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Articulatory synergies in the temporal organization of liquid clusters in Romanian

Stefania Marin*, Marianne Pouplier

Institute of Phonetics and Speech Processing, Ludwig-Maximilians University Munich, Schellingstr. 3/II, 80799 Munich, Germany

A B S T R A C T

This paper investigates on the basis of Romanian EMA data from five speakers which factors may affect the timing of liquid onset and coda clusters. American English /l/-obstruent coda clusters have been shown to pattern differently from obstruent–obstruent clusters. This has been attributed to perceptual constraints influencing articulatory timing relations. However, German codas showed no such differentiation of cluster types, casting doubt on the previously proposed perceptual account. Rather, it may be the lateral's degree of velarization that determines the contrasting patterns between languages. Romanian features, like German, a clear /l/ and a rhotic alveolar trill, allowing us to probe further into the potential role of articulatory synergies by broadening the investigation to liquid clusters generally. Results show that Romanian lateral codas patterned with German, and differently from English. However, Romanian rhotics patterned with the English lateral codas, with which they share a similar tongue rear articulation. We propose that these timing patterns reflect differences in articulatory properties between the various liquid types. Results further show that onset clusters patterned similarly to other onsets in Romanian and across languages. independently of liquid type. We further discuss the interaction of cluster type differences with intra-cluster timing.

1. Introduction

Empirical observations of the timing between a vowel and the consonant(s) preceding and following it have led to the proposal that syllables as prosodic units could be understood in terms of specific timing relations governing onsets and codas (Browman & Goldstein, 1988; De Jong, 2003; Krakow, 1999). Concerning particularly the timing between a consonant cluster and its tautosyllabic vowel, it has been shown that onset but not coda clusters reorganize temporally as a unit relative to singleton timing: under increasing onset complexity the onset as a whole as opposed to any of its individual consonants maintains a stable temporal relationship to the vowel. This contrasts with codas in which the timing of the individual consonants remains unaffected by changes in coda complexity (Browman & Goldstein, 1988, 2000; Honorof & Browman, 1995). This discovery has led to a recent surge of studies investigating the articulatory basis of the syllable by looking for a differentiation of syllable positions in terms of these characteristic timing patterns. While the basic asymmetric effect of increasing complexity on onset/coda timing has been observed for several languages (to be detailed below), it has also become clear that there seem to be both consonant-specific and language-specific factors influencing syllabic timing patterns. For example, Marin and Pouplier (2010) reported that while American English onset clusters conformed to the global timing stability first described by Browman and Goldstein (1988), for coda clusters consonant-specific effects emerged. Obstruent codas such as /-sp/, /-ps/ exhibited the hypothesized local timing pattern, whereas the liquid coda clusters /-lp/ and /-lk/ showed an unpredicted result: In going from singleton to complex coda (e.g., *gull*, *gulp*), the vowel shortened, which we took to be indicative of an increased overlap of the lateral with the vowel. Katz (2012) replicated our results in an acoustic study, and further reported analogous patterns for American rhotic clusters. Both studies interpreted this as pointing to the role of perceptual factors in articulatory timing: Increased VC overlap for liquid clusters, in contrast to obstruent clusters, enhances parallel transmission without endangering perceptual recoverability.

There are, however, contrasting results for German /l/ obtained by Pouplier (2012). The timing of German codas was not affected by coda complexity, irrespective of their composition, i.e. no change in VC timing was observed for either liquid or obstruent coda clusters. From the perceptual perspective proposed on the basis of the English results, the timing pattern of German lateral codas is surprising: even though American and German laterals differ in their gestural composition (American /l/ being dark whereas German /l/ is clear), there is little reason to assume that a German lateral would endanger vowel recoverability to a greater degree than an American lateral. If anything, we would actually expect a non-velarized (clear) /l/ to

* Corresponding author. Tel.: +49 89 2180 5752.
E-mail addresses: marin@phonetik.uni-muenchen.de (S. Marin), pouplier@phonetik.uni-muenchen.de (M. Pouplier).

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interfere *less* with perceptual recovery of vowel identity compared to a strongly velarized (dark) lateral such as English /l/, which considerably changes vowel quality (cf. Recasens's work on coarticulation properties of different lateral types, Recasens, Fontdevila, & Pallarès, 1995, 1996; Recasens, Pallarès, & Fontdevila, 1998). The American English and German results taken together suggest instead that the contrasting timing patterns for the two languages may be due to the different articulatory properties of the lateral consonant (i.e. the location and size of the tongue body constriction in the case of a clear vs. dark /l/), and thus more generally to the articulatory synergies of the consonants involved (Pouplier, 2012).

In this paper, we follow up on this possibility by examining liquid onset and coda clusters in a different language, Romanian, which similar to German and unlike American English, has a non-velarized /l/ in both onset and coda position (Pușcariu, 1994; Recasens, 2012). If the distinction between American English and German /l/-codas arises as a result of the lateral's articulatory characteristics, we expect that Romanian /l/-codas pattern with German rather than English. Importantly, Romanian also allows us to probe into the role of articulatory synergies of syllable timing further by including rhotic clusters. The Romanian rhotic is an alveolar trill, sometimes produced as a single tap (Pușcariu, 1994) and is not vocalized in coda position; hence its timing in both onset and coda position can be felicitously examined. Furthermore, because in terms of tongue body constriction, an alveolar trill shares articulatory properties (to be detailed below) with a velarized /l/ (Proctor, 2009, 2011; Recasens, 2013), we expect Romanian /r/-codas to pattern with English rather than Romanian or German /l/.

1.1. The coupled oscillator model of syllable structure and previous work on liquid clusters

It has been observed experimentally that two distinct timing patterns – synchronous vs. sequential – seem to characterize onset and coda positions, respectively. That is, single onset consonants begin their movements synchronously with the vowel gesture, while consonants in coda position are timed sequentially to the vowel (De Jong, 2003; Löfqvist & Gracco, 1999). This distinction has been formalized in Articulatory Phonology in terms of a coupled oscillator model of syllable structure. In this model syllable structure arises from pairwise in-phase or anti-phase coupling relations between gestures (Goldstein, Byrd, & Saltzman, 2006; Goldstein & Pouplier, 2014; Nam, Goldstein, & Saltzman, 2009; Pouplier, 2011). Syllable positions can therefore be understood in terms of specific patterns of coordination between consonants and vowels. Specifically, the onset (synchronous) pattern is assumed to be the result of in-phase coupling between the consonant and the vowel, while the coda (sequential) pattern is hypothesized to be the result of anti-phase coupling. Multiple consonants in onset position are assumed to be each coupled in-phase with the vowel but anti-phase with each other to ensure recoverability, resulting in competitive coupling demands between consonants and vowels. Because these demands cannot be fully met, a so-called c-center organization is hypothesized to emerge as a compromise solution to the competitive coupling: the vowel–adjacent consonant in a cluster shifts towards the vowel, and the vowel–remote consonant shifts away from the vowel relative to their timing as a singleton. The timing of the onset as a whole (usually measured as the temporal midpoint of the cluster and hence termed c-center) remains unaffected by changes in onset complexity (Fig. 1a). A coda consonant, on the other hand, is assumed to be coordinated anti-phase to the vowel; in a coda cluster gestures are added sequentially, so that the timing of the vowel–adjacent consonant to the vowel should not change significantly as coda complexity increases. The vowel–remote consonant, being added sequentially to the vowel–adjacent consonant, should be timed later (i.e. shift away from the vowel) relative to singleton timing (Fig. 1b).

The predictions of the coupled oscillator approach to syllable structure have been systematically tested in several recent studies (for a comprehensive survey of older studies, see Marin & Pouplier, 2010). Most of the studies on onsets have included obstruent–obstruent as well as obstruent-liquid/sonorant combinations and none of them have reported a significant difference in timing between these two cluster types. Thus a c-center organization conforming to model predictions has been reported for American English /sp-/, /sk-/, /sm-/, and /pl-/, /kl-/ onsets (Marin & Pouplier, 2010), for German /sk-/, /bl-/, /km-/, /gm-/ (with slightly different results for /pl-/; the German corpus is, however, more limited than the American English one; Pouplier, 2012), for Italian /pl-/, /pr-/, /kr-/ (Hermes, Grice, Mücke, & Niemann, 2012; Hermes, Mücke, & Grice, 2013) as well as for Romanian /sp-/, /sk-/, /sm-/ (Marin, 2013). Note however that a different timing has been observed for Romanian infrequent onsets /ps-/, /ks-/, /kt-/, /kn-/, for Italian /s/-initial clusters (Hermes et al., 2012, 2013), and for complex onsets in Slovak, (cf. Pouplier & Beňuš, 2011 for a discussion). A further, smaller study (Hoole, Pouplier, Beňuš, & Bombien, 2013) has also shown that German /tr-/, and to some degree French /br-/ are c-center organized (the rhotic in these languages is a uvular approximant or fricative).

