PRODUCTION REQUIREMENTS OF APICAL TRILLS AND ASSIMILATORY BEHAVIOR

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ABSTRACT

This paper investigates how the highly constrained articulatory and aerodynamic requirements of tongue-tip trills determine the assimilation of neighboring segments, specifically lingual fricatives. Articulatory, acoustic and aerodynamic analysis of trills and fricatives were made for three Catalan speakers. The assimilation of lingual fricatives to tongue-tip trills is due to the early onset of articulatory movements for the trill which override the critical articulatory configuration and time limen required to generate turbulence for fricatives. Phrasal boundaries proved to have an effect on fricative to trill assimilation suggesting effects of time constraints and programming units. Aerodynamic analysis showed that fricatives were more resistant to variations in pharyngeal pressure than trills. Thus trills allow a narrower range of pressure variation than fricatives, and have more constrained aerodynamic requirements. Assimilation of lingual fricatives to adjacent trills can be seen as an effect of articulatory and aerodynamic competition (and possibly of auditory integrity of onset consonants).

1. INTRODUCTION

This paper reports on a series of experiments directed to ascertain the articulatory and aerodynamic requirements of tongue-tip trills and how such requirements may lead to assimilation of neighboring segments. In particular, we address sequences of lingual fricatives and trills, segment types exhibiting highly constrained production characteristics, in order to account for the common assimilation of fricatives to following apical trills (*e.g.*, /sr/>/r**:**/), both within and across words, in a variety of languages (Portuguese, Catalan, Spanish).

Tongue tip trills involve a complex production mechanism requiring finely tuned neuromotoric adjustment of various parameters – positioning of the articulators, shape, articulator mass, stiffness and aerodynamic conditions [12] – which accounts for the difficulties lingual trills present to inexperienced (*e.g*., foreign learners) and immature (*e.g*., infants) speakers, and even to adult native speakers. Such precise requirements make trills very sensitive to variations in the articulatory and aerodynamic conditions, which may result in lack of tongue tip vibration. Thus, it is common that trills are realized as non-trilled variants (*e.g*., in Spanish, Toda, Italian), and that they alternate historically, dialectally and allophonically with fricatives, approximants and taps.

The precise articulatory and aerodynamic requirements of lingual trills allow little coarticulation and overlap with conflicting lingual configurations if trilling is to be preserved. It has been observed that sequences such as Spanish *dos **r**eales* 'halfpenny', *has **r**oto* 'you broke' are assimilated to a long trill [r:] or a sequence [ɹr] ([ɹ]= fricative r) [5]. Other examples are presented in (1a). Similarly Catalan presents the same assimilatory behavior of lingual fricatives and affricates to trills, as exemplified in (1b).

1(a) Spanish
/s(#)r/ *israelita* [ir:aeˈlita], *los ríos* [loˈr:ios] or [ɹr]
/θ#r/ *Cruz Roja* [ˈkruˈr:oxa], *voz ronca* [ˈboˈr:oŋka] or [ɹr]
(b) Catalan
/ʃ#r/ *peix rebossat* ['pe(j)r:əβu'sat]
/dʒ#r/ *boig rematat* ['bɔ(j)d̠r:əmə'tat]
/s#r/ *tens raó* ['tenr:ə'o], *els Reis* [əl'r:ejs]

It should be noted that (i) lingual fricatives assimilate exclusively to following trills (involving the same articulator), and are preserved (*i.e*., retain their fricative quality) in all other contexts[1], and (ii) sequences of fricatives+trill produced with different or independent articulators are not assimilated, *e.g*., Catalan *buf rodó* [vr].

Sequences of lingual fricatives and trills involve the overlap of two antagonistic gestures: In the case of alveolar fricatives, a raised and advanced tongue dorsum for /s/ (passively raised due to coupling effects with tongue blade raising), as opposed to predorsum lowering and postdorsum retraction for the trill to allow for the vertical vibration of the tongue-tip [9]; the tongue tip/blade shape is convex for the fricative (forming a medial groove) and concave for the trill; alveolar fricatives involve muscular activation of the tongue tip-blade whereas a relaxed articulator is required to vibrate.

