A stochastic approach to rhotic variation in Spanish codas

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ABSTRACT: A stochastic analysis using aerodynamic and temporal variables is presented to explain tap/trill variation in Spanish codas. Simultaneous intraoral pressure (P_o), translingual flow (F) and acoustic signals were obtained for two native speakers of Peninsular Spanish performing a rate-controlled reiterative task. Data were analyzed using linear mixed effects models fitted with random effects for speaker and repetition. The results show that tongue height and tongue anteriority of the preceding vowel affect the timing and aerodynamic parameters of the rhotic onset gesture, but the phonological specifications of the following consonants do not. Continuous variables were fit into a Bayesian logit regression model using noninformative priors which shows that tap/trill variation in coda can be predicted in part from aerodynamic and temporal parameters. Such a proposal obviates the need to resort to positional constraints to explain tap/trill variation in codas.

Keywords: aerodynamic parameters; Spanish rhotics; variation.

RESUMEN: *Análisis estocástico de la variación de las róticas en posición de coda en español.–* Se presenta un análisis estocástico con variables aerodinámicas y temporales para explicar la variación de las róticas en posición implosiva en español. Las señales acústicas, de presión orofaríngea y flujo traslingual, fueron obtenidas simultáneamente de dos sujetos nativos de habla hispana en una tarea de repetición controlada. Los datos fueron analizados utilizando una serie de modelos lineales de efectos mixtos tomando como efectos aleatorios programados tanto la variable hablante como repetición. Los resultados demuestran que la postura de la lengua en la vocal que precede a la rótica afecta a la temporización y los parámetros aerodinámicos del gesto inicial de la rótica. Las variables continuas se programaron en un modelo de regresión logística bayesiana utilizando una distribución de probabilidades *a priori* no informativa que demuestra que la variación entre la vibrante simple y la vibrante múltiple en posición implosiva en español es predecible en parte por los parámetros aerodinámicos y temporales. Tal propuesta hace innecesario explicar la variación de las róticas en posición implosiva con un modelo determinista que regule el surgimiento de segmentos en determinadas posiciones fonológicas.

Palabras clave: parámetros aerodinámicos; róticas en español; variación.

1. THE ARTICULATORY AND AERODYNAMIC CHARACTERISTICS OF SPANISH RHOTICS

Spanish has two quasi-contrasting rhotics, the apical alveolar tap [ɾ] and the apical alveolar trill [r]. Taps have been described as a coordinated progression of the tongue tip toward the alveolar ridge which makes a singular contact in the post-dental region (Ladefoged & Maddieson, 1996). Trills, in contrast, involve a short series of occlusions against the alveolar ridge, producing a tense, controlled and highly constrained gesture (Recasens, 1991). And whereas the simple tap [ɾ] requires lingual muscular control to carry out the tongue tip gesture, trill instantiation and maintenance depends on the antagonistic relationship between torsional force of the tongue mass and aerodynamic factors (Barry, 1997; Catford, 1977; Ladefoged & Maddieson, 1996; Recasens, 1991; Spajić, Ladefoged, & Bhaskararao, 1996; Solé, 2002). Taps show less predorsum lowering and postdorsum retraction than trills (Recasens & Pallarès, 1999), while the tongue body is more restricted for trills than for taps (Recasens, 1991). Further, there is believed to be a slight velar gesture inherent to the trill which constrains coarticulation with neighboring vowels (Recasens, 1987). Both rhotics con-

tain a non-syllabic, vocoid-like element which may be audible in certain contexts (Hall, 2006; Harms, 1976; Levin, 1987; Quilis, 1970, 1993; Schmeiser, 2009; Warner, Jongman, Cutler, & Mücke, 2001) and is attested cross-linguistically (for Catalan rhotics, see Recasens & Espinosa, 2007; for Hungarian, see Vago & Gósy, 2007; for Modern Greek, see Baltazani & Nicolaidis, 2011, 2013; for Polish, see Stolarski, 2011, June; for Romanian, see Avram, 1993; for Serbo-Croatian, see Gudurić & Petrović, 2005; for Slovak, see Pavlík, 2008; for Spanish, see Bradley & Schmeiser, 2003; Ramírez, 2006; Schmeiser, 2009).

The mechanics of trills have been outlined extensively in Barry (1997), Catford (1977), Ladefoged and Maddieson (1996), and Spajić, Ladefoged, and Bhaskararao (1996) while Solé (2002) characterizes the specific oropharyngeal pressure parameters for voiced and voiceless apical trills. As the tongue sides rise toward the upper molars, there is a lowering of the tongue dorsum to initiate tongue tip vibration. The tongue tip approaches the alveolar target, causing an increase in oropharyngeal pressure behind the linguopalatal constriction. Eventually, this pressure builds up to the point that its force becomes more powerful than the mass and torsional force of the contracted muscles of the tongue tip, pushing the articulator down away from the alveolar ridge and allowing airflow to escape. The tongue tip returns to the alveolar ridge due to the Bernoulli effect, taking the form of a self-sustained vibratory system.

Aerodynamic requirements for voiced trills are severely constrained in order to sustain muscular and laryngeal vibration (Solé, 2002). Solé (2002) demonstrated that slight perturbations to the parameters needed for vibration lead to the interruption of trilling and voicing. She showed that gradual reductions in oropharyngeal pressure extinguished voiced trills earlier than voiceless trills and the window of permissible pressure parameters for trills is narrower than that of fricatives, suggesting that voiceless trills tend to be more impervious to changes in aerodynamic conditions than voiced trills.

2. RHOTIC VARIATION IN SPANISH CODAS: CONTEXTUAL PARAMETERS VERSUS POSITIONAL CONSTRAINTS

Rhotic distribution is generally predictable in Spanish. The simple tap [ɾ] can appear as a singleton onset word-internally and as the second gesture of a complex onset word-initially and word-internally. In codas [ɾ] emerges frequently and can serve as the first gesture in one of only a few tokens which contain a complex coda: perspicaz, 'keen'. Trills contrast with the tap in word-internal onsets, while the trill appears exclusively in word-initial position. In syllable-final position, the tap and trill contrast in a paradigm of free variation, although taps are generally preferred.

A number of factors influence variation in codas. From the point of view of perception, coda consonants

are less salient than those found in onsets and hence play an inferior role in lexicon access and retrieval (Beckman, 1998), meaning consonants may vary more freely without signaling a rupture in communication. As regards spatio-temporal coordination, it has been proposed that coda gestures are phased linearly (180º) in relation to the preceding vowel (Browman & Goldstein, 1986, and many studies since), which translates to a reduction in stability compared to onset gestures (Byrd, 1996; Goldstein, Byrd, & Saltzman, 2006; Goldstein, Nam, Saltzman, & Chitoran, 2008, April). Due to this decreased stability, codas are often susceptible to non-categorical variation when speech rate increases (Goldstein, Pouplier, Chen, Saltzman, & Byrd, 2007; Pouplier, 2007a, 2007b), and are acquired later than onsets, often undergoing processes of substitution and deletion not found for onsets (Demuth & Fee, 1995; Fikkert, 1994; Gnanadesikan, 1996; Levelt, Schiller, & Levelt, 2000; Salidis & Johnson, 1997; Vihman & Ferguson, 1987). Syllable-final consonants appear to be especially prone to articulatory reduction (Ohala & Kawasaki, 1984) due to modifications of lingual posture and constriction degree (Recasens, 2004) which may lead to diachronic changes in the phonology (Browman & Goldstein, 1995; Fougeron, 1999; Solé, 2003). With regard to aerodynamics it was suggested that drops in subglottal pressure for coda fricatives may explain their tendency to lenite (Solé, 2003). In stuttering patients, it has been found that the emergence of a syllable-final gesture may trigger the destabilization of gesture sequences, codas being likely candidates for gestural reorganization (Huinck, van Lieshout, Peters, & Hulstijn, 2004).

Coda variation is one of the defining characteristics of both standard and non-standard dialects in Spanish. Aside from the tap/trill contrast, attested processes include aspiration and deletion of coda /s/ (see Kochetov & Colantoni, 2011; Lipski, 1994; Romero, 1995, for especially informative reviews), the optional velarization of /n/ (Canfield, 1960, 1981; Darias Concepción, Ruisánchez Regalado, & Dohotaru, 1997; Lipski, 1987, 1994; López Morales, 1981; Wireback, 1999), the non-standard lateralization of /r/ (D'Introno, Rojas, & Sosa, 1979; Marrero, 1988; Quilis-Sanz, 1998), the non-standard rhoticization of /l/ (López Morales, 1983; Quilis, 1999; Willis, 2006), devoicing of word-final obstruents (González, 2002) and complete deletion of a number of consonants.