For codas, less consistent results have been obtained across languages and clusters. While a sequential, local organization has been observed for American English /-sp/, /-sk/, /-ps/, /-ks/, /-ms/, for German /-ks/, /-kt/, /-bt/, /-lp/, /-lm/ and for Romanian /-sk/, /-sm/, /-ps/, /-ks/, /-pt/, /-kt/, /-mn/ (Marin & Pouplier, 2010; Marin, 2013; Pouplier, 2012), American English /l/-codas differed from the other codas in the language in several respects. First, they unsurprisingly showed great inter-speaker variability in production in that five of seven speakers produced a vocalized variant of /l/ with no reliably traceable tongue tip raising gesture. Yet secondly, the two speakers for whom a tongue tip raising gesture could be measured showed a shift of /l/ towards the vowel in /-lk/ (and one speaker also in /-lp/) relative to singleton /-l/ control, rather than the stable local timing predicted for codas and observed for other coda types (cf. Fig. 1b and c). Furthermore, an analysis of acoustic vowel duration (which could be done for all speakers) showed a shorter duration in the /-lk/ and /-lp/ words compared to control /-l/ words, consistent with the pattern observed in the articulatory data for the two speakers. In contrast there was no such co-variation in vowel duration and coda complexity for the obstruent coda clusters, again in line with the lack of timing differences observed articulatorily between simple and complex obstruent codas.

The acoustic vowel duration pattern in the context of /l/- vs. obstruent-codas has since been replicated by Katz (2012), providing further evidence for American English /l/-codas being timed differently from the obstruent codas in the language. He also observed that in terms of acoustic vowel

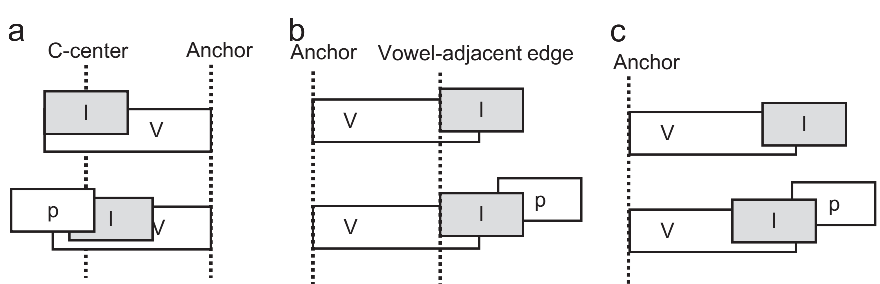

Fig. 1. Schematic timing pattern hypothesized by the coupled oscillator model of syllable structure for onsets (a) and codas (b), in contrast to the pattern actually observed for American English /l/ codas in Marin and Pouplier (2010) (c).

duration, /l/- and /r/-codas patterned together. Katz uses the fact that vowel compression effects vary as a function of coda composition to argue for the necessity to incorporate auditory constraints into gestural coordination principles. He argues that a high amount of VC overlap is only permitted to the degree that recoverability of the vowel is not endangered by the consonant. Since obstruents might obscure the vowel perceptually but liquids might not, more VC overlap is seen for liquid codas than for obstruent codas (similarly proposed in Marin & Pouplier, 2010).

Also Bombien and Hoole have provided evidence for the influence of perceptual factors on gestural timing in the context of /kn-, kl-/ onset clusters in German and French (Bombien, Mooshammer, & Hoole, 2013; Bombien, Mooshammer, Hoole, & Kühnert, 2010; Hoole, Bombien, Kühnert, & Mooshammer, 2009): /kn-/ was produced with significantly less overlap compared to /kl-/, and aerodynamic simulations confirmed that a great degree of overlap between velar and nasal would attenuate the velar burst characteristics due to nasal leakage and would thus presumably compromise perception. Overlap with the lateral, on the other hand, had no such effect on the aerodynamics of the velar release (Hoole et al., 2013). While this presents quite convincing support for the role of perceptual constraints in determining gestural timing in the case of liquid vs. nasal obstruent clusters, such an account fails to explain why lateral coda clusters in English vs. German pattern differently. Moreover perceptual recoverability alone does not explain why there is more VC overlap in liquid clusters compared to liquid singletons, which is the pattern observed for American English.

Another possibility is that the different lateral coda patterns are the result of articulatory particularities of the lateral in the two languages. Laterals are well known to be articulated cross-linguistically with different tongue body constrictions, often captured terminologically as ‘clear’ and ‘dark’ /l/. The differences between clear and dark laterals are known to be graded in terms of the location and size of the tongue body constriction as well as its timing to the tongue tip gesture (e.g., Gick, Campbell, Oh, & Tamburri-Watt, 2006; Ladefoged & Maddieson, 1996; Proctor, 2009, 2011; Recasens & Espinosa, 2005; Recasens, 2004, 2012). Broadly speaking, dark /l/ is characterized by a postdorsal retraction and concomitant lowering of the tongue in the velar region. Clear /l/ is characterized by a fronted, raised tongue body. Dark /l/s, due to their pronounced postdorsal retraction gesture show a high degree of coarticulatory resistance (Recasens & Espinosa, 2005; Recasens et al., 1995, 1996, 1998).

English dark /l/ and its prosodically conditioned allophony has been extensively studied: coda /l/ is produced with strong tongue body retraction that temporally precedes the coronal constriction, whereas onset /l/s are characterized by a wider tongue body constriction degree and a synchronous timing of the two gestures (e.g., Delattre, 1971; Giles & Moll, 1975; Narayanan, Alwan, & Haker, 1997; Scobbie & Pouplier, 2010; Sproat & Fujimura, 1993). The precise nature of dorsal control exerted by German /l/ and its timing properties are not known, but it is generally agreed that German has a clear /l/ (Geumann, Kroos, & Tillmann, 1999; Recasens et al., 1996, 1998; Recasens, 2012). Geumann and colleagues (Geumann et al., 1999) found in an EMA investigation of German coronals that the tongue body varied equally in different vowel contexts for /l/ and /n, d, t/, suggesting no stronger tongue body control for /l/ compared to the other coronals. Recasens et al. (1998, see also 1995, 1996) suggested that German /l/ is in some sense intermediate between the dark /l/ of Catalan and the clear /l/ of other languages such as Spanish or French: in their study, German /l/ showed less vowel coarticulation compared to Spanish and French /l/, albeit not as little as Catalan dark /l/. For the present purposes, the main point is that the tongue body component of German /l/ has been shown to be quite dissimilar to American English /l/. Therefore, the discrepancy of results in our earlier work concerning lateral-obstruent coda clusters for the two languages may have been due to the articulatory characteristics of the different lateral types. To follow up on this possibility, we extend our investigation to Romanian, which, like German, has a clear /l/.

To our knowledge, our publication is the first articulatory investigation of Romanian liquids, and their detailed characteristics are unknown. Recasens (2012) shows lower F2 values for Romanian compared to German in an /a/ context, yet in an /i/ context the F2 values are very similar for the two languages. In line with these data we would also impressionistically call dental Romanian /l/ slightly darker than German /l/, yet it can be generally categorized as a clear /l/. Also Recasens classifies the lateral as clear for both languages, in contrast to the American English lateral. We therefore predict that Romanian lateral coda clusters should follow the German rather than the American English pattern.

Another prediction concerns Romanian rhotics which are realized as trills. Crucially, the tongue tip raising for a trill is known to be supported synergistically by a uvular/dorsal retraction gesture: the tongue body has to lower and the tongue dorsum to retract for the tongue tip to be able to trill (Delattre, 1971; Hall & Hamann, 2010; Proctor, 2009, 2011; Recasens & Pallarès, 1999; Recasens, 1991; Romano & Badin, 2009). In terms of tongue configurations, therefore, dark /l/ and the alveolar trill, unlike clear /l/, are produced with similar tongue shapes: a tongue body lowering and retraction in the uvular region (Proctor, 2009, 2011; Recasens, 2013). If it is the nature of the tongue body gesture that conditioned the differences between German and English laterals, rather than perceptual factors, the Romanian alveolar trill should pattern with English /l/, and differently from German and Romanian laterals.[1] That is, Romanian /r/ codas should exhibit a temporal pattern similar to that observed for American English /l/ codas, and different from that of other codas within Romanian (lateral or obstruent). From a perceptual perspective, it is not immediately clear how to think about the effect a trill might have on the perceptual recoverability of a vowel; therefore we will take the arguably simplest prediction which is that the liquids as highly sonorous segments should pattern the same (as was the case for American English in Katz, 2012).

