Articulatory coordination in obstruent-sonorant clusters and syllabic consonants: Data and modelling

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Abstract

The first of two studies in this paper (both using electromagnetic articulography) focused on onset clusters in German and French. Less overlap of C1 and C2 was found in plosive-nasal and plosive-rhotic clusters compared to plosive-laterals. Articulatory modeling was used to identify why the preferred coordination patterns are acoustically advantageous, and implications for metathesis and other diachronic processes are discussed. The second study analyzed the syllabic consonants /l/ and /r/ in Slovak. These consonants did not become kinematically more 'vocalic' in nuclear compared to marginal position. However, nuclear consonants preferred low-overlap coordination with the preceding consonant, compared to onset clusters and to vocalic syllables. We suggest that a low overlap setting favours the emergence of syllabic consonants.

1. Introduction

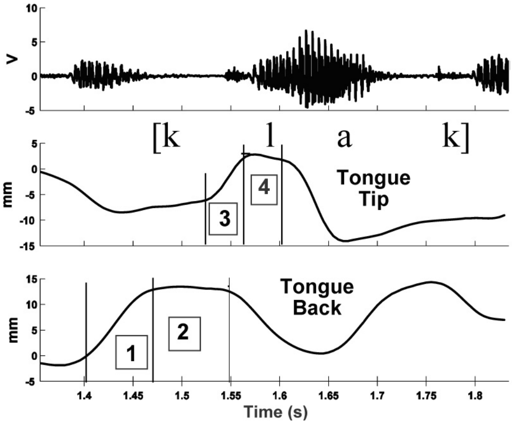
We consider two areas in which rhotics have proved fruitful for arriving at a better understanding of principles of articulatory coordination in consonant sequences. Both studies are based on recently-acquired articulatory (EMA) data. For the first area we look at onset clusters consisting of plosive plus lateral, nasal, or rhotic in German and French. The overall goal is to understand why these obstruent-sonorant clusters differ synchronically in their frequency of occurrence across languages (and differ in diachronic stability). The second area focuses on syllabic consonants (lateral and rhotic) in Slovak, seeking, in a rather similar vein, to understand why syllabic consonants are typologically rare, and, concomitantly, what factors may favour their emergence when they do occupy a prominent position in the sound structure of a language, as is the case in Slovak. Since for the syllabic consonants we focus in particular on their coordination with adjacent consonants there are substantial superficial similarities in the kinds of sounds sequences examined in both parts of the paper. And both parts are united at a less superficial level in that they aim for a better understanding of general principles of coordinating consonant with consonant and consonant with vowel, and how these principles are affected by position in the syllable and the segmental make-up of the sound sequences involved (for more background to our overall approach see e.g. Pouplier 2012).

2. Obstruent-sonorant clusters in German and French

In this section we first review earlier work in which we compared clusters such as /kl/ and /kn/, and then move on to more recent analysis of plosive-rhotic clusters.

2.1 Plosive plus lateral and nasal

The earlier findings (e.g. Hoole et al. 2009; Bombien et al. 2010; Bombien et al. submitted) revealed a consistent pattern of less articulatory overlap between C1 and C2 in German clusters such as /kn/ compared to /kl/.



Overlap (normalized%)=((Offset_2-Onset_4)/(Offset_4-Onset_2))*100
More positive values indicate more overlap of Phase 2 and Phase 4

Figure 1 – Illustration of measurement of articulatory overlap using EMA data. Top panel: audio; middle panel: vertical component of tongue-tip movement; bottom panel: vertical component of tongue-back movement. Phases 1 and 3 extend from onset of movement towards consonant target up to attainment of target position; both time points are based on a 20% velocity criterion. Phases 2 and 4 delimit the target plateau region. In the formula for overlap calculation 'Offset_2' refers to the time point of the right boundary of Phase 2 (analogously for other time points).

Fig. 1 illustrates how these measurements were carried out using EMA sensors (Carstens AG500 articulograph) located on tongue-tip (indexing constriction for /l/ and /n/) and tongue-dorsum (indexing constriction for /k/).