The majority of studies addressing the distribution of rhotics in syllable-final position in Spanish have been limited to a descriptive and/or theoretical approach, focusing more on the dialectal idiosyncrasies of the rhotics than the mechanical processes that trigger rhotic variation (see Bradley & Willis, 2012; Vásquez Carranza, 2006). Colina (2010) envisages tap emergence in coda as a function of positional constraints which prohibit the trill from emerging in coda. A number of important asymmetries, however, challenge a deterministic approach to tap/trill variation based on positional constraints. First, the realization of the trill for the tap does not comport with the general tendency toward lenition in Spanish codas, lenition understood as the reduction of articulatory effort as

per Kirchner (1998). Second, there is no lexical, semantic or syntactic ambiguity attributed to the realization of one variant over another which might suggest that tap/trill variation is actually a linguistic phenomenon (as opposed to a strictly mechanical process) as there is with lateralization/rhoticization and consonant deletion. Third, such a proposal ignores the random effects from the phonetic environment which may also condition variation. These asymmetries suggest that tap/trill variation may not be an objective function of the productive Spanish grammar, but rather is determined primarily, though maybe not exclusively, from the context-dependent articulatory and aerodynamic parameters established by the phonetic environment.

There are independent reasons, however, to espouse a stochastic approach of tap/trill variation which takes into account the context-dependent phonetic parameters which may favor or discourage trilling in certain environments. It has been reported that the articulatory settings for vowels condition the aerodynamic patterns of neighboring consonants (Chang et al., 1999; Fischer-Jørgensen, 1972; Klatt, 1975; Koenig & Fuchs, 2007; Netsell, Lotz, DuChane, & Barlow, 1991). Intra-oral pressure discharge for voiceless stops, for example, was shown to be slower preceding high vowels, possibly due to the higher degree of impedance (Chang et al., 1999; Fischer-Jørgensen, 1972; Koenig & Fuchs, 2007). Peak intraoral pressure values have been found to be lower in repetitions of voiceless labial stops followed by low vowels versus high vowels (Netsell et al., 1991) due to a more constricted oral cavity for high vowels. Solé (2002) found significantly higher mouthflow rates for trills coarticulated with a preceding [i], as compared to [a], yet effects were not consistent across speakers. Voice onset time has been found to be significantly longer leading into high-vowels as compared to low vowels (Klatt, 1975). To date, the effects of tongue anteriority on the aerodynamic parameters of neighboring consonants have received scant attention.

Given the precise aerodynamic and articulatory requirements for trilling, it is reasonable to expect the articulatory setting of the preceding vowel to affect the temporal and aerodynamic parameters of a following rhotic, and possibly play some role in tap/trill variation in Spanish.

In a similar way, the articulatory settings of vowels have also been found to affect coordination with neighboring consonants. Velar stops have been shown to be more fronted when followed by front vowels (Bloomfield, 1956). Later it was shown that the degree of fronting varies considerably across languages (Arbisi-Kelm, Beckman, Kong, & Edwards, 2008). Studying the pre-babbling stage of infants, Davis and MacNeilage (1995), MacNeilage (1998) and MacNeilage and Davis (1990) found that of all possible consonant/vowel combinations, velar consonants co-occurred more with back vowels, coronal consonants emerge more often with front vowels, while labial consonants patterned more with central vowels, showing a biomechanical preference for CV sequences with high degrees of coarticulation. It has also been

proposed that vowels with higher jaw settings are more resilient to coarticulatory effects, while being more likely to influence surrounding gestures (Recasens, 1985). Low vowels, on the other hand, are least resistant to coarticulatory effects, while being less likely to influence neighboring gestures. In the context of the current study, the degree of coarticulation may yield aerodynamic conditions which favor or discourage spontaneous trilling, in the sense that a higher degree of coarticulation between the vowel and rhotic onset could provide a longer temporal window in which to achieve the precise aerodynamic conditions required for trilling. High front vowels (fronting/predorsum raising) present conflicting articulatory demands on the lingual settings for trills (backing/predorsum lowering), which would constrain coarticulation. The tongue posture required for trilling may be less constrained, however, to coarticulate with mid-low and back vowels given their articulatory similarities. Thus if the degree of coarticulation is linearly related to mouthflow, and if mouthflow is a predictor of trilling, then a higher probability of spontaneous trilling following mid and back vowels would be expected.

The constriction degree of the following consonant plays a role in establishing articulatory parameters which may favor one rhotic variant over another by initiating modifications of vocal tract width which instigate alterations in oropharyngeal pressure and airflow. Voiceless stops, for example, have a narrower and more constricted tract than their voiced counterparts (Proctor, Shadle, & Iskarous, 2010). The larger pharyngeal volume for voiced stops is needed for vocal fold vibration. As airflow exits the lungs, friction causes vibration of the vocal folds, slowing the rate of air by absorbing the energy of the airflow. Lower pharyngeal volume for voiceless stops allows laminal airflow to increase rapidly, and produce a higher pressure buildup behind the tongue tip as the target gesture is reached, which may compete with the aerodynamic requirements for trill instantiation.

Likewise, the constriction location of a following consonant imposes both temporal and physical constraints on the preceding rhotic gesture. (For an especially enlightening review of the effects of following consonants on tap/trill variation, see Blecua, 2001.) In a sequence /r.d/, for example, it has been shown that no articulatory overlap is possible due to the fact that both consonant gestures involve the same primary articulator (Romero, 1996). The transition from a consonant with a relatively high stiffness specification ([+stiff]) to a consonant which is characterized as [-stiff] implies a reciprocal modification of torsional force in order to maintain the sequence stable. This stiffness/force equilibrium is well supported in classical rotational mechanics. Shadmehr and Arbib (1992) formulate the stiffness/force relationship in a biomechanical framework for a single joint system at isometric conditions, demonstrating that muscle stiffness must increase at least linearly with force in order to maintain stability. In the case of /r.d/, a damping behavior akin to that employed for the realization of the tap would be more adequate as opposed to vibration in order

to maintain equilibrium between tongue mass force and stiffness. In this context, the emergence of a trill should be discouraged by the phonetic environment. In sequences in which the consonant following the rhotic involves an active articulator from a distinct articulatory tier, however, the tongue tip for the rhotic is less constrained, or more free, to vary since the physical characteristics of the gestures do not make simultaneous demands on the same muscle mass. This assertion, however, is refuted by Blecua's (2001) extensive study of Spanish rhotics where it was found that rhotics followed by laterals (same active articulatory as the rhotic), then nasals and stops, showed the highest percentages of trilling.

The remainder of this article attempts to characterize the aerodynamic and temporal parameters (mouthflow) of apical taps and trills in syllable-final position. Consideration is directed toward the specific effects of the preceding vowel on the pre-closure phase of the rhotic, though the effects of the following consonant are also examined. Given that the parameters for intraoral pressure in voiced apical trills have been thoroughly outlined in Solé (2002), this article focuses attention on mouthflow parameters. Mouthflow patterns are especially informative because of their relation to glottal width, oropharyngeal pressure (mouthflow grows linearly with oropharyngeal pressure [= ΔP], Solé, 2002), oral volume and transglottal flow (Isshiki, 1964), in addition to providing indirect evidence with which to infer articulatory movement. Such a focus allows us to corroborate the effects of the vocalic environment on the aerodynamic conditions of the rhotic while presenting new kinetic data which may be relevant to tap/trill variation.

3. EXPERIMENTS

3.1. Data

A corpus of nonce words was used in order to control for the effects of stress and syllable structure on the aerodynamic and temporal patterns of the rhotics. To control for speech rate effects, a rate controlled reiterative task was employed in which subjects synchronized their utterances with a digital metronome set at 80 beats per minute.

The corpus included rhotic/C combinations in which C was specified for [lips], [tongue tip] or [tongue body]. Data were collected for both voiced and voiceless pairs: /p, b/, /t, d/, /k, g/. The sequences were tested with all possible vowel combinations for Spanish. Three repetitions were solicited for each token and speaker (3 repetitions x 150 tokens x 2 speakers = 900 tokens).