Since all of the studies mentioned above (except Slovak, Pouplier & Beňuš, 2011) have reported a general c-center pattern for liquid onset clusters, we simply take that to be the prediction for the Romanian data. The locus where we do expect to see differences in onset for the two liquids is consonant–consonant timing, as we will detail next.

1.2. Factors influencing consonant–consonant timing

We look at the potential role of articulatory synergies not only on the basis of cluster-vowel timing patterns, but also in terms of consonant–consonant timing *within* the respective cluster. We will refer to consonant–consonant timing within a cluster as *intra-cluster* timing. Specifically, we believe that intra-cluster timing should differentiate the two liquids in onset but not coda position (as we detail below), and furthermore that any differences in intra-cluster timing should be reflected in the timing of the vowel–remote consonant (C_1 in a $\underline{C}_1C_2V$ sequence, and C_2 in a $VC_1\underline{C}_2$ sequence). As mentioned above, c-center theory predicts that the vowel–remote consonant will shift away from the anchor relative to the singleton pattern. At the same time it is known that the segmental composition of a cluster can significantly affect intra-cluster timing (e.g., Bombien & Hoole, 2013; Chitoran, Goldstein, & Byrd, 2002), and these timing differences within various onset clusters have been shown to be primarily instantiated in the amount of shift of the vowel–remote consonant (Marin, 2013; Pouplier, 2012).

For our present data, we predict a lower amount of overlap for Cr- clusters compared to Cl- clusters in Romanian. This hypothesis is based among others on the results of Cunha (2012): In European and Brazilian Portuguese, the consonants in /pr-/ and /kr-/ are timed further apart than in /pl-/, /kl-/

[1] For convenience, we adopt the term ‘tongue body gesture’ to refer both to the tongue shape characterizing dark /l/ and the trill (a tongue body lowering and retraction), and to the tongue shape characterizing a clear /l/ (a tongue body raising and fronting), keeping in mind however that this covers a range of different tongue shapes.

clusters (in both varieties of Portuguese, the rhotic is an alveolar tap, sometimes trill).[2] We therefore expect a similar difference for Romanian. This should also be evident in a significant difference in the shift magnitude of the vowel–remote consonant.

We hypothesize that the overlap difference between lateral and rhotic onset clusters, at least when a trill rhotic is involved, might be due to the tight articulatory and aerodynamic parameters required to initiate a trill (cf. Solé, 2002 for a review and discussion). If this is the case, we predict no difference between the liquids in coda clusters, since the constraints for a trill hold for its constriction formation, not its release. We therefore predict a liquid effect in onset but not in coda position, or in other words, a position effect for intra-cluster timing for /r/, but not for /l/. In summary, we hypothesize therefore that liquid-type dependent production characteristics will affect intra-cluster timing differences in onsets but not codas.

Laryngeal settings associated with voicing contrasts are one additional factor known to influence intra-cluster timing, and since our corpus is balanced for voicing in both syllable positions, we use this opportunity to also include this factor in our analysis of intra-cluster timing. German /bl-/ and /gl-/ have been shown to be timed closer together than /pl-/ and /kl-/. In French on the other hand, where /p, k/ are realized as voiceless unaspirated but /b, g/ are fully voiced, no consistent difference in intra-cluster timing as a function of voicing was observed; the timing of the consonants in the French clusters /pl-/, /bl-/, /kl-/, /gl-/ was similar to that of German /pl-/ and /kl-/ (Bombien & Hoole, 2013; Bombien, 2011). For voicing effects, we expect a pattern similar to that revealed for French, given that the voicing contrast in Romanian is realized as in French, i.e. as a distinction between voiced and voiceless unaspirated consonants.

To summarize, we hypothesize that the temporal organization proposed for onsets and codas is further affected in the case of liquid clusters by the articulatory characteristics of these liquids. In this sense, we propose that prosodic structure on the one hand determines how consonantal (and vocalic) gestures are organized temporally, but on the other hand is itself affected by the gestural synergies of the particular consonants involved.

2. Method

2.1. Data acquisition

We recorded five native Romanian speakers (three female) with no reported speech, hearing or language problems, and naïve as to the purposes of the experiment. They all spoke standard Romanian without any pronounced dialectal features; at the time of the recording they lived in Munich but reported using Romanian at home on a daily basis. The speakers were familiarized with the list of utterances prior to data collection, and they were instructed to speak at a comfortable rate. During the actual data collection, speakers saw the target utterance on a computer screen and were visually cued when to speak. They repeated each utterance twice per trial in three randomized blocks, resulting in a targeted number of six repetitions per utterance.

Kinematic data were recorded using the electromagnetic articulography (EMA) system at the Munich Institute of Phonetics (AG500, Carstens Medizinelektronik). The system records articulatory movement over time by tracking, within an electromagnetic field, the five-dimensional position of sensors glued to various points on the speaker's vocal tract. The articulatory data were recorded at a sampling rate of 200 Hz. Acoustic data were recorded simultaneously at a sampling rate of 32,768 Hz.

For the articulatory recordings, four sensors were placed on the tongue, spaced fairly equidistantly: tongue tip (attached approximately 1 cm behind the actual tongue tip), anterior tongue body, posterior tongue body, and tongue dorsum (in the estimated velar constriction region). Additional sensors were placed on the upper and lower lips, and on the lower gums to measure jaw movement. Reference sensors were placed on the nose bridge, upper incisor (maxilla), and behind the ears (on the right and left mastoid process). All sensors except for the ones on the right and left mastoid process were fixed mid-sagittally.

Standard calibration and post-processing procedures were conducted for each recording session using an algorithm developed by Hoole and Zierdt (2010) at the Munich Institute of Phonetics. The kinematic signals were filtered at a 5 Hz cut-off frequency for the reference sensors, at 60 Hz for the tongue tip sensor, and at 20 Hz for all other sensors. The data were corrected for head movement on the basis of the reference sensors, and rotated to each speaker's occlusal plane.

2.2. Stimuli

The stimuli consisted of target words containing onset and coda consonant clusters, and singleton controls (Table 1). All clusters were mono-morphemic, and with one exception (the singleton stimulus for set ML-) all stimuli were real words. Because no good matching pair could be constructed for coda -LP, this coda set was not included in any of the analyses where a control singleton was needed. However, the cluster was included in the intra-cluster timing analysis. Sets FL- and -LF were recorded from only four of the speakers.

Within each set (cluster and corresponding singleton), the context preceding and following the target consonant(s) was held constant (e.g. Onset: /pa # plak/, /pap # lak/; Coda: /kolb # a.re/, /kol# ba.re/). Each target word included a constant anchor point in reference to which the timing of the consonant of interest was measured (e.g. consonant /k/ in onset set /plak/, /lak/ or in coda set /kolb/, /kol/).

The target phrases (target word plus preceding/following word controlling for context) were embedded in a simple carrier phrase, which varied slightly across sets to avoid monotony; within a set, the carrier phrase was kept constant (cf. the Appendix for a full stimulus list). The target sentences for this experiment were interspersed with filler sentences of similar formats constituting data sets for other experiments. While for each target word six repetitions were targeted per stimulus word, not all the repetitions could be used in the analysis due to technical problems with data recording/processing or labeling. Of a total of 1200 targeted utterances (20 sets*2 conditions*6 repetitions*5 speakers), 88 tokens across speakers and experimental conditions had to be excluded from the analysis for these reasons.

2.3. Segmentation

The articulatory data were analyzed using the Matlab-based *Mview* software algorithm developed by Mark Tiede at Haskins Laboratories. Labial consonants were defined on the basis of the variable lip aperture (LA), calculated as the Euclidean distance between upper and lower lip sensors. For

[2] Interestingly also in German and French, the consonants in clusters /fr-/, /pr-/ and /br-/ are timed further apart than in /fl-/, /pl-/, /bl-/, even though the rhotic is a uvular approximant/fricative, not a trill. This means that the difference between lateral and rhotic clusters seems to be robust cross-linguistically in spite of the different rhotics involved in German and French vs. Portuguese (see Hoole et al., 2013 for a discussion of aerodynamic factors which might condition the low overlap for uvular approximant /r/).

Table 1
Onset and coda stimuli: consonants of interest (singletons and clusters) are shown in bold face; anchor points are underlined. Glosses are given in the Appendix.