Various overlap measures have been suggested in the literature. The one used here is based on onset and offset of the target plateau regions for C1 and C2. If (Offset_2 - Onset_4) in the formula is positive this indicates that the articulatorily defined constriction for C2 has been reached before the constriction for C1 has been released. If this difference value is negative (actually the normal case in our data) this indicates a lag between the end of C1 constriction and the beginning of C2 constriction. To account to some extent for differences in speech rate between utterances and subjects the values are normalized by the total duration of the constriction phases (i.e. by the difference in time between the offset of C2 and the onset of C1).

The finding of a low degree of overlap in /kn/-clusters is probably to be explained by the fact that premature lowering of the soft palate for /n/ would destroy the acoustic characteristics of the /k/-burst. This interpretation has been confirmed by modelling work using TADA (Nam et al. 2009). TADA is an articulatory synthesis application based on task dynamics and the coupled oscillator model of syllable structure. It allows gestural parameters to be systematically modified, with the final synthesis being performed by generating control parameters for the pseudo-articulatory synthesizer HLSyn (Hanson & Stevens 2002). The connection with HLSyn is particularly interesting in this case, because HLSyn also synthesizes the pressures and flows in the vocal tract resulting from the articulatory input specification. Accordingly, it was possible to observe that when a plosive-nasal cluster is synthesized with TADA's default coordination relations then the intraoral pressure declined prematurely during the plosive because of nasal leakage, resulting in an absence of a burst at the articulatory release of the plosive. By using a low-overlap coordination topology originally suggested by Goldstein et al. (2009) to capture the difference between so-called homogeneous (high overlap) and non-homogeneous (low-overlap) clusters in Georgian the air-pressure trace became more typical of a plosive. However, for a completely satisfactory result it was also necessary to adjust the gestural parameters of the velar gesture itself (rather than just globally adjusting the overlap between C1 and C2) to ensure that it made a sharp transition from closed during oral closure for the plosive, to open for the following nasal. Thus it seems that plosive-/n/ clusters may be plausibly regarded as physiologically costly.

Fig. 2 compares the air-pressure traces resulting from the default and the 'tuned' coordination parameters when synthesizing a [pn] consonant sequence (preceded and followed by a vowel). The key points to notice are that in the curve labeled 'untuned' the peak air pressure is not quite as high, and also does not maintain a plateau after reaching its maximum at about 100 ms on the time axis. Since labial closure is not released until about 150 ms this indicates nasal leakage of air in the untuned case.

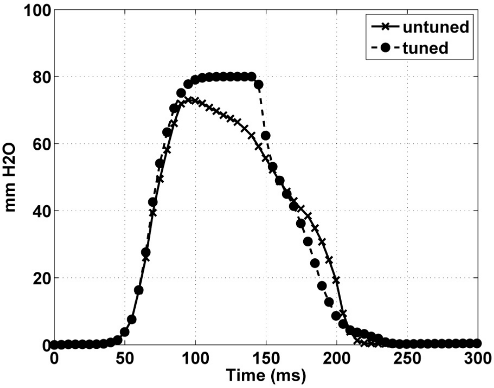


Figure 2 – Intraoral airpressure in synthesized /pn/ sequence comparing standard coordination parameters ('untuned') with adjusted ones ('tuned').

Overall, these results fit well into our guiding hypothesis that 'successful' clusters (/kl/ is clearly diachronically more stable than /kn/) are those that offer a good compromise between parallel transmission of segmental information (efficient production) and adequate recoverability in perception (cf. Chitoran et al. 2002), i.e. key acoustic features of /kl/ would be maintained even at high overlap, whereas /kn/ would suffer from reduced perceptibility due to impairment of burst characteristics from nasal air leakage.