The only available articulatory model that predicts the degree to which a particular segment is likely to affect neighboring segments and the direction of assimilatory effects, on the basis of degree of tongue dorsum involvement and compatibility of the lingual configurations, is Recasens' 'Degree of Articulatory Constraint' (DAC) model [10]. According to this model, lingual fricatives and trilled /r/s have the highest DAC value, 3 [9, 10], indicating that they are highly constrained and unyielding segments. They also involve conflicting gestures directed to the same articulator. Degree of coarticulation and assimilation is also dependent on aerodynamic conditions – in particular in fricatives and trills which are aerodynamically driven sounds – and manner requirements [11]. Possibly syllable position also plays a role in magnitude of assimilation since the articulatory properties of consonants (*e.g*., degree of overlap [1]) and the availability of auditory cues differ with position in the syllable.

The purpose of this study is to investigate the assimilation of lingual fricatives to adjacent apical trills in order to preserve the spectral integrity of the trill. First, the articulatory and acoustic result of the assimilation of lingual fricatives to trills and the prosodic factors affecting them are described in experiment 1. Second, the constrained aerodynamic requirements of trills which prevail over those of frication are explored in experiment 2. Finally, we attempt to account for the fricative to trill assimilation as an effect of articulatory and aerodynamic competition.

2. EXPERIMENT 1

Simultaneous EPG and acoustic data were obtained for three Catalan speakers reading a list of meaningful sentences involving word final lingual fricatives/affricates ([s, ʃ, tʃ]) followed by word initial /r/ (Final obstruents assimilate to the voicing of the following consonant in Catalan). Prosodic boundaries were varied to observe the effects of programming units on assimilation. Below is the list of experimental and control utterances used in the study. The boundary type occurring between the two sounds of interest is shown to the right. The /VsrV/ and /VrV/ sequences across word boundary in items 1-3 were in pretonic (prenuclear) position and those in 4 in tonic position. Control sequences were also recorded for comparison.

Experimental

1. A: Què li has recomanat que fés? B: Res Word+ Sentence //
 (*A: What did you recommend her to do? B: Nothing*)
2. Què li has recomanat que fés? Res? Word+ Sentence #
 (*What did you recommend her to do? Nothing?*)
3. Que li has recomanat que fés res? Word+ Phrase /
 (*Did you recommend her to do anything?*)
4. La carta la vas redactar i la vas revisar, oi? Word+ Word+
 (*You wrote and checked the letter, right?*)

Control

1. A: Què li ha recomanat fer[fe]? B: Res Word+ Sentence //
 (*A: What did he recommend her to do? B: Nothing*) (...)

The assimilatory behavior of fricatives to trills was analyzed articulatorily and acoustically. Only the results for /s#r/ sequences will be reported here. No assimilations were found across major *sentence boundaries* (//, #), which exhibited [zr] realizations. In all cases speakers produced two tone groups or input strings with a silence between the two segments of interest. The EPG data show that the onset of the articulatory gesture for the trill was delayed and thus did not overlap the antagonistic fricative gesture.

Minor boundaries, *i.e*., phrase and word boundaries, show varying degrees of assimilation of lingual fricatives to trills reflecting differences in the timing of the sequential inputs. One-way analyses of variance were performed with sequence type (/sr/ or /r/) as the independent variable, and indices of alveolar contact activation (CA)[2], duration of the [zr] and [r] sequence, and duration of the preceding vowel. The statistical tests were performed for each speaker separately and for all speakers pooled, for each trill type separately (two contact trill, three contact trill, fricative trill) and for all trill realizations pooled. The results are presented in Table I.

Across *word boundaries* in pretonic position (tokens 1-3), /sr/ sequences exhibit complete assimilation to a trill. Table I shows no significant differences between /sr/ and /r/ sequences in any of the variables studied. A Chi square test showed no difference in the distribution of trill realization in assimilated and control sequences ($\chi^2_{(2)} = 0.404$, $p = 0.817$). Assimilated /sr/ sequences exhibited slightly greater, but non-significant, variability in trill duration than control sequences ($F_{(1,\ 38)}=0.11$, $p=0.91$). ANOVAS were also performed on duration of lingual movement toward the consonant ($F_{(1,\ 38)} =1.29$, $p=0.263$). None of the results reached significance, suggesting that /sr/ sequences showed complete assimilation to a trill.

Table I. Statistical results for assimilated /VsrV/ and /VrV/ sequences across word boundary (pretonic and tonic position) and phrase boundary. Dependent variables are shown on the left. Asterisks indicate significant differences (Scheffé, p<0.05).