3.2. Subjects

The subjects were two native Peninsular Spanish-speakers from standard dialectal regions of Spain (Madrid and the Basque Country). Subject 1 (JLG) was a male aged 27 from Madrid and Subject 2 (BRA) was a female aged 29 from Bilbao. Subject 2 was chosen specifically because this particular variety of Spanish is characterized by a high distribution of trilled coda rhotics (Alonso, 1945, cited in Hualde, 2004). However, a higher distribution of coda trills due to the linguistic background of the subject does not necessarily entail differences in the trills internal mechanics (see Solé, 2002).

3.3. Methodology

Aerodynamic signals were obtained at a sample frequency of 6250 Hz using a wide-range, grid pneumotachograph to measure mouthflow and a catheter inserted between the lips to measure changes in intraoral air pressure (EVA2™ system). The instrument was calibrated before each speaker. Simultaneous audio signals were also obtained to analyze formant frequencies.

Aerodynamic instrumentation was chosen specifically due to the high aerodynamic setting for rhotics and to avoid perturbation of the tongue tip during articulation, which may occur with other methods such as EMA (Electromagnetic Midsagittal Articulography) or EMG (electromyography). Additionally, an integral part of this study is to understand the behavior of the tongue when linguopalatal contact is not being realized. For this reason, EPG (electropalatography) was rejected. Ultrasound was excluded due to the fact that the speed of the articulatory movements involved in trilling are often times unobservable due to low temporal resolution.

A computer program, Phonedit (v. 4.2.0.1; Laboratoire Parole & Langage, 2014), from the Université d'Aix-en-Provence, France was employed for post-data analysis while the acoustic signal was analyzed using Praat (v. 5.3.5.1). Statistics were performed using the R statistics software package (v. 3.2.1).

To categorize data before analysis, the aerodynamic and acoustic signals were examined by two trained Spanish-speaking phoneticians and a student of phonetics. Tokens were classified into one of three groups: taps, voiced apical trills and voiceless apical trills. Discrepancies arose between all three categories. In some instances the aerodynamic record seemed to indicate the existence of a weak trill. In this case, the problematic tokens were presented to untrained Spanish-speakers in order to make a determination based on a native speaker's perception of the unit (see Stevens' [1972, 1989] quantal theory for a discussion on the correlation between phonological distinction, production variation and perceptual salience).

In other instances, the definition of voiced versus voiceless trills was problematic since the initiation of the trill was voiced, but the trill itself was predominantly voiceless. These were excluded from the statistical analyses due to the different dynamic profiles of voiced and voiceless trills. It is interesting to note that all of these examples pertained to the same context: high-front vowels followed by the rhotic. This point is relevant in relation to findings which suggest that a higher larynx for

high vowels (Klatt, 1975), along with higher supraglottal impedance (Chang et al., 1999), can result in a cessation of phonation in high-vowel (especially front) contexts.

3.4. Measurements

Within the pre-closure phase, latencies were obtained for (1) vowel onset to rhotic onset, (2) rhotic onset to alveolar contact, and (3) vowel onset to alveolar contact. Vowel onset was defined by the initiation of phonation. Mouthflow parameters included peak flow (Max_F), as well as average flow (Avg_F). Average flow was obtained by summing mouthflow values obtained at quarterly temporal landmarks marked on the aerodynamic signal over the span of the onset gesture and dividing the sum by the total number of landmarks.

Timestamps were annotated manually on the filtered aerodynamic signal (see Figure 1). The vowel was delimited from the rhotic by marking the beginning of mouthflow and phonation (signaling the beginning of the vowel gesture) and the change in mouthflow contour (marking the onset of /r/). The end of the rhotic onset was determined by the downward slope in mouthflow after surpassing maximum flow (Max-F), and the surge in oropharyngeal pressure before initial contact between the tongue tip and alveolar ridge. Timestamps for the pre-closure phase included: onset-v, onset-/r/, max-F, end-gest-/r/.

Figure 1. Annotations on the filtered aerodynamic signal. The bold-dashed lines represent the timestamps for the pre-closure phase of the apical trill and preceding vowel. (a) marks the onset of the vowel (onset-v), (b) marks the onset of the rhotic (onset-/r/), (c) represents maximum mouthflow (max-F), and (d) marks the end of the rhotic onset (beginning of closure-phase).
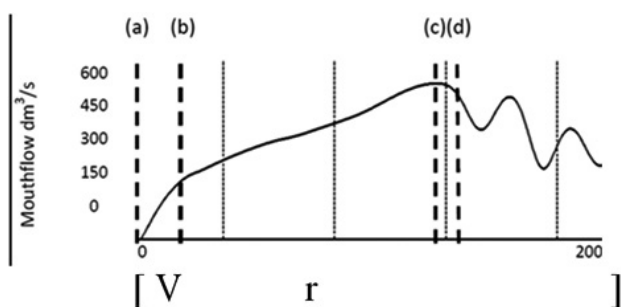
3.5. Statistical analyses

Linear mixed effects models were employed to analyze the effects of phonetic environment on the aerodynamic characteristics of apical taps and trills using the lme4 package in R (Bates, Maechler, Bolker, & Walker, 2015). Mixed effects models were preferred over a repeated measures multi-level ANOVA design in order to avoid potential inflation of the F-ratio which results from violations of the sphericity assumption. Continuous variables were divided into two domains: aerodynamic and temporal. An addition-al variable, CONT_P, reflecting the quantity of contact points for trills was also modeled. The aerodynamic variables included (1) peak mouthflow (Max_F), and (2) average mouthflow (Avg_F). The temporal variables were (1) the duration from the onset of phonation to the activation of the tongue tip gesture for the rhotic (Duration_v_rhotic_onset), (2) the duration of the rhotic onset gesture (and pressure buildup; Duration_r_onset), (3) the duration of the entire vowel and rhotic onset sequence (Duration_sequence), and (4) the degree of overlap (i.e., coarticulation) between the vowel and rhotic onset (Overlap). These variables were tested as functions of predictors which reference tongue posture settings for the preceding vowel (Anteriority [ANT] and Height [HGHT]), the constriction degree (CONS_DEG) and constriction location (CONS_LOC) of the following consonant, as well as the rhotic gesture itself ([SEG] Segment).

Continuous variables were subjected to logit transformations in order to ensure normal distribution of the response variables, and qq plots for the residuals were used as well to evaluate normal distribution. In all cases, models were tested for main effects and all interactions. To account for differences in speech rate and individual variation, repetition and speaker were modeled as random effects. Both random intercepts by subject as well as random by-subject slopes were included. Although variation in the continuous variables based on the sex of the speaker is possible, sex was left unspecified in the models since it is impossible to tease apart effects based on sex from speaker variation with only two subjects. Maximum likelihood chi-squared tests based on the deviance statistics were performed in order to determine significance. For post hoc comparisons, significance was determined using the Tukey adjusted contrast using the multcomp package in R (Hothorn, Bretz, & Westfall, 2008), which is an appropriate tool for post hoc analysis for mixed models.

Variance inflation factors (VIF) were obtained using the Car package in R (Fox & Weisberg, 2011) for potentially overlapping predictors before analyses in order to ensure no perfect collinearity existed in the model which would affect the results (Fox, 2008). For all factors, the VIF was (< 5), meaning collinearity is not detrimentally present in the models.

An outline of the dependent variables, predictors and random effects used for these models appears in Table 1.