2.2 Plosive-rhotic clusters

More recently, we have compared the onset clusters /pl, bl/ with /pr, br/ (and also /fl/ with /fr/) for five speakers of French and four of German[1]. The basic procedure remains as in Fig. 1, except that now a sensor on the lower-lip is used to analyze articulatory activity for C1, and, since all speakers produced a dorsal /r/ the tongue-back sensor was used to analyze C2 in the /r/-clusters. The plosive-rhotic clusters are of interest precisely because it is not immediately

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[1] We will be using /r/ as a phonemic symbol to indicate what was in fact a dorsal articulation in the uvular region: approximant or voiced fricative following voiced C1, usually voiceless fricative following voiceless C1. A fifth German speaker who produced an apical variant was left out of consideration here. Obviously, a systematic comparison of apical and dorsal rhotics would be an interesting task for future work.

clear what overlap pattern to expect. On the one hand, based on sources such as Vennemann (2000, 2012) there seems no reason to assume that /r/-clusters are disfavoured compared to /l/-clusters (if anything, the reverse). On the other hand, there are well-documented cases of instability involving r-clusters, namely metathesis such as the following[2]:

1. French, standard vs. dialectal: *premier*: /pʁœmje/ vs. /pɛʁmje/ (from Russell Webb & Bradley, 2009);
2. Germanic: *hross* (Icelandic) vs. *horse* (rhotic English dialects);
3. English, standard vs. dialectal: *pretty* vs. *perty*.

In fact, there was a very consistent result of ***lower*** overlap in the /r/-clusters compared to the /l/-clusters (see Fig. 3).

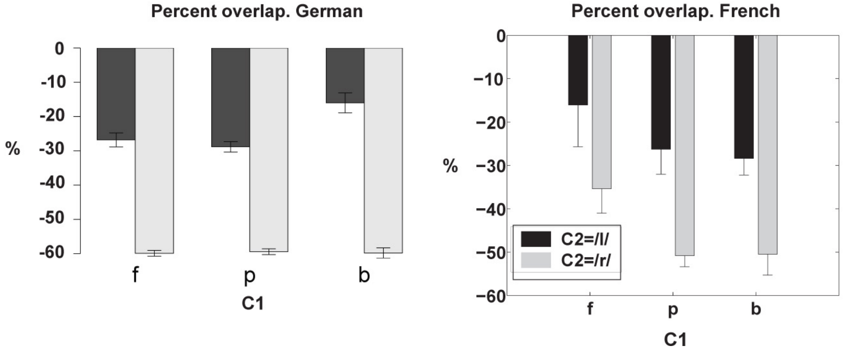

Figure 3 – Articulatory overlap in onset clusters /fl, fr, pl, pr, bl, br/ (from left to right in each panel). Overlap computed as illustrated in Fig. 1: for /l/-clusters overlap of lip and tongue-tip; for /r/-clusters overlap of lip and dorsum. Averaged over 4 speakers of German and 5 speakers of French. More negative values indicate less overlap. Error bars indicate standard error of mean over speakers.

The examples of metathesis just mentioned would emerge rather naturally from low overlap between the consonants of the onset cluster, particularly if this were accompanied in turn by a high degree of overlap between the rhotic and the following vowel. This would indeed be a prediction of the c-center principle of coordination identified by Goldstein et al. (2009): as the number of elements

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[2] A reviewer suggested that these examples might be better captured by vowel insertion before the rhotic followed by deletion of the original post-rhotic vowel, rather than metathesis in the traditional sense. Such a scenario would fit in equally well with the patterns of gestural shift and the link between gestural overlap and vowel epenthesis that we discuss below. The label attached to these examples is less crucial than the basic point that the seeds of change and instability may be found in specific coordination relations.

in the onset increases the left edge of the onset moves to the left and the right edge to the right leaving the center of the onset in the same position relative to an anchor point in the vowel, regardless of the number of elements in the onset. Extending this to the present case, a complex onset with a low degree of overlap should show a particularly pronounced right shift of the rightmost consonant over the vowel compared to a control simple onset condition[3].