Series	Set	Cluster (CC)	Singleton (C)
/l/-onsets	PL-	/'pa # '**pl**ak/	/'pap # '**l**ak/
	BL-	/'ku # '**bl**at/	/'cub # '**l**at/
	ML-	/'ka # '**ml**aʃ.ti.na/	/'kam # '**l**aʃ.ti.na/
	FL-	/'pa # '**fl**a.ma/	/'paf # **l**a.ma/
	KL-	/'pa # '**kl**a.mə/	/'pak # '**l**a.mə/
	GL-	/'ba # '**gl**as/	/'bag # '**l**as/
/r/-onsets	PR-	/'pa # '**pr**ag/	/'pap # '**r**ag/
	BR-	/'ku # '**br**ad/	/'cub # '**r**ad/
	MR-	/'ka # '**mr**a.ni.tsa/	/'kam # '**r**a.ni.tsa/
	KR-	/'pa # '**kr**a.mə/	/'pak # '**r**a.mə/
	GR-	/'ba # '**gr**as/	/'bag # '**r**as/
/l/-codas	-LP	/'ska**lp** # 'a.re/	–
	-LB	/'ko**lb** # 'a.re/	/'ko**l** # 'bare/
	-LM	/'ka**lm** # 'a.re/	/'ka**l** # 'ma.re/
	-LF	/'go**lf** # 'a.tʃe/	/'go**l** # 'fa.tʃe/
	-LK	/'ka**lk** # 'a.re/	/'ka**l** # 'ka.re/
	-LG	/'mu**lg** # 'as/	/'mu**l** # 'gaz/
/r/-codas	-RP	/'ko**rp** # 'a.re/	/'ko**r** # 'pa.re/
	-RB	/'ko**rb** # 'a.re/	/'ko**r** # 'ba.re/
	-RK	/'pa**rk** # 'a.re/	/'pa**r** # 'ka.re/
	-RG	/'mu**rg** # 'as/	/'mu**r** # 'gaz/

some utterances, due to technical problems for the lower lip sensor during recording, the labial constriction had to be measured on the basis of upper lip movement only. The consonants produced with lingual constrictions were defined on the basis of the vertical movement of the relevant tongue sensor (tongue tip – TT for dentals/alveolars, tongue dorsum – TD for velars).

Kinematic events defining target achievement and release were determined on the basis of changes in the velocity profile of lip aperture/vertical tongue movement (cf. Marin & Pouplier, 2010; Marin, 2013; Pouplier, 2012 for details). First, two velocity peaks corresponding to the articulator moving towards and away from target (henceforth Peak 1 and Peak 2 respectively) were automatically detected in the region of interest. Target achievement (henceforth Target) was defined as the point in time at which velocity fell below 20% of the preceding velocity peak (Peak 1). Target release (henceforth Release) was defined as the point where velocity exceeded 20% of the following velocity peak (Peak 2). Consonant constriction (plateau) was defined as the interval between Target and Release; its temporal midpoint is henceforth referred to as constriction midpoint. In the case of /r/, the automatic algorithm reliably detected these landmarks for tap productions. For trill productions, in some cases the Target and Release labels had to be manually adjusted so that they would be associated with the achievement of the target of the first tap and release of the last tap, rather than with achievement and release of just one tap.

2.4. Analyses

Consonant timing was determined by measuring the timing of the target consonant(s) relative to a fixed anchor point (cf. Table 1 for a list of anchors per sets). For onset targets, the anchor point was the constriction midpoint of a consonant following the target (e.g. /t/ in /blat/-/lat/, or /m/ in /klamə/-/lamə/); for coda targets, the anchor point was the constriction midpoint of a consonant preceding the target (e.g. /k/ in /kolb/-/kol/). For each cluster word, two timing measures were computed between various cluster landmarks and anchor point, as illustrated in Fig. 2:

(1) *Vowel-adjacent* (*V-adjacent*) *lag* was defined as the temporal lag from the V-adjacent landmark to the anchor point. The *V-adjacent landmark* was defined as the midpoint of the consonant adjacent to the vowel. For example, in both /b**l**at/ and /ko**l**b/ the V-adjacent landmark was the constriction midpoint of /l/, and its temporal lag to anchors /t/ and /k/ respectively was the V-adjacent lag.
(2) *Vowel-remote* (*V-remote*) *lag* was defined as the temporal lag from the V-remote landmark to the anchor point. The *V-remote landmark* was defined as the constriction midpoint of the consonant remote to the vowel, e.g., /b/ in /**b**lat/ and /kol**b/**.

For singletons, the lag between singleton and anchor constriction midpoint was computed, and this measure served simultaneously as control for the V-adjacent and V-remote lag measures in the cluster words.[3]

2.4.1. Temporal shift

The lags computed for each individual production were averaged across repetitions, and then relative lag ratios between mean cluster lags and mean singleton lags (CC/C) were calculated for each speaker and set. By this measure, a ratio under 1 would indicate that the cluster lag was smaller than the singleton lag, and hence that the consonant in the cluster condition shifted towards the anchor (and implicitly overlaped increasingly with the vowel) relative to the singleton condition. A ratio greater than 1 would mean that the cluster lag was larger than the singleton lag, indicating that the consonant in the cluster condition shifted away from the anchor relative to the singleton condition. Finally, if the singleton and cluster lags were similar, a ratio of 1 would be expected.

2.4.2. Intra-cluster timing

The temporal relationship between the members of a cluster (C_1C_2) was calculated as the difference between the release of the first consonant (C_1) and the target achievement of the second consonant (C_2): Intra-Cluster Timing $= C_2\text{Target} - C_1\text{Release}$. This measure reveals whether the

[3] For onsets, the V-adjacent lag corresponds to what is referred to as the right-edge in other studies (e.g. Browman & Goldstein, 1988; Marin & Pouplier, 2010); for codas, it corresponds to the left-edge. Likewise, the V-remote measure corresponds to the left-edge for onsets and to the right-edge for codas.

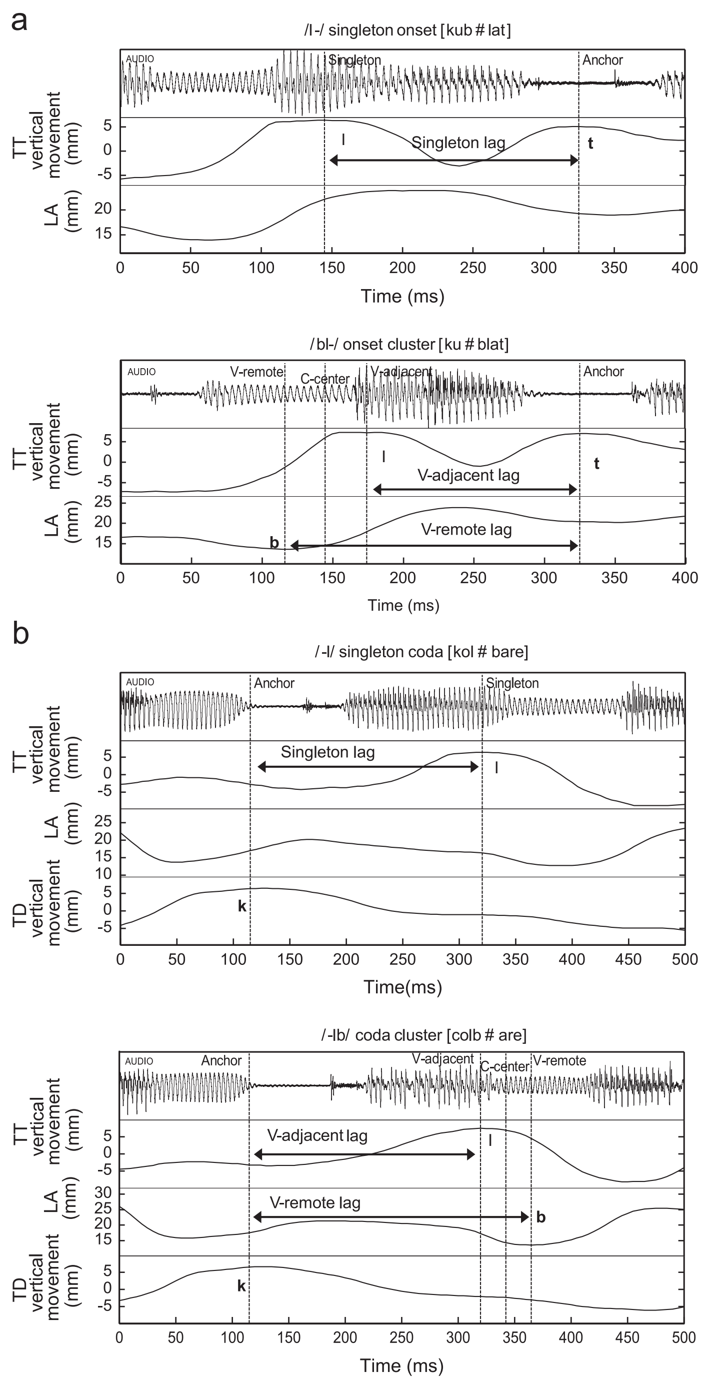

Fig. 2. Example articulatory measurements for singletons (top) and clusters (bottom) in onset (a) and coda (b) position (individual utterances from sets BL- and -LB, produced by a female speaker). Measurement points are indicated by dotted vertical lines. The C-center is the temporal midpoint between V-adjacent and V-remote measurements.

achievement of target of the second consonant temporally overlaps (and hence potentially masks) the release of the first consonant. Negative values for this measure indicate that C_2 has already achieved its target when C_1 is released (i.e. the constriction plateaus of the two consonants overlap temporally). Positive values indicate that achievement of target of C_2 follows temporally the release of C_1, with greater numbers indicating greater lags between the two. Absolute intra-cluster timing values were normalized relative to the total constriction duration of the cluster (cf. Bombien, 2011): Normalized Intra-cluster Timing $=(C_2\text{Target}-C_1\text{Release})/(C_2\text{Release}-C_1\text{Target})$.