Finally, a Bayesian logit regression programmed with non-informative priors (13,000 iterations of the Markov chain Monte Carlo algorithm with a burn-in of 3,000, and thinning of 10) was used to examine the distribution of trill production as a function of the continuous temporal and aerodynamic variables outlined above using the MCMCglmm package in R (Hadfield, 2010). A Bayesian logit regression was chosen over maximum likelihood models (generalized linear models, for example) due to the fact that generalized linear models may not perform under separation, and may give noisy answers for small data sets (Gelman, 2008). Additionally it has been shown that non-bayesian machine learning algorithms underestimate uncertainty in predictions (Gelman, in press). To account for

**Table 1.** Summary of fixed effects, variables and random effects.

Fixed effects	Levels
Anteriority (ANT)	Front, mid, back
Height (HGHT)	High, mid, low
Constriction Degree (CONS_DEG)	Wide, narrow
Constriction Location (CONS_LOC)	Lips, tongue tip, tongue body
Segment (SEG)	Tap, trill
Dependent variables	**Descriptions**
Duration_v_rhotic_onset	Onset of phonation to onset of rhotic
Duration_r_onset	Onset of tongue tip to first contact
Duration_sequence	Onset of phonation to onset of contact plateau
Overlap	Duration of the (entire) vowel + the duration of the rhotic onset divided by the duration of the vowel and rhotic onset sequence
Max_F	Peak mouthflow
Avg_F	Sum of mouthflow values divided by number of temporal landmarks
Contact points (CONT_P)	Number of contact points
Random effects	
Speaker	1, 2
Repetitions	1, 2, 3

the variation between speakers, and different repetitions by the same speaker, repetition was nested within speaker and were then modeled as random effects. A Markov chain Monte Carlo algorithm was used to derive posterior distributions for model parameters. Goodness of fit for the model was assessed using the deviance information criteria (DIC), which provides a hierarchical modeling generalization of the AIC (Akaike information criterion) and BIC (Bayesian information criterion). As with the AIC and BIC, a lower DIC indicates better model fit.

3.6. Results

3.6.1. Temporal parameters

Tongue anteriority for the preceding vowel has a main effect on the latency from the initiation of phonation to the onset of the tongue tip gesture ($\chi^2[1, N = 865] = 864$, $p < .001$), as does tongue height ($\chi^2[1, N = 865] = 864$, $p < .0001$), but not their interaction ($\chi^2[1, N = 865] = 864$, $p = 1.0$). Pooled means are plotted by factor in Figure 2.

Figure 2. Pooled mean durations by factor from the onset of phonation to the onset of the tongue tip gesture for the rhotic.
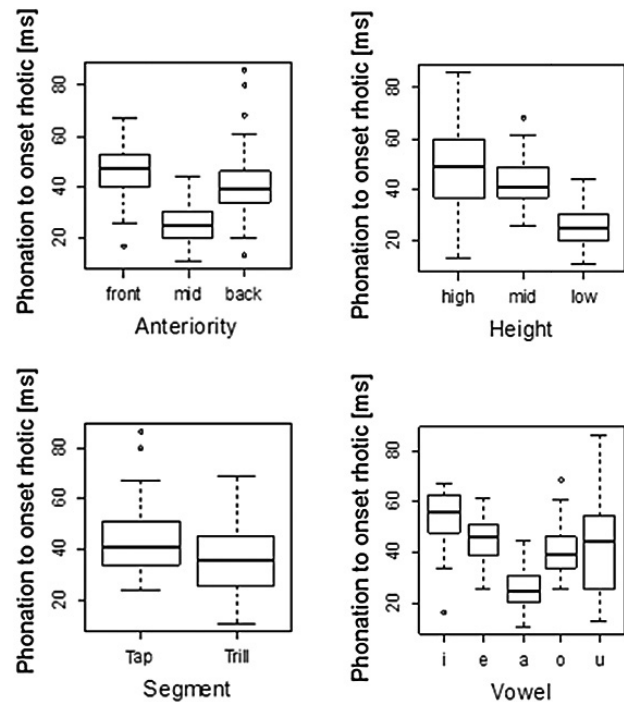
As regards anteriority, the mid vowel (Table 2) showed the shortest period between phonation and the onset of the tap for both speakers (Speaker 1: $M = 36.2$ ms, ± 8.1 ms; Speaker 2: $M = 29.8$ ms, ± 7.3 ms), a trend which was obtained for trills as well (Speaker 1: $M = 24.6$ ms, ± 7.6 ms; Speaker 2: $M = 28.4$ ms, ± 7.1 ms). With regard to height, high vowels had the longest duration between the onset of phonation and the onset of tongue tip ascension in taps (Speaker 1: $M = 57.5$ ms, ± 20.4 ms; Speaker 2: $M = 51.8$ ms, ± 9.6), though in trills the maxima between high and mid vowels fluctuated, mid vowels showing a longer duration for Speaker 1.

There was no main effect for the tap/trill contrast ($\chi^2[1, N = 865] = 864$, $p = .35$) on the vowel to rhotic onset measure, though a significant three-way interaction between segment, height and anteriority was found ($\chi^2[1, N = 865] = 864$, $p = .007$). A summary of the means and standard deviations by speaker appears in Table 2.

Neither constriction degree nor constriction location had any effect on the temporal distance between the two landmarks (CONS_DEG: $\chi^2[1, N = 865] = 864$, $p = 1.0$; CONS_LOC: $\chi^2[1, N = 865] = 864$, $p = 1.0$), nor interactions with other predictors ($p = 1.0$ for all contrasts).

As regards the duration of the tongue tip gesture leading up to the first alveolar contact point (Figure 3), no main effect for either height ($\chi^2[1, N = 865] = 864$, $p = 1.0$) or anteriority ($\chi^2[1, N = 865] = 864$, $p = .33$) was found, though their interaction was significant ($\chi^2[1, N = 865] = 864$, $p < .001$). Pooled means are plotted by factor in Figure 3.

Table 2. Duration from onset of phonation to rhotic onset (ms) by factor. ANT = anteriority; HGHT = height.

Segment	Speaker	Factor	Level	Duration_v_onset_r Mean	SD
Tap	1	ANT	front	48.6	9.8
			mid	36.2	8.1
			back	50.8	22.0
		HGHT	high	57.5	20.4
			mid	41.9	5.0
			low	36.2	8.1
	2	ANT	front	47.9	10.7
			mid	29.8	7.3
			back	40.4	12.3
		HGHT	high	51.8	9.6
			mid	36.5	8.5
			low	29.8	7.3
Trill	1	ANT	front	46.6	10.3
			mid	24.6	7.6
			back	40.7	9.8
		HGHT	high	42.6	16.5
			mid	43.6	9.0
			low	24.6	7.6
	2	ANT	front	42.4	14.3
			mid	28.4	7.1
			back	33.2	11.4
		HGHT	high	43.4	13.1
			mid	39.5	10.3
			low	28.4	7.1

Figure 3. Pooled means (ms) for rhotic onset duration plotted by factor.
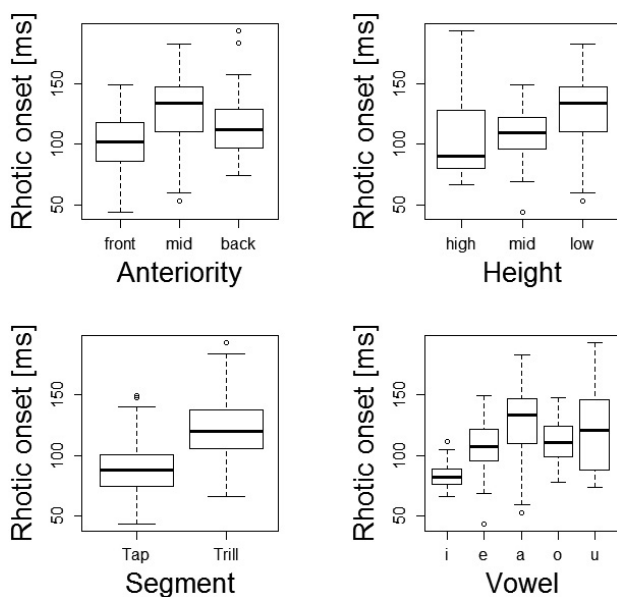
Concerning anteriority (Table 3), the tongue tip gesture following a mid vowel had the shortest duration in taps for Speaker 1 ($M = 72.4$ ms, ± 21.8 ms), but the longest for trills ($M = 136.9$ ms, ± 23.2 ms). For Speaker 2, the rhotic onset gesture following back vowels showed the longest duration in both taps ($M = 101.3$ ms, ± 25.5 ms) and trills ($M = 141.1$ ms, ± 28.7 ms). As for height, the tongue tip gesture for the rhotic following the low vowel had the shortest latencies in taps for both speakers (Speaker 1: $M = 72.4$ ms, ± 21.8 ms; Speaker 2: $M = 85.0$ ms, ± 16.0 ms), yet the longest duration for both speakers in trills (Speaker 1: $M = 136.9$ ms, ± 23.2 ms; Speaker 2: $M = 126.0$ ms, ± 15.9 ms). A significant three-way interaction was found between anteriority, height and segment ($\chi^2[1, N = 865] = 864$, $p < .001$). A summary of the means and standard deviations by speaker appears in Table 3.