Currently, only a rather small subsection of our corpora is suitable for testing this prediction because we require target items that contrast simple and complex onsets but have the same nucleus vowel and coda (in practice the formation of consonantal closure for the coda usually provides a kinematically better-defined anchor-point than a time-point in the vowel). Thus the test is not as rigorous as we would like. Fig. 4 shows the results for the items that we were able to select from the German and French corpora, namely *tat* vs. *trat* for German and *bac* vs. *braque* for French.

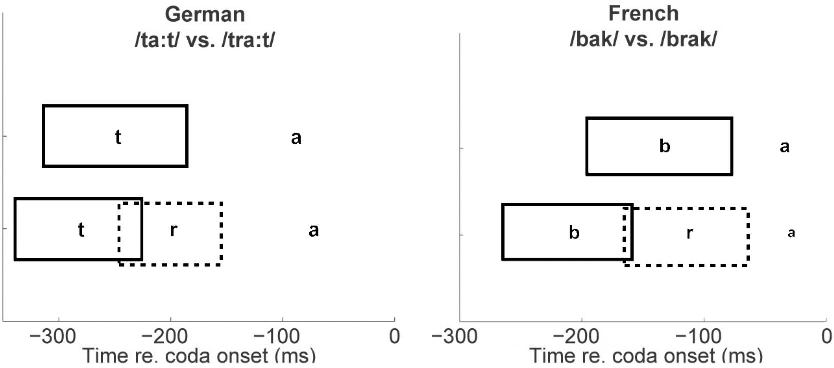

Figure 4 – Timing of syllable onsets with and without rhotic relative to common anchor point in coda consonant, i.e. relative to achievement of /t/ constriction target for German (left) and of /k/ constriction for French (right).

The German data basically show the pattern expected from the c-Center hypothesis: the right edge of the complex onset (i.e. the right edge of /r/ in /tra:t/) is further to the right than the right edge of the simplex onset (/t/ in /ta:t/). However, in marked contrast, for the French data the right shift of the right edge is very weak, whereas the left edge of the onset (i.e. the left edge of the /b/) shifts substantially to the left. This is not the pattern that would be expected

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[3] Russell Webb & Bradley (2009) take this line of thought even a step further by simply assuming in their optimality theory account of metathesis that the centre of the rhotic is coordinated with the centre of the vowel.

if we want to argue for a particular affinity between the rhotic and the vowel. Given these mixed results, it would clearly be premature at this stage to claim that this kind of metathesis is accounted for by a particularly strong propensity of the rhotic to overlap the following vowel (with the potential for a categorical diachronic shift in position). Nevertheless, it would clearly be interesting to follow up this line of analysis with a new corpus that is purpose-designed to provide appropriate anchor points. It is also worth noting here a further prediction that emerges from the contention that metathesis is related to the degree of consonantal overlap: based on the results shown in Fig. 3 it should be less common in clusters with lateral than in clusters with rhotic[4]. Currently we are not aware of any quantitative data from the sound-change literature that allows this question to be answered[5].

Even though the articulatory patterns found in rhotic clusters were not necessarily the ones initially expected we have recently been able to use articulatory synthesis to gain some further insight into why speakers appear to avoid high overlap in these clusters. For this we used the VocalTractLab package (Birkholz 2012; Birkholz et al. 2006). As a point of departure we used gestural timing parameters that would give a reasonable approximation to the German syllable onset /br/ as in *brat*. The overlap between the onset consonants was then increased by 50 ms. The most striking result was that the duration of voicelessness following release of the /b/ increased substantially (sounding perceptually more like /pr/ than /br/), even though no changes were made to the synthesis control parameters directly related to voicing. This indicates that a dorsal constriction in the velar or uvular region results in aerodynamic conditions that are very unfavourable to restarting voicing (German /b/ is essentially voiceless during the labial closure) if it follows very shortly after the labial release. This illustrates quite elegantly how supraglottal coordination can have repercussions on the realization of the voicing contrast.

Fig. 5 illustrates these results by showing the sonagrams for the normal and high-overlap condition.