2.4.3. *Statistical analyses*

All statistical procedures were carried out using the SPSS 13 for Windows statistical package. ANOVAs with speaker as a random factor were used whenever appropriate; when a random factor is included in the analysis, SPSS calculates denominator degrees of freedom using the Satterthwaite approximation, which is a conservative method of computing degrees of freedom with no assumption of equal variances (cf. Keselman, Algina, Kowalchuk, & Wolfinger, 1999). Due to built-in post-hoc analyses in this procedure not taking into account the random factor, we avoided using factors with more than two levels whenever possible by selecting pair-wise comparisons of interest for the hypotheses being tested. Because ANOVA is robust to violations of the normality assumption (cf. Rutherford, 2001), we used it for all comparisons involving either ratio data or timing values.

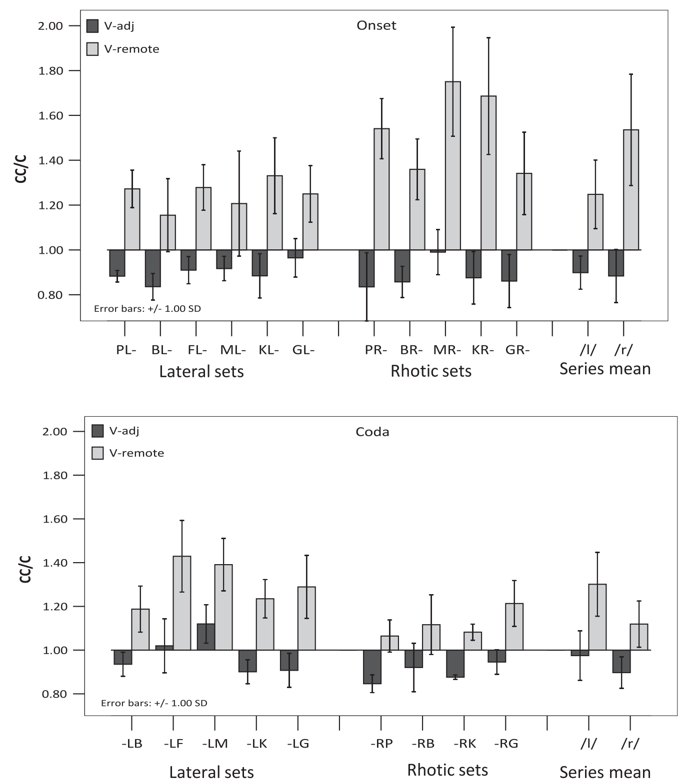

Fig. 3. Average lag ratios in onset (top) and coda (bottom) sets. Averages for the /l/ and /r/ series are shown on the right hand side of the graphs. Ratios smaller than 1 indicate that the consonant shifted towards the anchor point in the cluster vs. singleton condition.

3. Results

3.1. Temporal shift

We predict both lateral and rhotic onsets to follow a c-center organization pattern, with lag ratios under 1 for the vowel–adjacent consonant, and no significant difference between the two liquid types. On the other hand, we predict codas to show different V-adjacent lag ratios as a function of liquid type, reflecting their difference in tongue dorsum control: specifically, we predict /l/-codas to exhibit coda-typical lag ratios close to 1, and /r/-codas to exhibit ratios smaller than 1. We further expect V-remote lag ratios greater than 1 regardless of syllable position, with a difference however in magnitude between liquid types in onset (reflecting the tight articulatory constraints required for producing the rhotic), but not in coda position. Mean lag ratios per set and series are plotted in Fig. 3. For onsets, on average it can be observed that the V-adjacent lag ratios were smaller than 1 regardless of liquid type, which is the predicted pattern for onsets. For codas, the V-adjacent lag ratios were on average close to 1 for /l/-codas (the expected pattern in this syllable position), but were smaller than 1 for /r/-codas. The individual sets behaved similarly, except for –LF and –LM, which, unlike all other coda sets, exhibited a shift away from the vowel. V-remote lag ratios were as expected all greater than 1 and were larger for /r/- than for /l/- onsets, and for /l/- than for /r/-codas.

To statistically verify our predictions, ANOVAs with fixed factor: Liquid Type (/l/, /r/) and random factor: Speaker, were carried out separately by syllable position (Onset, Coda) and lag ratio type (V-adjacent, V-remote). *V-adjacent ratios* were as predicted comparable for /l/ and /r/ onsets ($F(1, 4.003)=0.159$, $p=0.710$). Also as predicted, they were smaller for /r/ than for /l/ codas ($F(1, 4.038)=22.335$, $p=.009$), indicating a greater shift towards the vowel of /r/ than of /l/ in the cluster relative to the singleton condition. *V-remote ratios* were significantly greater for /r/- compared to /l/-onsets ($F(1, 4.004)=17.003$, $p=0.015$) and for /l/- compared to /r/-codas ($F(1, 4.078)=22.\ 130$, $p=0.009$). The V-remote ratios differing as a function of liquid type in coda may be a corollary of the V-adjacent timing differences, a point we will take up again below.

We also hypothesized that Romanian /l/-codas should pattern, like in German, with the other codas in the language whereas /r/-codas should differ from other types of codas (similar to English /l/-codas differing from English obstruent codas). To test this prediction, we compared the V-adjacent lag ratios of the liquid series to those of obstruent codas analyzed previously (cf. Marin, 2013 for details).[4] The following Romanian obstruent-codas were available for comparison: -SK, -SM, -PS, -KS, -KT, -PT, -MN (their temporal pattern did not differ as a function of set). The lag ratio pattern as a function of coda type (/l/-, /r/- or obstruent-coda) is shown in Fig. 4. Each liquid coda series was compared to the obstruent coda series in two ANOVAs with fixed factor: Cluster Type (liquid, obstruent) and random factor: Speaker. The lag ratios of /r/-coda sets differed significantly from those of the obstruent-codas ($F(1, 4)=12.737$, $p=0.023$), but /l/- and obstruent-codas showed comparable ratios ($F(1, 4.015)=0.051$, $p=0.832$).

Because in terms of the V-adjacent measure, sets –LF and –LM patterened differently from the other lateral codas, we also statistically compared /l/-, /r/- and obstruent-codas excluding sets –LF and –LM from the analysis. When doing so, the V-adjacent ratios of /l/- and /r/-codas were no longer significantly different ($F(1, 4)=0.818$, $p=0.417$), but the ratios of /l/ and obstruent codas still remained comparable ($F(1, 4)=4.634$, $p=0.098$).

[4] The Marin (2013) data were collected as part of the same recording session reported here, i.e. the data are from the same speakers recorded under identical experimental conditions.

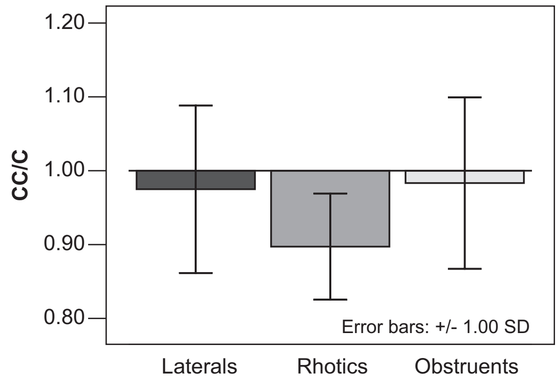

Fig. 4. Average lag ratios for lateral, rhotic and obstruent codas.