		Pretonic Word +	Tonic Word +	Phrase /
		r r	r	
Trill duration	sr		*	*
CA	sr			* (DR)
VowelDuration	sr			

Acoustic analysis showed that assimilated /VsrV/ sequences (1) usually involved aperiodic energy between 2.5-4kHz (6-18dB), whereas /VrV/ sequences did not usually exhibit energy beyond 2.5kHz, and (2) tended to have less voicing than the control sequences. To validate the results perceptually the sequences 'has recomanat' and 'ha recomanat' were excised from the test and control sequences and presented to two speakers for identification as '(tu) has recomanat' (2nd person singular) or '(ell) ha recomanat' (3rd person singular). A Chi square performed on the results of the listening test showed that speakers could not reliably tell /sr/ and /r/ apart ($\chi^2_{(1)} = 0.278$, $p= 0.598$). Listeners exhibited a bias to identify fricative realizations as /sr/ sequences irrespective of their phonological status as /sr/ or /r/.

In tonic position, /sr/ sequences across word boundaries (token 4) also assimilate to [r]. As Table I shows, none of the variables studied reached significance except trill duration in two-contact trills ($F_{(1,\ 8)}=15.18$, $p= 0.004$) – with assimilated sequences showing a longer trill than control sequences. This reflects a lesser degree of overlap between the two gestures in tonic position due to weaker time constraints vis-à-vis pretonic position.

Across *phrase boundary* (token 3), /sr/ sequences showed a lesser degree of fricative to trill assimilation than across word boundaries. The EPG data show that the tongue-tip contact for /sr/ sequences is generally more anterior than for /r/ sequences as illustrated in Fig. 1.

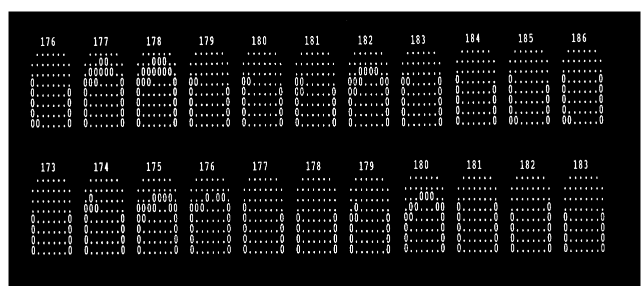

Fig. 1. Linguopalatal contacts for assimilated /sr/ (top)and /r/ sequences (bottom). Speaker DR.

Due to small sample size the differences in alveolar contact activation (CA) for test and control sequences only reached significance for speaker DR ($F_{(1,6)}=8.56$, $p=0.026$). Differences in trill duration were also significant ($F_{(1,10)}=7.47$, $p=0.021$). No other significant differences were found.

The observed duration of the control /r/ and assimilated /sr/ sequences ranged between 55.1-81.5ms, 61-98ms, and 80-120ms for /r/, and 59.4-83.5ms, 73-102ms and 110-140ms for /sr/ across word boundary (pretonic and tonic position) and phrase boundary, respectively.

The different degrees of lingual fricative to trill assimilation may reflect differences in timing of the sequential inputs, as schematically illustrated in Fig. 2. In cases of major boundary, delayed motor instructions and a delayed onset of articulatory movements for the trill, (c) in Fig. 2, allow enough time to sequence the two antagonistic gestures. In the case of phrase boundaries, the more anterior contacts for /sr/ than for /r/ sequences suggest that the articulatory movements for the apicoalveolar target for /s/ have been overlapped by competing motor commands for the trill, (b), shortly *before* (or at the same time as) the articulator reaches the goal for /s/ (broken vertical line), with inertial effects being responsible for residual frontmost contacts. Alternatively, the motor command for the trill may arrive shortly *after* the articulator attains the specified target for /s/, affecting the time limen required to generate turbulence for the fricative. The early onset of the articulatory movements for the trill thus affect the trajectory for /s/, changing the spectral properties associated with the fricative. The lack of anterior contacts in /sr/ sequences across word boundaries may reflect a greater overlap of the motor instructions for the trill, (a), which reach the articulator before it has attained the specified goal for /s/. The greater temporal overlap of the two gestures is consistent with the lack of durational differences found in /sr/ and /r/ sequences across word boundaries. Thus, the timing of the sequential inputs, which is dependent on phrasal boundaries, accounts for different degrees of assimilation. In other words, *ceteris paribus*, degree of assimilation seems to be inversely proportional to the time constraints imposed by prosodic structure.