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[4] See Yanagawa (2003) for an illustration of how constraints on gestural overlap and cohesion may underlie certain metathetic processes in Hebrew.

[5] There may well, however, often be a higher rate of apparent vowel epenthesis in rhotic than lateral clusters. This is discussed in detail in section 2.3 below.

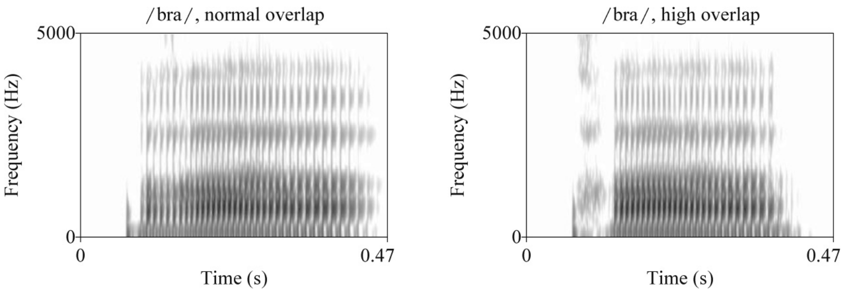

Figure 5 – Comparison of acoustic output for onset consonants of syllable /bra/ synthesized with normal overlap (left) and high overlap (right). Note greater duration of voicelessness after /b/ release in right panel.

2.3 Articulatory coordination in onset clusters: Implications and further discussion

We believe that the analysis of articulatory coordination presented in the preceding sections can throw useful light on the phonological processes apparently affecting these clusters. For example, based on some interesting acoustic observations of stop+lateral and stop+rhotic clusters in French Colantoni & Steele (2007, 2011) point to the particular prevalence of vowel epenthesis in voiced stop+rhotic sequences. Epenthesis is much rarer in voiced stop+lateral sequences and virtually non-existent in voiceless stop+rhotic sequences[6]. The latter in turn are claimed to be particularly affected by a process of voicing assimilation since devoicing of the liquid is stronger in voiceless plosive+rhotic than in voiceless plosive+lateral. We feel, however, that there are grounds for caution if the claim is that e.g. /br/ and /pr/ are affected by radically different processes, at least if a process such as epenthesis is to be interpreted as a cognitive operation on the phonological representation (with the aim, in Colantoni & Steele's terms of cluster 'simplification' or 'repair'). Looking back to Fig. 3 it is clear that the articulatory overlap between C1 and C2 is very similar for the voiced/voiceless pairs /br/ and /pr/. To us, this immediately reduces the attractiveness of assuming epenthesis just for the first case but not the second. The introduction of a vocalic element between two consonants should clearly affect the observable coordination relations between these consonants (assuming epenthesis in both cases, with the epenthetic vowel invariably voiceless in /pr/, might be a logical possibility but nonetheless not particularly attractive or useful).

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[6] Colantoni & Steele (2007, 2011) also discuss Spanish, where the situation is different: i.e. apparent epenthesis following both voiceless and voiced stops. Probably language differences in apicality vs. dorsality are relevant here.