We suggested above that V-remote timing differences among liquid types may co-vary with the liquid-specific V-adjacent timing differences. If the determining factor of V-remote timing is indeed the timing of the V-adjacent consonant to the vowel, we expect a positive correlation between the two measures. In the absence of a strong correlation, we can infer that V-remote timing is influenced by factors other than V-adjacent timing (such as cluster composition). A bivariate correlation analysis showed that the two lag ratios were overall moderately correlated ($r(98)=.409$, $p<0.001$; $R^2=.167$). This suggests that V-remote timing is not conditioned by V-adjacent timing alone. Analyzing the data by position we found a stronger relationship in coda than onset (Onset: $r(54)=.442$, $p=.001$, $R^2=.195$; Coda: $r(44)=.776$, $p<.001$, $R^2=.602$). This means that V-remote timing is affected differently as a function of syllable position: while for codas, V-remote timing seems to be strongly predicted by V-adjacent timing, for onsets, V-remote timing differences are only marginally predictable on the basis of V-adjacent timing, pointing to the influence of other factors. We will follow up on this point in more detail when investigating intra-cluster timing.

To summarize, there was no difference between lateral and rhotic *onsets* in the magnitude of V-adjacent consonant shift. The V-remote consonant however shifted away from the vowel more in the case of /r/- than /l/-sets. For *codas*, the temporal pattern of the V-adjacent consonant was different as a function of liquid type (if all clusters were included): /r/-codas differed from both /l/- and obstruent-codas, while /l/- and obstruent-codas did not differ from each other. The timing of /r/-codas was thus similar to that of American English /l/-codas, in that the V-adjacent consonant shifted towards the vowel as coda complexity increased, thus differing from other coda types (cf. Marin & Pouplier, 2010). The correlation analysis revealed that in codas but not onsets V-remote timing was predictable from V-adjacent timing.

3.2. Intra-cluster timing

In addition to the clusters analyzed so far, coda /-lp/ was also available for this analysis (see Methods). Except for the absence of coda /-rm/, the clusters included here are symmetrically distributed in onset and coda position. Intra-cluster timing for each onset and coda set is shown in Fig. 5. Overall, the pattern of results was very similar across the absolute and normalized measures.

Absolute intra-cluster timing patterns as a function of syllable position, liquid type and voicing are shown in Fig. 6. To test whether these factors had an influence on the intra-cluster timing pattern, we carried out two ANOVAs (once on the absolute, once on the normalized values), with fixed factors: Position (onset, coda), Liquid Type (l, r), and Voicing (voiced, voiceless), and random factor: Speaker. The results are summarized in Table 2. Only significant interactions are reported. Position and Liquid Type, as well as the interaction between the two were significant for both measures. Voicing of the non-liquid consonant in the cluster did not overall affect intra-cluster timing, nor were the interactions between Voicing and the other factors significant.

Further tests corroborated our predictions: they indicated that the interaction between Position and Liquid Type was due to factor Position being significant for /r/ but not /l/ clusters (/l/: $F(1, 4.015)=3.120$, $p=0.152$; /r/: $F(1, 4.000)=70.329$, $p=0.001$), and to factor Liquid Type being significant in onset but not in coda position (Onset: $F(1, 4.018)=155.832$, $p<0.001$; Coda: $F(1, 4.001)=3.105$, $p=0.153$). Specifically, the consonants within /r/-clusters were timed further apart in onset than in coda position; additionally, in onset position the consonants making up an /r/-cluster were timed further apart than the consonants in /l/-clusters. The results were the same if the comparisons were carried out on the absolute or normalized intra-cluster timing values, so only the results for the absolute values are reported here.

Overall therefore, intra-cluster lags were larger in onset than in coda position, and for /r/-clusters compared to /l/-clusters (cf. Fig. 6), a pattern that replicates previous results. However, for Romanian liquid clusters specifically, the position effect was statistically robust for rhotic but not for lateral clusters. Likewise, the intra-cluster difference between /l/- and /r/-clusters held in onset position (replicating previous studies by Cunha (2012) and Hoole et al. (2013) that only analyzed onset clusters), but could not be generalized to clusters in coda position. These patterns confirmed our predictions by which the tight articulatory and aerodynamic control needed for initiating the trill would result in the consonants in the cluster being timed further apart in /r/- compared to /l/-onsets (with no such difference having been predicted or observed for codas). Also as expected, there was no effect of voicing: Romanian clusters patterned in this respect with French clusters (with which they share the same type of voicing contrast), rather than with German clusters.

The correlation analysis in the previous section showed that the predictability of V-remote timing based on V-adjacent timing varies as a function of syllable position: For codas, V-remote timing was by and large predictable from V-adjacent timing. For onsets, however, there was only a weak correlation between the two measures, suggesting that other factors, possibly intra-cluster timing played a role in determining V-remote timing. We now follow up on our prediction that intra-cluster differences in timing are instantiated primarily in the timing of the V-remote consonant on the basis of bivariate correlation analyses. Overall, intra-cluster timing was strongly and significantly correlated to the V-remote ratios ($r(98)=.748$, $p<0.001$; $R^2=0.560$), but not to the V-adjacent ratios ($r(98)=-.006$, $p=.957$; $R^2=.000$). The analysis by syllable position showed that the correlation between intra-cluster timing and V-remote timing was stronger in onset than in coda position (Onset: $r(54)=.763$, $p<.001$; $R^2=.582$; Coda: $r(44)=.603$, $p<.001$, $R^2=.363$); no syllable position effect was observed for the correlation with V-adjacent timing (Onset: $r(54)=.082$, $p=.557$; $R^2=.007$; Coda: $r(44)=.044$, $p=.775$, $R^2=.002$). The lack of a correlation between V-adjacent and intra-cluster timing confirms that cluster specific effects are reflected in the vowel-remote measure. The stronger correlations for onset than coda confirms that onset intra-cluster timing is more susceptible to cluster-specific effects.

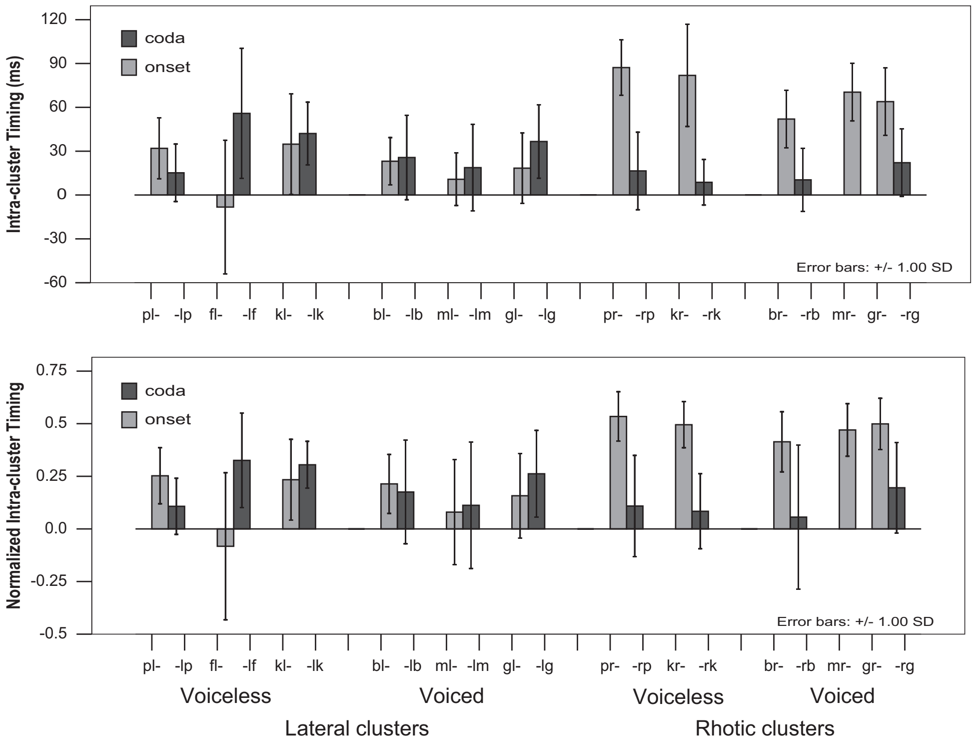

Fig. 5. Average intra-cluster timing by cluster and position: absolute values in milliseconds (top), normalized values (bottom). For both measures, larger positive values indicate more lag (less overlap) between consonants, negative values indicate that C2 reaches its target before C1 is released.