Again, no main effects or interactions were found for the constriction degree or constriction location of the following consonants ($p > .05$ for all contrasts).

Table 3. Duration for rhotic onset (ms). ANT = anteriority; HGHT = height.

Segment	Speaker	Factor	Level	Duration_r_onset Mean	SD
Tap	1	ANT	front	95.2	32.4
			mid	72.4	21.8
			back	96.9	20.6
		HGHT	high	87.6	10.9
			mid	106.1	34.0
			low	72.4	21.8
	2	ANT	front	80.9	7.5
			mid	85.0	16.0
			back	101.3	25.5
		HGHT	high	87.13	17.6
			mid	95.0	24.4
			low	85.0	16.0
Trill	1	ANT	front	106.2	19.4
			mid	136.9	23.2
			back	116.3	19.2
		HGHT	high	116.9	34.6
			mid	110.6	16.0
			low	136.9	23.2
	2	ANT	front	104.9	22.9
			mid	126.0	15.9
			back	141.1	28.7
		HGHT	high	93.0	18.7
			mid	119.3	22.3
			low	126.0	15.9

With regard to the latency for the entire vowel + rhotic onset sequence (Duration_sequence), the only main effect was found for the tap/trill contrast ($\chi^2[1, N = 865] = 864$, $p <.001$). Neither the anteriority ($\chi^2[1, N = 865] = 864$, $p = .81$) nor the height ($\chi^2[1, N = 865] = 864$, $p = 1.0$) of the preceding vowel showed any effect for either subject, nor did their interaction with the tap/trill contrast ($\chi^2[1, N = 865] = 864$, $p = 1.0$). Pooled means are illustrated by factor in Figure 4.

Figure 4. Duration of entire vowel and rhotic onset sequence.
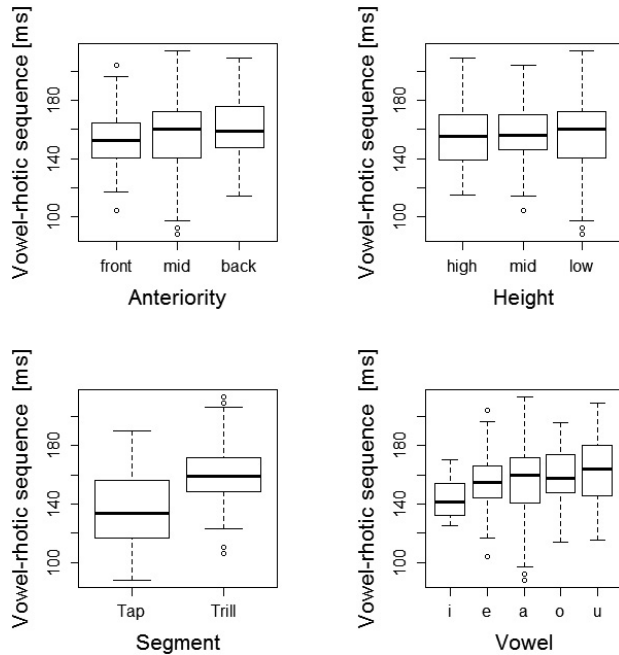
Pooled means show a 31.3 ms increase in the duration of the vowel + rhotic onset sequence in trills ($M = 164.8$ ms, ± 13.8) over taps ($M = 133.4$ ms, ± 19.3) (Tukey HSD: $p < .001$). For Speaker 1, the mean duration for sequences with taps was 139 ms (± 26 ms), while sequences with trills showed a mean duration of 161 ms (± 23 ms), though this difference is not significant (Tukey HSD: $p = .06$). For Speaker 2, mean duration in sequences with taps was 128 ms (± 15 ms), while mean duration of the sequences which contained trills was significantly longer ($M = 169$ ms, ± 21 ms, Tukey HSD: $p = .002$).

Concerning the effects of anteriority of the preceding vowel on the duration of the sequence (Table 4), the mid vowel + rhotic onset sequence in taps was shortest for both subjects (Speaker 1: $M = 105.6$ ms, ± 20.5 ms; Speaker 2: $M = 114.8$ ms, ± 20.3 ms). In trills, however, the mid-vowel + rhotic onset sequence for Speaker 1 showed the longest duration ($M = 164.4$ ms, ± 23.7 ms). For Speaker 2 the back vowel + rhotic onset sequence showed the highest value in trills ($M = 176.1$ ms, ± 23.4 ms). For both speakers, the front-vowel + rhotic onset sequences had the shortest duration in trills (Speaker 1: $M = 156.7$ ms, ± 17.6 ms; Speaker 2: $M = 154.9$ ms, $\pm$

Table 4. Duration of vowel + rhotic onset sequence (ms). ANT = anteriority; HGHT = height.

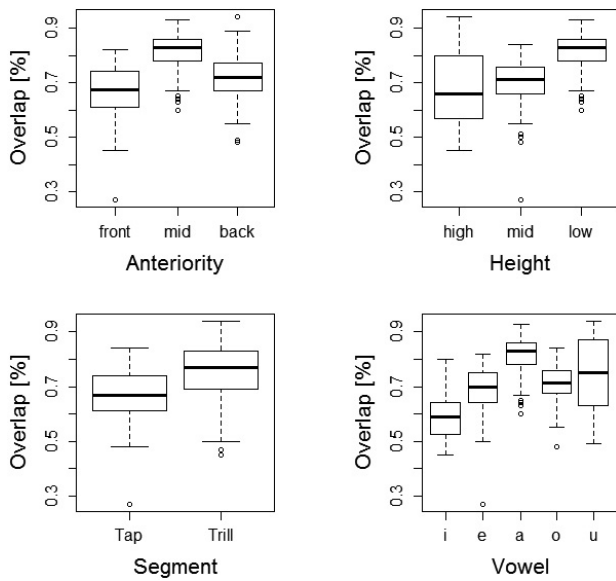| Segment	Speaker	Factor	Level	Duration_sequence Mean	SD
Tap	1	ANT	front	156.6	20.1
			mid	105.6	20.5
			back	154.4	21.1
		HGHT	high	147.9	20.6
			mid	163.1	17.1
			low	105.6	20.5
	2	ANT	front	127.5	15.7
			mid	114.8	20.3
			back	141.6	24.2
		HGHT	high	138.9	18.7
			mid	130.3	23.5
			low	114.8	20.3
Trill	1	ANT	front	156.7	17.6
			mid	164.4	23.7
			back	160.4	18.2
		HGHT	high	162.8	19.0
			mid	157.9	17.7
			low	164.4	23.7
	2	ANT	front	154.9	8.4
			mid	155.2	13.8
			back	176.1	23.4
		HGHT	high	206.4	39.4
			mid	163.3	17.1
			low	155.2	13.8

8.4 ms). A summary of the means (ms) and standard deviations for the vowel + rhotic onset sequence by speaker appears in Table 4.

Once more, neither constriction degree $\chi^2[1, N = 865] = 864$, $p = 1.0$) nor constriction location ($\chi^2[1, N = 865] = 864$, $p = 1.0$) had any effect on the test variable.

As for the overlap between the preceding vowel and tongue tip gesture for the rhotic onset (Figure 5), anteriority ($\chi^2[1, N = 865] = 864$, $p = .02$), height ($\chi^2[1, N = 865] = 864$, $p < .001$) and segment ($\chi^2[1, N = 865] = 864$, $p < .001$) all showed significant main effects for both subjects, as well as a three-way interaction ($\chi^2[1, N = 865] = 864$, $p = .002$). A plot of the pooled means by factor appears in Figure 5.

Generally, trills showed more overlap than taps (Tukey HSD: $p < .001$; see Table 5). With regard to vowel height, the low vowel exhibited the most gestural overlap for both speakers and segments (Taps: Speaker 1: $M = 0.68$, ± 0.07; Speaker 2: $M = 0.74$, ± 0.04; Trills: Speaker

Figure 5. Overlap patterns plotted by factor.

Table 5. Summary means and standard deviations for overlap by speaker. ANT = anteriority; HGHT = height.