The absence of fricative to trill assimilation across major boundaries is consistent with coarticulatory effects found by other investigators [4] and would reflect input strings of the size of the tone group in accordance with Kozhevnikov and Chistovich model [2].

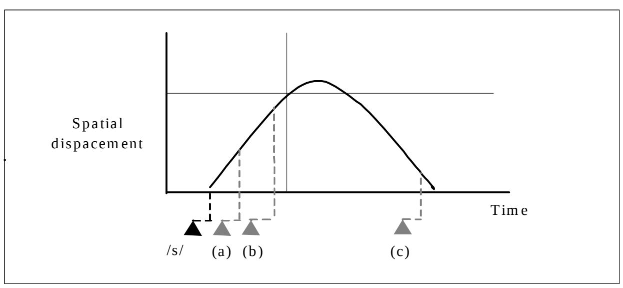

Fig. 2. Schematized representation of varying degrees of overlap in /sr/ sequences (see text).

In the few cases where sibilant frication *is* achieved in /sr/ sequences across minor boundaries, tongue tip trilling is not present – the trill is a weak postalveolar fricative– suggesting that the two antagonistic segments cannot be coproduced.

3. EXPERIMENT 2

A second experiment identified the highly constrained aerodynamic requirements for tongue-tip trilling which prevail over those for frication. Oro-pharyngeal pressure (Po) and airflow were recorded simultaneously in two subjects producing steady state and intervocalic trills and fricatives. Po during trill and fricative production was intermittently vented with catheters of varying impedance or resistance to exiting air (as described in [7, 12]), and the result was analysed acoustically. The catheters venting the Po simulated variations in the volume of the oral cavity due to coproduction with adjacent segments.

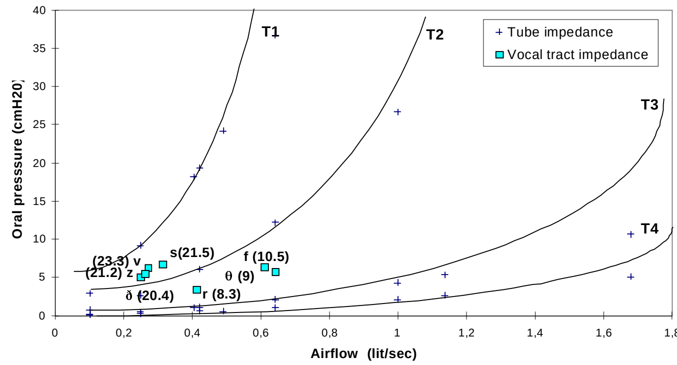

Fig. 3. Measured impedances for various fricatives and the trill. Impedance at various flowrates of the four tubes used to vent the Po.

Figure 3 shows the values for impedance for various fricatives and the trill, and the impedance of the catheters at various flowrates. It was found that venting the fricative with catheters with a higher impedance than that at the oral constriction (Tube 1) did not affect the quality of the fricative. Catheters with values for impedance similar to those at the oral constriction (Tube 2) had noticeable effects on fricatives: they lost much of their high-frequency aperiodic energy. Sibilant fricatives sounded non-sibilant and voiced fricatives became frictionless continuants (*i.e*., exhibited a lower C/V energy ratio). Tubes 3 and 4, with a lower impedance than that in the vocal tract, extinguished frication, since airflow exited through the aperture with lower impedance, thus inhibiting the generation of turbulence at the oral constriction.

Trills, on the other hand, were extinguished much earlier than fricatives, at catheter impedances substantially *higher* than those at the lingual constriction, *i.e*., venting the Po with Tube 1 extinguished tongue-tip trilling. Thus small variations in Po (>2.5 cmH2O) bled the Po below the threshold necessary for trilling. Hence trills allow a narrower range of Po variation than fricatives, and thus have more highly constrained aerodynamic requirements.

Interaction of articulatory movements and aerodynamics (Po is a function of cavity volume) accounts for the little allowable accommodation of trills to adjacent consonants if trilling is to be preserved. Thus, the more severely constrained aerodynamic requirements of trills over those of fricatives account for trills dominating the assimilatory processes.