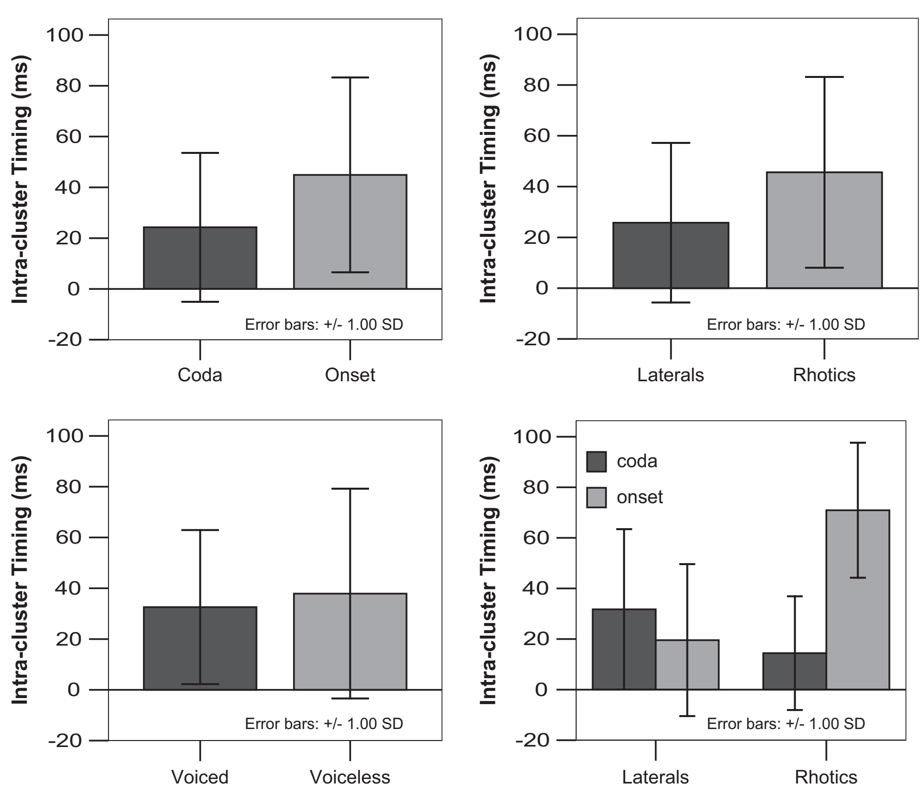

Fig. 6. Averages of absolute intra-cluster timing by Position (top left), Liquid Type (top right), Voicing of the non-liquid consonant (bottom left), and Position by Liquid Type (bottom right).

4. Discussion

The purpose of our study was to investigate the temporal organization of liquid clusters in Romanian in order to shed light on the origins of previously obtained cross-linguistic results on lateral cluster timing. Our results showed that the Romanian lateral codas exhibited a local timing

Table 2
Results for univariate ANOVAs with dependent variable: absolute/normalized intra-cluster timing, fixed factors: Position (onset, coda), Liquid Type (/l/, /r/), Voicing of non-liquid consonant (voiced, voiceless), and random factor: Speaker.

Factor	Absolute intra-cluster timing	Normalized intra-cluster timing
Position	$F(1, 4.009)=64.109$, $p=0.001$	$F(1, 4.024)=95.895$, $p=0.001$
Liquid Type	$F(1, 4.004)=16.953$, $p=0.015$	$F(1, 4.005)=10.612$, $p=0.031$
Voicing	$F(1, 4.004)=3.036$, $p=0.156$	$F(1, 4.028)=1.728$, $p=0.259$
Position*Liquid Type	$F(1, 4.002)=34.133$, $p=0.004$	$F(1, 4.013)=100.215$, $p=0.001$

pattern (i.e. the V-adjacent consonant exhibited comparable temporal lags across codas of varying complexity), parallel to German and different from American English. Rhotic codas, on the other hand patterned similarly to American English dark /l/, and differently from the other Romanian codas, in that the vowel–adjacent consonant shifted towards the anchor as a function of coda complexity. This is the pattern we predicted as a function of the articulatory (dis)similarities between the various liquid types, specifically the tongue body control differentiating an alveolar trill and a dark /l/ on the one hand, from clear /l/ on the other. We discuss this point in more detail after a summary of the remaining results.

A caveat to the generalization of the results for the vowel-adjacent measure is that /l/-coda sets in Romanian did not all behave uniformly: while -LB, -LK, -LG showed lag ratios under 1, -LF and -LM showed lag ratios over 1. For the rhotics, all sets behaved similarly, but unfortunately sets -RF and -RM were not recorded, so it is not entirely clear from the current data whether a similar variability would be observed for /r/-codas, had more sets been available. When sets -LF and -LM were excluded from the analysis, /l/- and /r/-coda sets no longer differed from each other, but importantly, /l/-codas were similar to the obstruent sets independently of whether sets -LF and -LM were included in the analysis or not. This issue will have to be followed up in future research based on numerically balanced data sets with controlled cluster composition between all conditions.

The behavior of the V-adjacent consonant in onset clusters did not differentiate the two liquids – both /l/- and /r/-onsets exhibited a pattern consistent with the predictions of a c-center organization, i.e. the V-adjacent consonant shifted towards the anchor as onset complexity increased. Our results further revealed a significant difference in intra-cluster and vowel–remote consonant timing between the liquids in onset clusters, but no intra-cluster difference for coda clusters. This is in line with our hypothesis that articulatory constraints interact with intra-cluster timing: the strong tongue body control of /r/ in conjunction with the particular aerodynamic requirements needed for trill initiation condition a low degree of overlap with a preceding consonant (see also Hoole et al., 2013). For codas there is no such effect since these constraints play a role when forming the constriction, not at its release (Solé, 2002). For coda clusters, we did observe a difference between liquids in terms of V-remote consonant timing, not matched by an intra-cluster timing difference. We believe the V-remote difference in this case is related to the V-adjacent difference itself: relative to the singleton condition, /l/ in the cluster is timed later than /r/ in the cluster (as indicated by overall larger V-adjacent ratios for /l/- than for /r/-codas), and consequently the obstruent in the /l/-codas, being added sequentially, is also timed later relative to the singleton condition than in the /r/-codas. This interpretation is supported by the strong positive correlation between the V-adjacent and V-remote measures in coda position (compared to only a weak/moderate correlation between these measures in onset position). This suggests that in coda position, timing of the V-adjacent consonant influences timing of the V-remote consonant, all else (e.g., intra-cluster timing) being equal.

Overall, our data show that the liquids do not behave alike with respect to our timing measures. Specifically for the previously proposed perceptual account (Marin & Pouplier, 2010, Katz, 2012), it is difficult to explain why dark and clear /l/, or a clear /l/ and trilled /r/ should pattern differently in coda timing – there is no compelling reason to assume that either one should interfere more with vowel perception that the other. Articulatorily however, an alveolar trill rhotic and a dark /l/ have been shown to share similar tongue configurations, specifically a tongue body lowering and retraction, a configuration different from the tongue body raising and fronting observed for clear /l/ (Proctor, 2009, 2011; Recasens, 2013). Therefore, dark and clear /l/, or clear /l/ and trill /r/ could be distinguished on an articulatory basis. We discuss in what follows why a difference in tongue body gesture may translate into the timing pattern distinctions measured.[5]

Both Katz (2012) and Marin & Pouplier (2010) assume that the acoustic vowel compression effect observed for American English /l/ in the context of increasing coda complexity (in our data: a shorter lag of V-adjacent consonant to anchor) arises due to an increased overlap of the coda lateral with the preceding vowel. Yet neither study has looked at the effects of coda complexity on consonant duration. It is indeed well known that consonants in clusters are of shorter duration compared to their singleton counterparts (e.g., Haggard, 1973a, 1973b), and this factor may provide an explanation for our results. Recall that we are measuring the liquids in terms of the tongue tip constriction only, therefore the duration of the tongue body gesture, to the extent that it precedes the tongue tip constriction (as has been argued for alveolar trills in all positions and for American English /l/ in coda position), factors fully into our coda V-adjacent lag measure. If the tongue body gesture is shortened in the cluster condition, the lag of the tongue tip to the anchor will concomitantly decrease, giving rise to shorter V-adjacent lags just as observed here and in Marin and Pouplier (2010).

Unfortunately, since we have a low vowel context, the dorsal component of the liquids cannot be measured independently of the vowel neither acoustically nor articulatorily, and even in a different vowel context this would present a major methodological challenge, especially for a clear /l/. Therefore we report some duration measurements here in summary rather than in the Results section proper. Comparing tongue tip plateau duration for coda singleton and cluster for the two liquids (ANOVA with factors: Complexity, Liquid, random factor: Speaker), there is a statistically significant main effect for Complexity ($F(1, 4)=20.68$, $p=0.01$), a marginal effect for Liquid ($F(1, 4)=5.07$, $p=0.088$), and a non-significant interaction ($F(1, 4)=0.45$, $p=0.58$). The relevant means and standard deviations are: /l/ mean singleton 46 ms (SD 19.14), cluster 42 ms (SD 17.93), /r/ mean singleton 52 ms (SD 23.25), cluster 45 ms (SD 18.59). Therefore, both consonants shorten when forming part of a cluster, and we can probably assume that both gestures (tip, body) of the consonants are affected by the shortening in parallel. In this case a tongue body gesture timed earlier than the tongue tip, as typical for rhotics but not necessarily clear /l/s (recall also the bigger lag values for Cr clusters in onset) will affect our lag measure such that the tongue tip consistently shifts towards the anchor for /r/ but not /l/ in Romanian. Overall, this strongly suggests that what looks like an increased vowel-rhotic overlap may simply be due to a shortened tongue body gesture with equal vowel duration.