Segment	Speaker	Factor	Level	Overlap	
				Mean	SD
Tap	1	ANT	front	0.61	0.16
			mid	0.68	0.07
			back	0.63	0.13
		HGHT	high	0.60	0.10
			mid	0.65	0.18
			low	0.68	0.07
	2	ANT	front	0.64	0.06
			mid	0.74	0.04
			back	0.71	0.09
		HGHT	high	0.63	0.06
			mid	0.72	0.07
			low	0.74	0.04
Trill	1	ANT	front	0.68	0.09
			mid	0.83	0.06
			back	0.72	0.07
		HGHT	high	0.71	0.16
			mid	0.70	0.06
			low	0.83	0.06
	2	ANT	front	0.68	0.14
			mid	0.81	0.04
			back	0.80	0.07
		HGHT	high	0.61	0.10
			mid	0.73	0.10
			low	0.81	0.04

1: $M = 0.83$, ± 0.06; Speaker 2: $M = 0.81$, ± 0.04). Conversely, high vowels showed the least amount of overlap, the only exception being for trills by Speaker 2 (high vowel: $M = 0.71$, ± 0.16; mid vowel: $M = 0.70$, ± 0.06). However, between the high vowels, [i] showed significantly less overlap than [u] (Tukey HSD: $p < .001$) for both speakers, suggesting it is not merely height, but rather height combined with fronting that which impedes overlap between the vowel and rhotic onset.

With regard to anteriority, mid vowels, followed by back vowels, showed the most gestural overlap, while front vowels exhibited less gestural overlap for both segments and speakers.

A summary of the means and standard deviations for the overlap patterns by speaker appears in Table 5.

No main effects were found for the constriction degree and constriction location of the following consonants.

A summary of the main effects for all fixed effects appears in Table 6.

3.6.2. Aerodynamic parameters

Peak mouthflow proved to be a function of tongue posture in both the vertical and horizontal planes. Strong main effects were found for anteriority ($\chi^2[1, N = 865] = 864$, $p < .001$), height ($\chi^2[1, N = 865] = 864$, $p < .001$), and segment ($\chi^2[1, N = 865] = 864$, $p < .001$). Interestingly, no interaction between these fixed effects was found ($\chi^2[1, N = 865] = 864$, $p = .35$). In line with previous models, neither the constriction degree ($\chi^2[1, N = 865] = 864$, $p = 1.0$) nor the constriction location ($\chi^2[1, N = 865] = 864$, $p = 1.0$) had a main effect on peak flow values. Pooled means for both speakers are plotted by relevant factor in Figure 6.
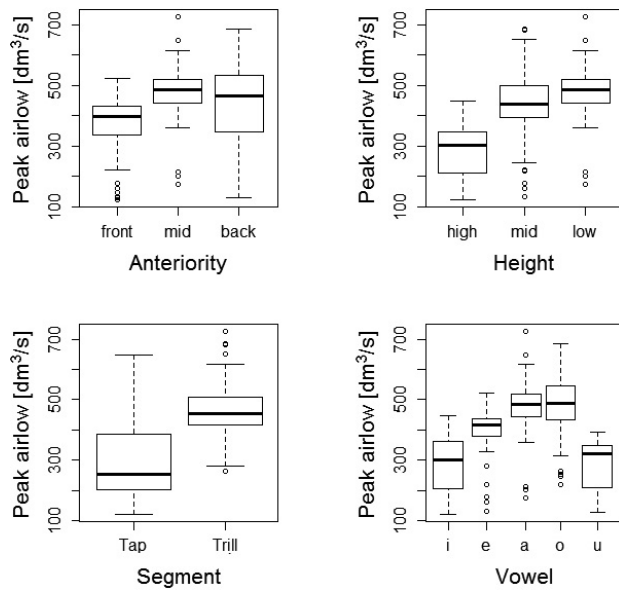
Table 6. Main effects by variable (rows) and predictors (columns). Shaded cells represent interactions between predictors. v_r_onset = duration from onset of phonation to rhotic onset; r_onset = duration for rhotic onset; sequence = duration of vowel + rhotic onset sequence. ANT = anteriority; HGHT = height; SEG = segment; CONS_DEG = constriction degree; CONS_LOC = constriction location.

Duration	ANT	HGHT	SEG	CONS_DEG	CONS_LOC
v_r_onset	***	***	ns	ns	ns
r_onset	ns	ns	***	ns	ns
sequence	ns	ns	**	ns	ns
Overlap	**	***	***	ns	ns

Significance codes: '***' .001 /'**' .01 /'*' .05 / 'ns' .1

Peak mouthflow was higher in trills than taps for both speakers (Table 7). As regards anteriority, the mid vowel showed the highest mouthflow values (Taps: Speaker 1: $M = 0.453$ dm³/s, ± 0.070 dm³/s; Speaker 2: $M = 0.310$

Figure 6. Mean peak mouthflow values by factor.

1: high-mid, $p < .001$; mid-low, $p < .001$; high-low, $p < .001$; Speaker 2: high-mid, $p < .001$; mid-low, $p < .001$; high-low, $p < .001$).

As for the tap/trill contrast, pooled means show a 0.131 dm³/s increase in peak flow for trills ($M = 0.440$ dm³/s, ± 0.060 dm³/s) over taps ($M = 0.309$ dm³/s, ± 0.110 dm³/s) across all vowel categories. For Speaker 2, the difference in peak flow between taps and trills (0.210 dm³/s) was higher than for Speaker 1 (0.054 dm³/s), though the results of post hoc Tukey HSD tests show significance for both speakers (Tukey HSD: $p < .001$ for Speakers 1 and 2).

A summary of the means and standard deviations for peak mouthflow by speaker appears in Table 8.

Average mouthflow leading up to the first contact point with the alveolar region was also found to be influenced by tongue posture and the tap/trill contrast. Specifically, high-front vowels showed slower flow (and faster P_o buildup)

Table 7. Summary of means and standard deviations for peak mouthflow (Max_F) by speaker. ANT = anteriority; HGHT = height.

Segment	Speaker	Factor	Level	Max_F Mean	Max_F SD
Tap	1	ANT	front	0.338	0.060
			mid	0.453	0.067
			back	0.384	0.126
		HGHT	high	0.284	0.048
			mid	0.439	0.067
			low	0.453	0.067
	2	ANT	front	0.156	0.032
			mid	0.310	0.227
			back	0.211	0.047
		HGHT	high	0.158	0.035
			mid	0.209	0.048
			low	0.310	0.227
Trill	1	ANT	front	0.409	0.045
			mid	0.481	0.052
			back	0.483	0.096
		HGHT	high	0.359	0.051
			mid	0.464	0.080
			low	0.481	0.052
	2	ANT	front	0.417	0.104
			mid	0.507	0.078
			back	0.436	0.094
		HGHT	high	0.304	0.054
			mid	0.442	0.087
			low	0.507	0.078

dm³/s, ± 0.230 dm³/s; Trills: Speaker 1: $M = 0.481$ dm³/s, ± 0.050 dm³/s; Speaker 2: $M = 0.442$ dm³/s, ± 0.090 dm³/s), except for Speaker 2 in trills, where the back vowels showed a slightly higher mean than the mid vowel (0.483 dm³/s for back vowels as opposed to 0.481 dm³/s for the mid vowel). Front vowels showed the lowest mean peak mouthflow values for both speakers and rhotics (Taps: Speaker 1: $M = 0.338$ dm³/s, ± 0.060; Speaker 2: $M = 0.156$ dm³/s, ± 0.030 dm³/s; Trills: Speaker 1: $M = 0.409$ dm³/s, ± 0.050; Speaker 2: $M = 0.417$ dm³/s, ± 0.100 dm³/s). Post hoc Tukey HSD tests are significant for all contrasts based on anteriority (Speaker 1: front-back: $p < .001$; mid-back: $p < .001$; mid-front: $p < .001$; Speaker 2: front-back: $p < .001$; mid-back: $p < .001$; mid-front: $p < .001$).

