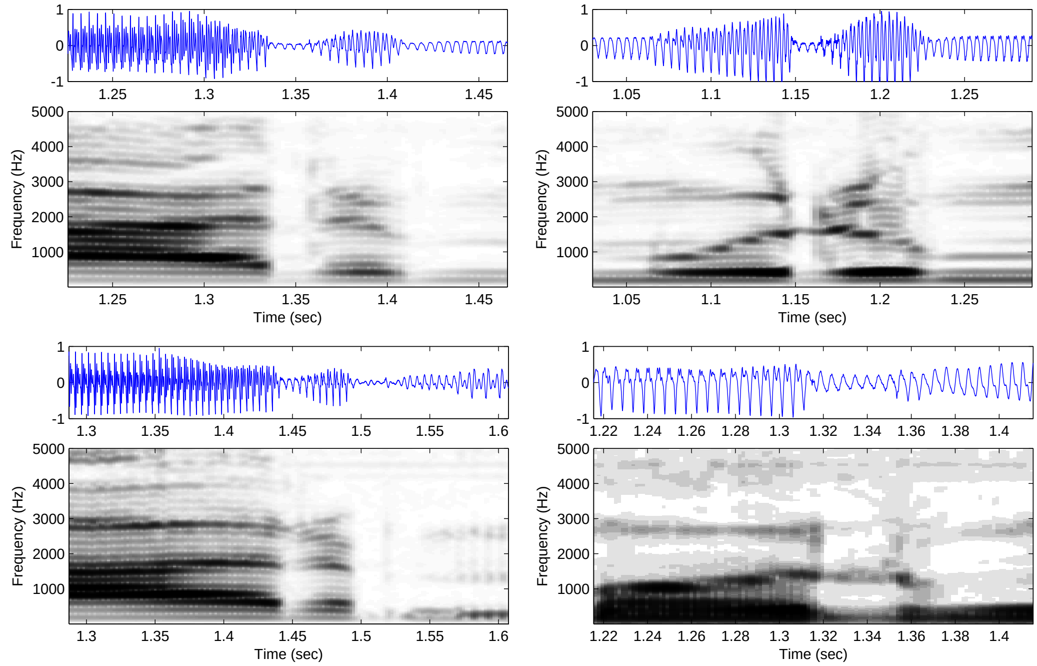

FIGURE 4.39: **Svarabhakti fragments in medial coda rhotics**: Top left: subject W1 [arm]; Top right: [urm]; Bottom left: subject W3 [arm]; Bottom right: [urm].

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

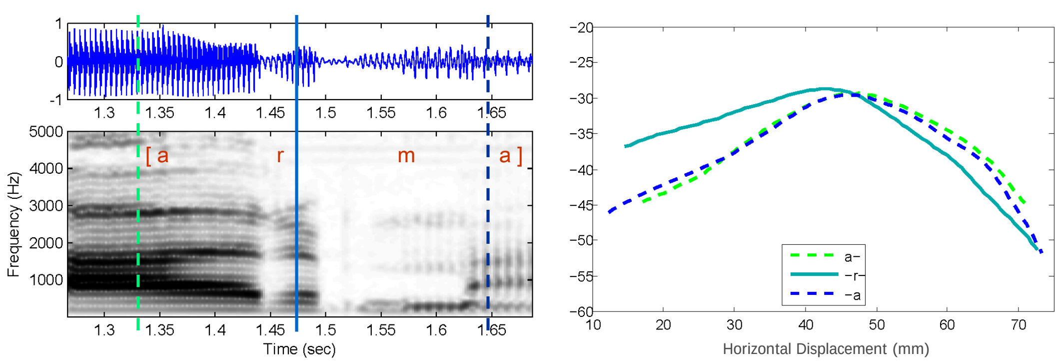

FIGURE 4.40: **Dorsal articulation in coda svarabhakti**: Left: [arma] waveform and spectrum (subject W3); Right: midsagittal articulation at three points in time: [a]–[ɾ]–[a].