4. DISCUSSION

The results show that lingual trills exhibit highly constrained articulatory and aerodynamic requirements and small variations result in lack of tongue-tip vibration. In order to preserve spectral identity (*i.e*., trilling) in onset position, aerodynamic and articulatory variation will tend to remain within very narrow bounds. In /sr/ sequences anticipation of the lingual movements to attain the constrained positioning, tongue configuration and aerodynamic requirements for the trill affects the lingual configuration and the time limen required to generate turbulence for the fricative, resulting in fricative to trill assimilation.

We suggest that (i) the more highly constrained production requirements of trills over those for fricatives, and (ii) the greater auditory salience of onset consonants vis-à-vis coda consonants [6], are responsible for the /r/ gesture overriding the gesture for the preceding fricative[3]. The narrowly constrained requirements for the trill, vis-à-vis those for lingual fricatives, are further shown by:

(a) Coarticulatory effects. Trills are more resistant to coarticulation with adjacent vowels (i.e. they exhibit significantly smaller V-to-C effects, both anticipatory and carryover) and exhibit more prominent coarticulatory effects, both in time and magnitude, on preceding and following vowels, than fricatives [9, 10]. The strong coarticulatory effects of trills are responsible for allophonic variation in adjacent vowels, which can reliably be used by listeners to identify a trill vs a tap [3].

(b) Manner requirements. Data on accommodation of fricatives and trills to adjacent consonants involving the same [8] and different articulators [1] show that these segments assimilate less to (and are less overlapped by) a following consonant than other segment types, *e.g*. stops. The finding that fricatives are invariably overlapped by following trills, when fricatives are known to be very resistant to coproduction with adjacent consonants, reveals tighter constraints for trills.

(c) Trills involve antagonistic stiffness requirements for adjacent articulators: active tongue sides and predorsum and relaxed tongue tip and blade to allow vibration. Coupling biomechanical effects may affect the tongue tip/blade tension, inhibiting the vibratory motion. Such antagonistic stiffness conditions in adjacent articulators, requiring fine neuromotoric control, are not present in lingual fricatives.

(d) The rather unique phonological patterning of lingual trills in these languages reflect their precise production requirements: (i) Trills do not combine with other consonants in the syllable to form consonant clusters. Coproduction of trills with tautosyllabic obstruents would affect the narrowly constrained lingual and aerodynamic conditions required for trilling. (ii) Trills exhibit a limited pattern of contrast – they only contrast in syllable onset position – where the precise production requirements for trilling can optimally be met (coda consonants involve larger gestural reduction and more overlap with adjacent consonants [1] which affect the aerodynamic conditions for trilling).

The fricative to trill assimilation is in agreement with the Recasens model which predicts a higher resistance to coarticulatory and assimilatory effects of highly gesturally constrained segments. The results further suggest that other production requirements (*e.g*., degree of aerodynamic constraint and stiffness conditions), as well perceptual requirements (e.g., availability of spectral cues in different syllable positions) also play a role in assimilatory processes.

5. CONCLUSIONS

First, we have illustrated the constrained and conflicting articulatory requirements of trills and lingual fricatives, which inhibit coproduction of the two segments. Articulatory analysis showed gradient assimilation of lingual fricatives to trills or sequencing of the two gestures, reflecting effects of temporal constraints and programming units. Second, we have shown that trills involve narrower aerodynamic requirements than fricatives and thus allow little accommodation to adjacent consonants in order to preserve tongue-tip trilling. Third we have argued that the severe articulatory and aerodynamic constraints on tongue-tip trills override the critical articulatory configuration and time limen required to generate turbulence for fricatives. Thus, assimilation of lingual fricatives to adjacent trills can be seen as an effect of articulatory and aerodynamic competition (and possibly of auditory integrity of onset consonants).

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NOTES

1. Though /s/ in coda position is aspirated in many dialects of Spanish, the dialects described here do not aspirate coda /s/. In Catalan coda /s/ is always pronounced.
2. The EPG data were converted to Contact Anteriority (CA) index values (CA indeces are the weighted sum of activated electrodes along the sagittal dimension of the palate).
3. The historical assimilations [rs]>*[ss]>[s] (Class. Latin *versus* > Vulg. Latin *vessus; ursus*'bear'> Spanish *oso*, Catalan *ós*) are not counterevidence to the claim that the requirements for the trill dominate the antagonistic consonant sequence , since the coda rhotic is not a trill. In lack of the requirements for trilling, the gesture for the onset consonant prevails.

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