As regards the effects of tongue height on mouth flow, there is an inverse relationship between height and flow such that a lower posture yields higher peak flow values (Table 7). High vowels showed the lowest mean peak flow values for both speakers and rhotics (Taps: Speaker 1: $M = 0.284$ dm³/s, ± 0.050 dm³/s; Speaker 2: $M = 0.158$ dm³/s, ± 0.040 dm³/s; Trills: Speaker 1: $M = 0.359$ dm³/s, ± 0.050 dm³/s; Speaker 2: $M = 0.304$ dm³/s, ± 0.090 dm³/s), followed by mid vowels (Taps: Speaker 1: $M = 0.439$ dm³/s, ± 0.070 dm³/s; Speaker 2: $M = 0.209$ dm³/s, ± 0.050 dm³/s; Trills: Speaker 1: $M = 0.464$ dm³/s, ± 0.080 dm³/s; Speaker 2: $M = 0.442$ dm³/s, ± 0.090 dm³/s). The low vowel showed the highest peak flow values for both speakers and rhotics (Taps: Speaker 1: $M = 0.453$ dm³/s, ± 0.070 dm³/s; Speaker 2: $M = 0.310$ dm³/s, ± 0.230 dm³/s; Trills: Speaker 1: $M = 0.481$ dm³/s, ± 0.050 dm³/s; Speaker 2: $M = 0.507$ dm³/s, ± 0.080 dm³/s). Post hoc Tukey HSD tests show significant results for all contrasts based on height for both speakers (Speaker

leading up to the first contact point than mid, low and back vowels, presumably due to greater impedance in the vocal tract during the production of high vowels. A strong main effect on average mouthflow was found based on the anterior/posterior position ($\chi^2[1, N = 865] = 864$, $p < .001$), while a weak effect was found for the tap/trill contrast ($\chi^2[1, N = 865] = 864$, $p = .03$), but only for Speaker 2. Tongue height showed no main effect on mouthflow leading up to trilling ($\chi^2[1, N = 865] = 864$, $p = 1.0$). There was no interaction between these fixed effects ($\chi^2[1, N = 865] = 864$, $p = .29$). No effects were found for the constriction degree ($\chi^2[1, N = 865] = 864$, $p = 1.0$) or the constriction location ($\chi^2[1, N = 865] = 864$, $p = 1.0$) of the following consonant. Data from the models are plotted in Figure 7.

Figure 7. Pooled means of average mouthflow plotted by factor.
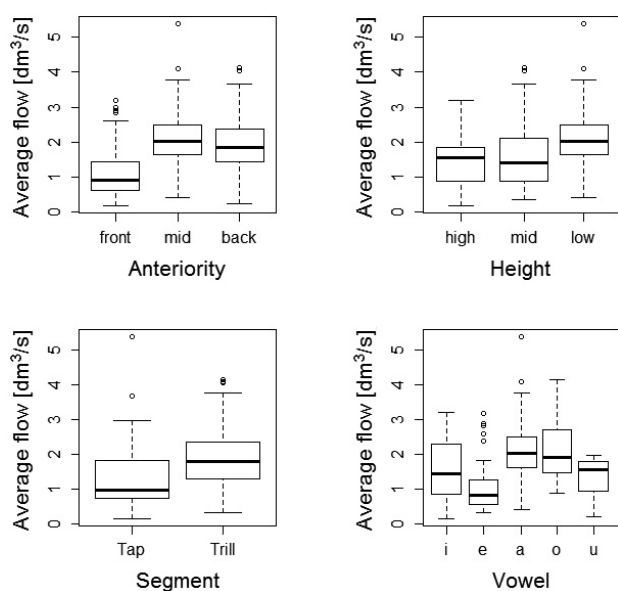
Pooled means show an average flow of 0.129 dm³/s (± 0.068 dm³/s) for taps, while the average flow for trills is slightly higher ($M = 0.177$ dm³/s, ± 0.040 dm³/s). However, across subjects, this trend does not hold. For Speaker 1, average mouthflow values for both taps and trills are only marginally different, taps having higher flow values than trills (Taps: $M = 0.190$ dm³/s, ± 0.052 dm³/s; Trills: $M = 0.184$ dm³/s, ± 0.033 dm³/s) (Tukey HSD: $p = 1.0$, *ns*). For Speaker 2, there is significantly lower mouthflow in taps ($M = 0.110$ dm³/s, ± 0.035 dm³/s) than in trills ($M = 0.170$ dm³/s, ± 0.048 dm³/s) (Tukey HSD: $p < .01$).

As for tongue anteriority (Table 8), the mid vowel showed the fastest mean mouthflow for both speakers, the exception being in trills for Speaker 1. In this context, the back vowels showed higher mouthflow than the mid vowel, although this difference was not significant (Tukey HSD: $p = .975$). Front vowels consistently showed the lowest mouthflow for both segments and speakers (Tukey HSD: mid-front: $p < .001$; front-back: $p < .001$).

With regard to height (Table 8), the low vowel had the fastest mouthflow for both segments and speakers, contrasting with Solé's (2002) findings. The high vowels had the lowest average mouthflow values in all but one context. For Speaker 1, average flow for the high vowels in trills surpassed that of the mid vowel (though still fell short compared to low vowels), rendering a significant difference (Tukey HSD: $p = .02$). A summary of the means and standard deviations for mouthflow are listed in Table 8.

Table 9 summarizes the results of the aerodynamic variables (rows) for each predictor (columns).

3.6.3. Contact points

To examine the effects of the surrounding gestures on the number of contact points for trills, both categorical and continuous predictors were modeled. Across all factors,

Table 8. Average mouthflow (Avg_F) values by factor and speaker. ANT = anteriority; HGHT = height.

Segment	Speaker	Factor	Level	Avg_F Mean	Avg_F SD
Tap	1	ANT	front	0.132	0.07
			mid	0.253	0.06
			back	0.185	0.08
		HGHT	high	0.145	0.04
			mid	0.172	0.10
			low	0.253	0.06
	2	ANT	front	0.050	0.02
			mid	0.180	0.02
			back	0.101	0.06
		HGHT	high	0.052	0.03
			mid	0.102	0.06
			low	0.180	0.24
Trill	1	ANT	front	0.124	0.07
			mid	0.203	0.05
			back	0.213	0.07
		HGHT	high	0.196	0.06
			mid	0.167	0.09
			low	0.203	0.05
	2	ANT	front	0.148	0.13
			mid	0.223	0.08
			back	0.160	0.04
		HGHT	high	0.100	0.03
			mid	0.163	0.07
			low	0.223	0.08

Table 9. Main effects by variable (rows) and predictors
(columns). ANT = anteriority; HGHT = height;
SEG = segment; CONS_DEG = constriction degree;
CONS_LOC = constriction location.

	ANT	HGHT	SEG	CONS_ DEG	CONS_ LOC
Peak Flow	***	***	***	*ns*	*ns*
Average Flow	***	*ns*	*	*ns*	*ns*

Significance codes: '***' .001 /'**' .01 /'*' .05 / 'ns' .1

the median number of contact points was three. Minima
and maxima reached two and five, respectively. Results of
the model show that no factor has any significant effect on
the number of contact points for the trill: ANT (χ^2[1, N =
191] = 190, p = .09); HGHT (χ^2[1, N = 191] = 190, p =
.48); CONS_DEG (χ^2[1, N = 191] = 190, p = .78); CONS_
LOC (χ^2[1, N = 191] = 190, p = 1.0); Max_F (χ^2[1, N =
191] = 190, p = .33); Avg_F (χ^2[1, N = 191] = 190, p =
.74); Duration_r_onset (χ^2[1, N = 191] = 190, p = 1.0);
Duration_sequence (χ^2[1, N = 191] = 190, p = .39); Over-
lap (χ^2[1, N = 191] = 190, p = .43). These results indicate
that although the surrounding gestures may have micro-
effects on the internal mechanics of trilling, the trill mo-
tion itself is highly resilient to environmental influences.

3.6.4. *Bayesian logit regression model to predict tap/trill distribution*

The Bayesian model posits tap/trill variation as a di-
chotomous outcome model. In the previous sections it has
been shown that the tongue posture for the vowel preced-
ing the rhotic affects to a greater or lesser extent the aero-
dynamic parameters and timing of different stages of the
tongue tip's trajectory for the rhotic. So far it has been
shown that the lower, and more back, the tongue posture,
the higher the peak mouthflow values and the faster
mouthflow accelerates going into the contact phase of the
trill. At the same time it has been shown that the position
in the vertical and horizontal planes affects the timing of
the onset of the tongue tip gesture. In this section, a
Bayesian model tests whether the distribution of trills can
be predicted using these continuous variables. Proper
convergence of the parameter estimation and thinning
rate were first tested with trace plots, histograms and
autocorrelations.

The data show a categorical preference for the apical
trill to emerge in certain phonetic environments. There ap-
pears to be a preference for trilling in conjunction with [a]
(39.8 % of total) followed by [e] and [o] (24.6 % and
27.2 % of the cases respectively). Importantly, 91.6 % of
all trills emerged with [a], [e], and [o]. The high vowels [i]
and [u] on the other hand show a discernible preference
for the tap. A summary of the number of trilled tokens by
vocalic and consonantal contexts appears in Table 10.