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

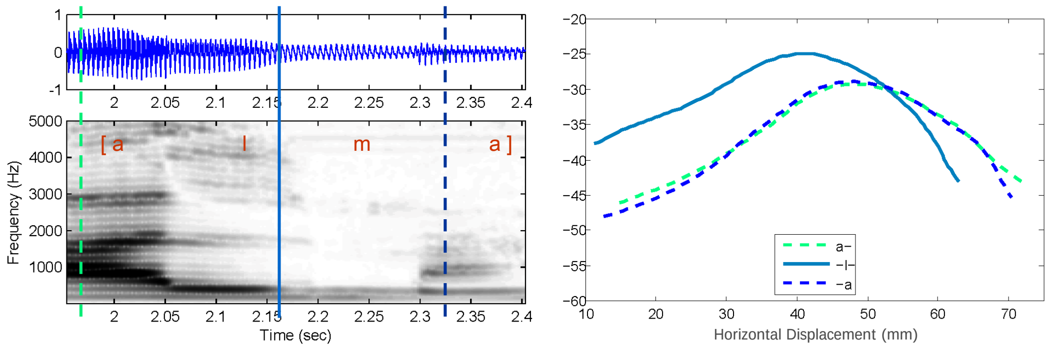

FIGURE 4.41: **Dorsal articulation of Spanish medial coda lateral** (subj. W3): Left: [alma] waveform and spectrum; Right: midsagittal articulation at three points in time: [a]–[l]–[a].

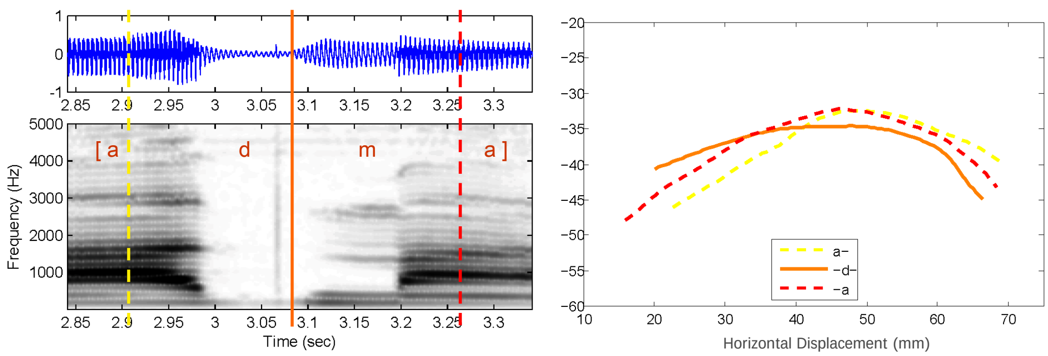

FIGURE 4.42: **Dorsal articulation of Spanish medial coda stop** (subj. W3): Left: [adma] waveform and spectrum; Right: midsagittal articulation at three points in time: [a]–[d]–[a].

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

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

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

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

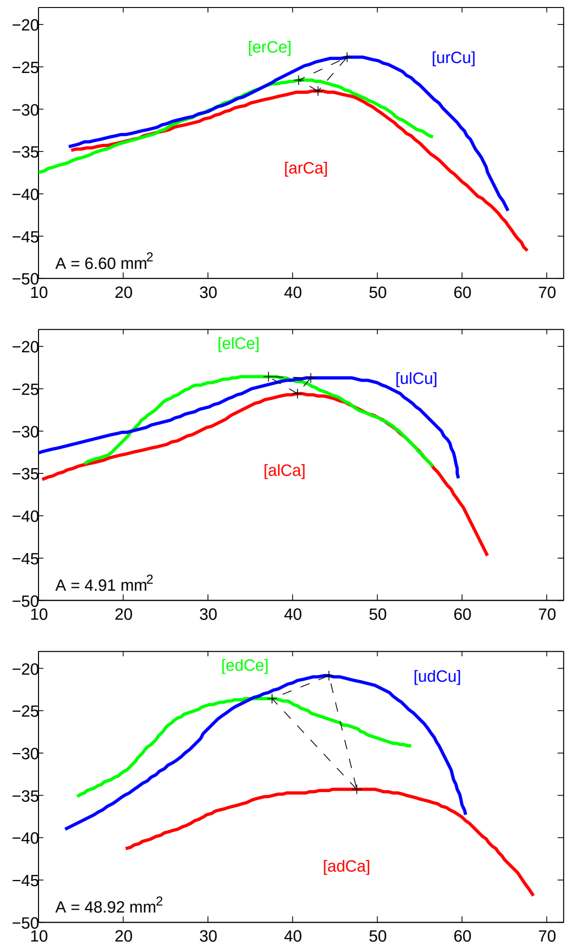

FIGURE 4.43: **Mid-consonantal articulation of Spanish medial coda consonants in three vowel contexts** (subject W3): Top: [ɾ] in VrmV; Middle: [l] in VlmV; Bottom: [d] in VdmV.

4.5 Conclusions

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

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

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

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

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