Essentially, we would argue that /br/ and /pr/ have a very similar gestural specification in terms of the coordination of C1 and C2. Whether an epenthetic vowel appears at the acoustic surface is simply a side-effect of the voicing properties of C1 and does not require an account in terms of phonological processes. (This idea of epenthetic vowels as a side-effect of voicing patterns is supported by the informal observation that they are much less obvious in German /br/ than French /br/: phonologically voiced plosives are indeed fully voiced in French but usually substantially devoiced in German so the strength of voicing in the period immediately following /b/ will be much weaker in German, weakening in turn any impression of a vocalic transitional element.) Note that Colantoni & Steele's observation of a weaker tendency to epenthesis in the lateral clusters also fits in well with our overlap measurements: i.e. the higher overlap for lateral than rhotic clusters. The crucial question is then what drives the low overlap in rhotic clusters. We indicated above one direction that an explanation could take: dorsal constrictions may be particularly unconducive to voicing (e.g. Ohala 1993; see also Colantoni & Steele 2011); accordingly, reducing the amount of overlap reduces the chances of an inappropriate amount of voicelessness at the release of a phonologically voiced consonant. Note that we assume that this could apply equally to German and French voiced stops despite their clear phonetic differences: excessive overlap may result in a delay in re-initiation of voicing after devoiced German /b/, but also in interruption of voicing of normally continuously voiced French /b/. A corollary of this line of thought also explains Colantoni & Steele's further observation of the particularly extensive devoicing of /r/ in /pr/: even if French is traditionally regarded as not having long VOT in voiceless stops the glottal conditions at the release of /p/ are certainly not favourable to voicing, and probably remain so over the transitional period until the formation of constriction for /r/. Since voicing is well-known to show a hysteresis effect in the sense that conditions for initiating voicing are more stringent than those necessary to maintain ongoing voicing (e.g. Hirose & Niimi 1987) then once voicing has ceased at the onset of /p/ re-initiation is not possible until the dorsal constriction has substantially weakened at the offset of /r/. This means that the low overlap between rhotic and plosive can on the one hand make it easier to maintain (or re-start) voicing for voiced C1 but also result in a particularly long period of voicelessness once voicing is interrupted for voiceless C1. Once again we would argue that the devoicing of /r/ in /pr/ does not require an explanation in terms of phonological processes but is, to a first approximation, a simple coarticulatory effect of the devoicing gesture of the initial C1 in combination with the effect of a dorsal constriction on aerodynamic conditions in the vocal tract[7].

3. Syllabic consonants in Slovak

This second main section continues very much in the vein of the first, since it will again provide evidence that an understanding of the emergence and development of sound patterns can depend crucially on an understanding of the patterns of articulatory coordination involved.

As already mentioned in the introduction, the overall aim of the work in this section was to arrive at a better understanding of why the occurrence of syllabic consonants is highly restricted. This can be understood as part of the ongoing aim of ourselves and others to understand how sounds are modified and their coordination patterns change depending on their role in the syllable. Many investigations have compared consonants in onset vs. coda position; here we now look at consonants in nucleus position based on work carried out by Pouplier & Beňuš (2011). This leads to a number of more specific questions along the following lines:

- To what extent do syllabic consonants become more vocalic?
- How does coordination of two consonants differ for example, when both are in the onset versus when one is in the onset and one in the nucleus?
- Does onset-nucleus timing depend on whether the nucleus is vocalic or consonantal?

The basic research strategy is to exploit a language such as Slovak in which the occurrence of syllabic consonants is actually quite unrestricted. In addition to the fact that specifically /l/ and /r/ occur in nucleus as well as onset and coda position, these syllabic consonants are – unlike English, German etc. – not restricted to unstressed syllables and can themselves take complex onsets (as in words like *smrt*, with nucleus /r/). Moreover, they are fully integrated into the Slovak morphology of nucleus length alternations (see Pouplier & Beňuš 2011, for further details on the linguistic background).

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[7] We use the proviso "to a first approximation" because, extrapolating from our earlier work on German using laryngeal fiberoptic endoscopy and transillumination (Hoole 2006), we expect there to be subtleties to glottal coordination in clusters that we are not yet able to do justice to in French. This work is currently in progress. For more background to the general idea of coarticulatory devoicing see e.g. Browman & Goldstein (1986).

3.1 Recordings

Basically the same EMA setup was used as for the experiments described in Section 2 above (sensors on tongue, lips, jaw). Five Slovak speakers participated. Six repetitions of each target word were recorded per speaker. Target words were embedded in the carrier phrase: *Už hovoríme* ________ *hodinu*. Examples of the target words are given in each analysis section below.

Two main sets of analyses were performed. First, the basic kinematic properties of the liquids were examined as a function of position in the syllable; second, analyses of articulatory coordination similar to those exemplified already in Fig. 1 were carried out.