[5] We would like to point out here that the pattern from American English, in which lateral and rhotic codas exhibited a similar acoustic vowel compression effect (cf. Katz, 2012), is compatible with either a perceptual account (both liquids being highly sonorous), or an articulatory account (the rhotic in American English, like the lateral, involves a postdorsal/pharyngeal retraction, cf. Alwan, Narayanan, & Haker, 1997). In contrast, the Romanian data, with the different pattern as a function of liquid type, strongly point to an articulatory basis of the liquid coda temporal pattern. Of course, the fact that articulatory rather than perceptual factors seem to influence the timing of lateral codas, does not imply that perception (and its interplay with articulation) does not shape other aspects of the temporal organization of consonants and vowels (cf. Hoole et al., 2013).

Yet how can this scenario explain the cross-linguistic differences we have reported between American English, German, and Romanian? Note that even though statistically there was no significant difference between lateral and obstruent codas in either Romanian or German, the data still show a shift (cf. Fig. 4 and Pouplier, 2012 Fig. 2), albeit small compared to the one observed for dark /l/ and /r/. What seems to be the relevant difference between dark /l/ and a trill on the one hand and a clear /l/ on the other then is the degree to which the tongue body gesture shortens: If the tongue body gesture involving a large retraction as is typical for dark /l/ and /r/ were shortened to a greater degree in a cluster relatively to the weaker tongue body gesture of a clear /l/, this would explain the results we have observed across languages quite straightforwardly, and no special theoretical account for codas is needed in terms of models of syllable timing. But even if there is no such correlation between the magnitude or nature of the tongue body gesture and its degree of shortening, and even if the tongue body gesture is shortened to an equal degree across liquid types, timing differences between the tongue body and tongue tip gesture could likewise determine the observed results. Gick et al. (2006) show in a cross-linguistic ultrasound study that the timing of the two gestures in coda can be quite different ranging from the well-known American English pattern of the tongue body preceding the tongue tip gesture over Serbo-Croatian with no lag to Korean with the tongue tip preceding the tongue body constriction. This underscores that there are multiple layers of liquid timing which may factor into our results but which we unfortunately are not able to tease apart given our stimuli. Generally, it is quite likely that language-specific timing differences for the liquid gestures will interact with syllable-position specific timing relations. A comprehensive cross-linguistic study on different types of liquids in conjunction with syllable complexity effects is called for. In sum, consonant duration differences conditioned by syllable complexity combined with the articulatory properties of a velarized vs. non-velarized liquid may give rise to the apparent timing differences between a trill or dark /l/ on the one hand, and clear /l/ on the other.

Relatedly, Shaw, Gafos, Hoole, and Zeroual (2011) have previously raised the issue that lag measures of the kind employed here may be affected by consonant duration differences. Specifically, they argue that consonant shortening in word-initial position may result in an apparent onset-like organization for consonants that are actually not parsed as complex onsets in Moroccan Arabic. Crucially for our study however, they show that an onset c-center organization is actually not affected by consonant duration differences: if anything, a shortening in consonant duration in the cluster condition results in an apparently smaller shift towards the vowel than if no shortening had occurred.

Concerning *intra-cluster timing*, the overall results showed that consonants were timed further apart in onset than in coda position, and in rhotic compared to lateral clusters, corroborating previous results from other languages (Byrd & Choi, 2010; Byrd, 1996; Chitoran et al., 2002; Cunha, 2012; Hoole et al., 2013; Pouplier, 2012). Our study adds to the literature by showing that the position effect was carried by the rhotic clusters (larger inter-consonantal lags for /r/ onsets than /r/ codas), and that the liquid type effect was only robust in onset position (larger lags for /r/ compared to /l/ onsets). These are the same conditions where V-remote lag ratios differed as a function of liquid (/r/ onset vs. /l/ onset), suggesting that intra-cluster timing differences are reflected in the relative timing of the V-remote rather than V-adjacent consonant (cf. Pouplier, 2012 for a similar observation for German). Indeed, a strong and significant correlation was observed overall in our data between intra-cluster timing and V-remote lag ratios, but not between intra-cluster timing and V-adjacent ratios. Thus, we can conclude that a smaller or larger intra-consonant lag is reflected in the shift magnitude of the V-remote consonant, but not necessarily in the timing pattern of the V-adjacent consonant. Our correlation analyses showed that V-remote timing in coda varies largely as a function of V-adjacent timing. Not so in onset: here, V-remote timing reflected differences in intra-cluster timing and varied little as a function of V-adjacent timing. This shows that there is a much stronger interaction between C-C and onset-vowel timing than there is between C-C and coda-vowel timing. One the one hand, the basic onset-coda asymmetry in this respect is consistent with the gestural model in which codas are timed locally, but onsets show a global organization. However, the intra-cluster effect on V-remote timing is not yet modeled in the gestural approach to syllable structure. That the V-remote consonant of an onset cluster accommodates intra-cluster timing requirements could be modeled by assigning different bonding strengths between the vowel and the V-remote and V-adjacent consonants of an onset cluster (see Goldstein et al. 2008, for a recent discussion of bonding strength). A careful consideration of production requirements of the consonants involved, together with potential aerodynamic repercussions of different timing relations should provide testable hypotheses for the interaction between intra-cluster and cluster-vowel timing.

No intra-cluster timing difference as a function of voicing of the non-liquid consonant was found in our data, as expected given the French pattern (Bombien & Hoole, 2013; Bombien, 2011) and given that the two languages realize the phonological voicing contrast in the same manner.

In summary, Romanian liquid onsets exhibited overall the timing patterns predicted by a c-center organization. Liquid codas confirmed the predictions we made on the basis of previous results from other languages. Thus, /l/-codas showed a temporal organization similar to obstruent codas, to German lateral codas, and different from American English lateral codas. For /r/-codas, an increased shift of the rhotic towards the vowel was observed as coda complexity increased, similar to the pattern observed for American English lateral codas. We propose that this temporal shift reflects differences in articulatory organization between dark and clear liquids, in conjunction with duration changes conditioned by coda complexity. The results suggest that the lag measures are insufficient as diagnostics for syllabic organization unless the timing and duration of all gestures involved is taken into account.

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Appendix

List of stimuli embedded in carrier phrases, given in Romanian orthography (*c*=/k/, ce=/tʃe/, ș=/ʃ/, ț=/ts/, ă=/ə/).

PL-	Zic pa plac/pap lac așa. I say bye liking/I eat (a) lake like this.
BL-	Spuneam cu blat/cub lat așa. I was saying with (a) sheet/wide cube like this.
ML-	Zic ca mlaștina/cam laștina așa. I say like the swamp/rather/non-word] like this.
FL-	Zic pa flama/paf lama tare. I say bye the flame/poof the blade loudly.

KL-	Zic pa clamă/pac lamă tare. I say bye hair-pin/bang blade loudly.
GL-	Zic ba glas/bag las așa. I say indeed voice/I insert I let like this.
PR-	Zic pa prag/pap rag așa. I say bye threshold/I eat I yell like this.
BR-	Spun cu brad/cub rad așa. I say with fir-tree/cube I shave like this.
MR-	Zic ca mranița/cam ranița mereu. I say like the manure/rather the back-pack always.
KR-	Zic pa cramă/pac ramă tare. I say bye wine-cellar/bang frame loudly.
GR-	Zic ba gras/bag ras așa. I say indeed fat/I insert (a) shaving like this.
-LB	Citeam colb are/col bare bine. I was reading dust (s)he has/cervix rods well.
-LM	Ziceam calm are/cal mare bine. I was saying calmness (s)he has/big horse well.
-LF	Zic golf ace/gol face așa. I say golf needles/naked (s)he does like this.
-LK	Ziceam calc are/cal care bine. I was saying copy-paper (s)he has/horse which well.
-LG	Zic mulg as/mul gaz bine. I say I milk (an) ace/mule gas well.
-RP	Spuneam corp are/cor pare bine. I was saying body (s)he has/choir it seems well.
-RB	Spuneam corb are/cor bare bine. I was saying raven (s)he has/choir rods well.
-RK	Zic parc are/par care mereu. I say park (s)he has/pole which always.
-RG	Spun murg as/mur gaz bine. I say dark horse ace/bluberry bush gas well.

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