Not immediately obvious from the data is the highly
individual nature of the tap/trill contrast in syllable-final

Table 10. Number of trilled tokens by context.

	r.p	r.b	r.t	r.d	r.k	r.g	Total
i	0	0	6	0	0	1	7
e	11	6	14	7	6	3	47
a	14	12	13	9	14	14	76
o	11	9	5	4	13	10	52
u	3	3	2	0	0	1	9
Total	39	30	40	20	33	29	191

position. Of the 191 total trilled tokens, only 17 were pro-
duced by speaker 1, constituting only 8.9 % of the total
apical trills collected for the study, while the remaining
174 were produced by speaker 2, constituting 91.1 % of
the total trills. Of the 450 tokens for each subject, the trill
emerged in only 3.7 % of the total tokens for speaker 1,
while for speaker 2, the trill emerged in 38.7 % of the to-
tal cases.

As regards the aerodynamic parameters specified in the
model (Table 11), peak mouthflow ($p < .001$) and average
mouthflow ($p = < .002$) are significant predictors of trilling.
The posterior means for the coefficients for these variables
(Max_F [-7913.8], AVG_F [0.1050060]), fall between the
95 % credibility intervals (Max_F [-13960.8] - [-2141.5],
Avg_F [0.0334342] - [0.1694055]), indicating significance.
A comparison of the deviance information criterion (DIC)
between a model specified with peak mouthflow and one in
which peak mouthflow was not specified shows an overall
better fit for the former model (DIC-fully specified model
[4.55]; DIC-model without peak mouthflow [123.27], 4.55
< 123.2658). This procedure was repeated for average
flow, obtaining similar results (DIC-fully specified model
[4.55]; DIC-model without rate increase [84.77], 4.55 <
84.77). These results indicate that trill distribution is pre-
dictable in part by the aerodynamic conditions of the local
phonetic environment.

Concerning the temporal measures, results of the
model show that the duration of the vowel + rhotic se-
quence ($p < .001$), overlap ($p < .001$) and the duration of
the tongue tip gesture leading up to contact ($p = .016$) are
significant predictors of trill distribution. Again posterior
means for the coefficients for each variable fall within the
95 % credibility intervals (Table 11). Additionally, DIC
for the fully specified models are considerably lower than
those models not fitted with the temporal variables (v +
rhotic sequence: DIC [97.85] unspecified model, [4.55]
fully specified model; 4.55 < 97.85; Duration_rhotic_on-
set: DIC [92.65] unspecified model, [4.55] fully specified
model; 4.55 < 97.85; Overlap: DIC [64.22] unspecified
model, [4.55] fully specified model; 4.55 < 64.22).

4. CONCLUSIONS

Combined results of this study indicate that the tongue
posture of a preceding vowel affects the temporal organi-
zation of gestures leading up to an apical trill and the aer-

Table 11. Summary of results for Bayesian model.

Iterations = 3001:12991
Thinning interval = 10
Sample size = 1000
DIC: 4.55
G-structure: ~Speaker

	post.mean	l-95 % CI	u-95 % CI	eff.samp
Speaker	1.652	4879314	7.156	694.9

R-structure: ~units

	post.mean	l-95 % CI	u-95 % CI	eff.samp
units	1.522	5.55	2.92	4.15

	post.mean	l-95 % CI	u-95 % CI	pMCMC
(Intercept)	4.675336	2.936962	6.675061	0.00988 **
Peak mouthflow	−7913.8	−13960.8	−2141.5	< 0.001 ***
Overlap	−2.121	−3.220	−1.132	< 0.001 ***
Average mouthflow	0.1050060	0.0334342	0.1694055	0.002**
Duration v_r_onset	−357.7	−38860.4	34134.0	0.984
Duration_v_r_sequence	−2.785	−4.349	−1.220	< 0.001 ***
Duration_r_onset	−29253.5	−60437.0	−626.1	0.016 *
Constriction degree	−68465.8	−257196.0	99245.7	0.482
Constriction location	42903.5	−133413.8	249000.2	0.660

odynamic parameters which fallout therein. It was also shown that these variables (and presumably their pressure correlates) condition tap/trill variation in Spanish codas. With regard to tongue anteriority/posteriority, mid and back vowels show a shorter period of phonation before the initiation of the onset gesture for the rhotic. The more posterior posture imposes less articulatory constraint on the tongue tip. As a result the tongue tip gesture for the rhotic may initiate earlier for mid and back vowels, which results in a longer onset gesture for mid and back vowels. Front vowels, on the other hand, have longer phonation periods, and shorter onset gestures for the rhotic, possibly due to the fact that the tongue must retract slightly in order achieve the articulatory target. With regard to height, low and mid vowels (especially mid and back) have shorter phonation periods preceding tongue tip activation, which possibly results from the fact that less predorsum lowering is needed (as opposed to high vowels) in order to achieve the precise articulatory posture for the production of the rhotic. High vowels (especially front), on the other hand, show a longer phonation period before tongue tip activation, and a shorter onset gesture leading up to alveolar contact.

No significant difference was found in the timing between the onset of phonation and initial contact with the alveolar ridge (though differences in timing between taps and trills are significant). This is consistent with the results for the overlap patterns. Mid (especially back) and low vowels permit more overlap than high vowels (especially front), which is line with Recasens' (2012) results showing low vowels to be more susceptible to coarticulation than high vowels. Although the timing of the gestures vary as a function of the tongue posture of the pre-

ceding vowel, the results show that the global timing of the vowel + rhotic sequence remains stable.

Tongue posture of the preceding vowel was found to affect the aerodynamic patterns of the rhotic onset as well. As for the effects of tongue anteriority, the mid and back vowels had higher mouthflow peaks and faster average flow than front vowels. Tongue height as well affects peak flow, high vowels having the lowest maxima, but no main effect of tongue height was found for average mouthflow.

Significant differences in the temporal and aerodynamic parameters of taps and trills were found as well. Trills have higher overlap than taps, with longer onsets and longer overall durations for the vowel and onset gesture sequences than taps. Peak mouthflow for trills was considerably higher than for taps, while average flow leading up to alveolar contact was faster in trills than in taps.

No significant effects on the temporal and aerodynamic variables were found for the following consonant. This should not be interpreted, however, as evidence that the following consonant does not affect the aerodynamic and temporal parameters of trills and taps. This study dealt with a limited set of measures which pertained to the rhotic onset. A detailed analysis of the closure and post-closure phase of taps and trills is currently in progress. Further, this study only dealt with the effects of voiced and voiceless stops in order to construct an initial model of tap/trill variation. In the future, it is planned to augment the models created for this study to include all constriction degree and constriction location specifications.

By collapsing the factors reflecting tongue posture of the preceding vowel into singular vowel categories (/i/, /e/, /a/, /o/, /u/), a preference emerges between spontane-

ous trilling following [a] and [o], which may be related to the similarities in the articulatory settings, especially in the predorsum region, between trills and low mid and back vowels. Since the position of the tongue body is already low for the production of [a], minimal predorsum lowering is needed in order to achieve the articulatory setting required for trilling. At the same time, the concentration of tongue body action in the mid section of the oral cavity translates to a less constrained tongue tip (as it would for back articulation for posterior vowels as well). These articulatory postures lead to a more fluid coupling of the vowel and rhotic gestures, attested in the overlap patterns presented in this article.

Finally, from a theoretical perspective, the models in this study show that trill distribution in Spanish codas can be explained without having to resort to structural constraints for which there is very little evidence. Trilling in coda ensues when there is a high degree of overlap between the vowel and onset gesture of the following rhotic (after approximately 78%, odds of trilling increase linearly with overlap), and when mouthflow (and corresponding intraoral pressure parameters) reaches a certain threshold (at 0.181 dm^3/s [pooled means] odds of trilling increase linearly with mouthflow). It was shown that both of these parameters are functions of the different tongue body specifications of the preceding vowel, meaning trilling is more probable in certain phonetic environments. Although it was shown that these thresholds may be reached in any vocalic context, certain vowel environments favor the attainment of these parameters. By including this element of randomness, it leads the way to account for the effects of other variables such as speech rate, style and a range of prosodic effects which may also condition rhotic variation in coda.

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