3.2 Basic kinematic properties of /l/ and /r/

The main thrust of this group of analyses was to determine whether the liquids became in any sense more vocalic when they formed the nucleus (as opposed to onset or coda). In terms of kinematic measurements this was defined as an expectation for longer durations, lower velocities and lower stiffness (ratio of amplitude to peak velocity) in nucleus position.

The following list shows the words used to compare the kinematic properties of the three syllable positions (upper case L is used here and in Table 2 below to indicate a liquid nucleus).

Onset **C**VC: *lak, lob; rak, raky, rok*
Nucleus C**L**C: *chlp, blb; mrk, krk, krb*
Coda CV**C**: *kal, mol; bar, ker, mor*

Table 1 shows results averaged over the five speakers. For brevity, only duration of the consonantal constriction phase (‘plateau duration’; this corresponds to Phase 4 in Fig. 1) and peak velocity are shown here. The velocity measure is based on the closing movement.

		onset	nucleus	coda
plateau duration (ms)	/l/	53.3 (12.8)	49.6 (27.0)	40.5 (13.7)
	/r/	15.3 (8.3)	27.7 (15.4)	19.4 (12.2)
peak velocity (cm/s)	/l/	31.8 (15.0)	24.1 (8.8)	35.1 (13.1)
	/r/	39.4 (13.0)	45.4 (11.9)	51.7 (14.2)

Table 1 – Mean (and standard deviation) plateau duration and peak velocity for /l, r/ as a function of syllable position.

The basic point to observe is that there is no consistent pattern distinguishing nucleus from onset and coda; the nucleus is not consistently longer and does not have lower peak velocity than the marginal positions. If only onset and nucleus are compared then there are no patterns that are consistent across both consonants. Thus at this level of analysis it does not seem that liquids take on more vocalic properties when they form the syllabic nucleus: syllabic consonants are kinematically speaking still consonants (the results given here are representative of the other measures as well, see Pouplier & Beňuš 2011 for details).

3.3 Articulatory coordination

Articulatory coordination will be examined from two complementary points of view, firstly in terms of consonant-consonant coordination (comparing pairs where one member of the pair contains the nucleus and one does not), and secondly in terms of onset-nucleus coordination (comparing consonantal versus vocalic nuclei with the same onset).

3.3.1 Consonant-consonant coordination

For this analysis pairs such as ***mr**ak* vs. ***mr**k* (onset cluster vs. onset+nucleus) and *pa**rk*** vs. *m**rk*** (coda cluster vs. nucleus+coda) were examined (target consonant sequence highlighted in boldface). Coordination between the consonants was captured by a measure that we will refer to as plateau lag, corresponding to the timepoint of the onset of Phase 4 minus the timepoint of the offset of Phase 2 in Fig. 1. The results are given in Table 2.

		PLATEAU LAG (MS)	
		/l/	/r/
ONSET	onset cluster (CC-)	50.2 (20.5)	83.7 (16.2)
	onset-nucleus (CL)	64.4 (19.1)	90.2 (16.5)
CODA	coda cluster (-CC)	23.9 (17.8)	27.1 (19.0)
	nucleus-coda (LC)	32.3 (15.5)	40.8 (13.2)

Table 2 – Mean plateau lag (and SD) for consonant-consonant sequences differing in syllable position.

Please note that since this table shows a lag measure (rather than the overlap measure used in Section 2) larger (more positive) values indicate a wider spacing between the consonants (i.e. ***less*** overlap). The main result to note is that the lag is greater (overlap is less) when the liquid is in the nucleus, i.e. CL and LC versus CC- and -CC, respectively. The other main result, which in fact is numerically stronger than the first result, is that lags are greater in onset than in coda position (i.e. compare the first two rows to the bottom two data rows of the table). In traditional phonetic terminology this means that CC transitions are more open (in the sense of Catford 1977) to the left of the nucleus. Note that this applies not just to the comparison of onset clusters vs. coda clusters (comparing data rows 1 and 3 of the table) but also to the comparison of onset+nucleus vs. nucleus+coda (data row 2 vs. 4). For standard syllables with a vocalic nucleus it has become almost a commonplace observation in recent years that syllable structure is expressed in typical coordination relations among the structural elements of the syllable. The above two results make the important point that this also applies to syllables with a consonantal nucleus, i.e. these syllables, too, have internal structure: words like *mrk* are not just a simple concatenation of C+C+C[8]. Putting this another way: for any given sequence of consonants in Slovak the precise coordination relations among adjacent consonants will depend on the structural position in the syllable to which each consonant is assigned.

3.3.2 Onset-nucleus coordination

The second set of coordination analyses compares words such as *blb* (lateral nucleus) with words such as *bib* (vocalic nucleus). Preliminary examination indicated that articulatory movement for the vowel could be more reliably captured in terms of time of peak velocity of the movement towards the vowel (rather than in terms of the time of attainment of a constriction plateau), so a new lag measure was defined as timepoint of peak closing velocity for nucleus minus timepoint of peak closing velocity for onset consonant. The results of peak velocity lag for the different nucleus types averaged over speakers were as follows (mean +/- standard deviation, in ms):

Vowel	82.5 +/- 23.7
/l/	106.4 +/- 16.4
/r/	151.9 +/- 10.2

Lag values are shortest for the vocalic nuclei. Note, though, that there are also clear (and statistically significant) differences between the rhotic and the lateral nuclei. As in Section 2 (and as just pointed out in footnote 8) the rhotics show particularly high lag (low overlap).

The consonant-consonant coordination results indicated that syllables with

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[8] It is perhaps interesting to point out a similarity with Section 2 here: lags are generally greater for the rhotics than the laterals (especially in onset position). Note that this is the case even though the rhotics are apical in Slovak but dorsal in German and French.

consonantal and vocalic nuclei have similar internal structure. The present results for onset-nucleus coordination make clear that coordination patterns for consonantal and vocalic nuclei are nevertheless not necessarily identical.

3.4 Syllabic consonants: Discussion

As part of the general discussion of the Slovak results we will now try to offer some ideas as to what could be driving the low-overlap coordination pattern for the consonantal nuclei.

Useful background is given by the assumption in much work in articulatory phonology and coupled-oscillator models of syllable structure that onset consonants are timed in-phase with the following vowel (in effect, their activity starts at the same time). In normal CV syllables this does not result in the vowel being obscured by the consonant because the vowel has longer duration (lower stiffness). For the Slovak syllables with consonantal nuclei this would be a problem, however, because as we saw in the first part of the results consonants in nucleus position do not have clearly different durational properties from those in marginal positions. Thus for the onset C and the nucleus C to be reliably recoverable by the listener a low-overlap pattern of coordination is required. This links up in turn with ideas in the first part of the paper: one reason for the typological rarity of syllabic consonants may be that they require a departure from default CV coordination patterns. Put slightly differently, syllabic consonants interrupt the basic construction principle for spoken language of a slow continuous vocalic substrate with overlaid consonantal constrictions.

We believe that one reason why these typologically rare patterns were able to emerge in Slovak is that the language in general favours a low-overlap setting for consonant-consonant coordination. Thus while the values for plateau lag for onset clusters shown in the first data line of Table 2 are shorter than those for the onset+nucleus case (in the second line of the table) they are nevertheless still quite long in absolute terms, ‘long’ meaning that it is very typical in Slovak to find a sonorant transition (‘epenthetic schwa’) between C1 and C2 (see Pouplier & Beňuš 2011, for further details and illustrations).

4. Conclusions

The two main parts of this paper have both tried to make the point that understanding how sound systems develop crucially requires an understanding of how the various articulatory subsystems are coordinated by the speaker. Combining articulatory measurements with articulatory modeling helps in turn to better understand what coordination patterns result in sound structures that can reliably be recovered by the listener in perception. Rhotics, and liquids in general, are particularly advantageous in these contexts because complex syllable structures make such heavy use of them.

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