Phonological Structure and Articulatory Phonetic Realization of Syllabic Liquids

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Abstract: Syllabic liquids, such as /l/ or /r/ in Slovak words such as vlk ("wolf") or krb ("fireplace"), occur freely in stressed positions and with complex onsets. Phonologically, they behave like vowels, which can be seen in several morpho-phonological alternations. The paper addresses two questions: how a phonetic consonant with a significant obstruction in the vocal tract can function phonologically as a vowel, and why liquids are cross-linguistically more marked syllable nuclei than vowels. Previous proposals suggested that the syllabicity of liquids relates to their coordination patterns: liquids in the nucleus position require so-called "open transition," which facilitates the recoverability of the consonants adjacent to the syllabic liquid. Here we extend this research by examining the differences between the two articulatory liquid gestures: consonantal tongue tip raising and vocalic tongue dorsum retraction. Our articulatory data suggest that the coordination of the vocalic liquid gesture with the consonantal onset gesture also facilitates the syllabicity of Slovak liquids.

Keywords: syllabic liquids; articulation; phonetics-phonology relation

1. Introduction

The syllable is a basic organizational unit of speech. This applies to many levels of the cognitive system underlying human speech, such as speech planning: e.g., research on speech errors (Fromkin 1971; Shattuck-Hufnagel 1979), speech production (review in Krakow 1999), or speech perception (Mehler et al. 1981; Cutler et al. 1986). The syllable also formalizes the fundamental insights into the differences between consonants and vowels and their functions. More specifically, vowels always appear in the syllable nucleus position, while consonants mostly occupy the syllable edges, i.e., onsets and codas.

Additionally, consonants in the pre-vocalic onset positions were found to differ systematically from the same consonants appearing post-vocally in coda positions (Krakow 1999), and this applies particularly to sonorant consonants. Sonorants commonly consist of two articulatory gestures: one of these gestures is more "vocalic" and the other is more "consonantal." For example, English has two basic allophones of /l/: one appearing in the onsets, where it is so-called "clear," and another which is possible only in the coda position, the so-called "dark" /l/. This allophonic difference has been described as a difference in coordination between the two articulatory gestures of /l/: tongue tip raising and tongue dorsum retraction (Sproat and Fujimura 1993). While the two gestures are timed roughly synchronously in the onset position, in the coda tongue body retraction precedes tongue tip raising. Other sonorants, such as nasals (Krakow 1999), glides, or /r/ (e.g., Gick 2003), have also been shown to have two gestures and their timing to function similarly in terms of their syllabic affiliation.

In addition to these differences in coordination, one of the fundamental insights of articulatory research into syllables is that the coordination of onsets and codas with respect to vowels as syllable nuclei is also different. The beginning of the articulatory movement toward forming the onsets consonant tends to be timed roughly synchronously with the beginning of the vocalic movement. Additionally, the temporal midpoint of the onset as a whole (whether it is a singleton consonant or consonantal cluster) exhibits little variability in its timing in relation to the vowel. This notion has been called the c-center effect (e.g., Honorof and Browman 1995; Goldstein, Chitoran, and Selkirk 2007; but see also Marin and Pouplier 2010). It was further suggested that the consonants in the onset are underlyingly coordinated simultaneously, and perceptual recoverability dictates their surface order (Browman and Goldstein 2000). Contrary to the synchronous nature of timings associated with the left edge of the syllable, coda consonants exhibit asynchronous timing both with the preceding vowel and between each other when in a cluster. These results of experimental studies, as well as dynamic modeling, have been taken as supporting the view that syllable onsets have greater phonetic and phonological stability of syllables than codas do.

Hence, vowels in the syllable nucleus position seem to form the basis for articulatory coordination. This applies both intra-syllabically, given the differential coordination of onsets and codas with the vowel, as well as inter-syllabically, given the basic rhythmic coordination that takes place between adjacent vowels relatively independently of the intervening consonants, commonly referred to as vowel-to-vowel coordination (Fowler 1983).

Given the strong link between syllabic affiliation on the one hand and consonants and vowels on the other hand, it is hardly surprising that the phonological difference between consonants and vowels is one of the strongest universals observable in all languages. However, this strong link may also be considered a confounding factor supporting the view that the differences between vowels and consonants are solely attributable to the differences in their syllable affiliation. Since the variability of affiliation (onset and coda vs. nucleus) varies, as does the nature of the sound (consonant vs. vowel), one of the ways of illuminating this issue is to control one dimension and vary the other one. Vowels cannot form syllable edges, and we thus cannot compare syllables in the nucleus and edge positions. Nevertheless, consonants can form both the edges and the nuclei of syllables. Cross-linguistically, the most common syllabic consonants are sonorants.

Syllabic liquids, such as /l/ or /r/, are not particularly rare cross-linguistically. For example, Bell (1978), surveying 182 languages of the world, reported that 46% of them have some syllabic consonants, and of these, there are twice as many languages with syllabic sonorants as those that also have syllabic obstruents. However, in many languages that have syllabic sonorants, they are significantly restricted to occurring predictably in certain phonotactic contexts and prosodically weak (unstressed) syllables (Bell 1978), which happens, for example, in English or German. These restrictions most plausibly arise from the phonetic differences between vowels and consonants mentioned above.

1.1 Slovak Syllabic Liquids

Slovak is a West Slavic language with two basic syllabic liquids: dental-alveolar lateral /l/ and apical trill /r/. Similarly to many other Slavic languages, Slovak exhibits relatively minor restrictions in the distribution of syllabic liquids. In Slovak, strong phonological evidence suggests that syllabic liquids behave phonologically in a manner identical to vowels. First, they occur in monosyllabic words such as *vlk* ("wolf") or *krb* ("fireplace") and can thus freely form stressed syllables. Furthermore, they can occur in syllables with complex onsets, e.g., *smrť* [smrc] ("death") or *stlč* [stltʃ] ("beat" – imperative), and can have a maximum of three onset consonants, *štvrť* [ʃtvrc] ("quarter"), and two coda ones, *krst* ("baptism"). Moreover, since vowel duration is phonemic in Slovak, liquids in the syllable nucleus position can also be short or long.

The most convincing evidence for the identical phonological behavior of syllabic consonants and vowels comes from several morpho-phonological alternations, including the so-called rhythmic law (e.g., Kenstowicz and Rubach 1987), in which syllabic nuclei change their phonemic length either by shortening or lengthening (Pouplier and Beňuš 2011). These phonological processes take place irrespective of the nature of the syllabic nuclei; they target vowels and liquids alike, thus putting these two phonetically quite different types of sounds into a natural class. A subset of these alternations taken from Pouplier and Beňuš (2011) is shown in (1); acute accents denote phonemically long nuclei and apostrophes or "hačeks" denote palatal consonants. The first two lengthening alternations (1a)–(1b) and the third shortening one (1c) show the data for syllabic consonants in the leftmost two columns and the same alternations with vocalic nuclei in the rightmost two columns. These nuclei are targets for the processes. The rhythmic law data in (1d) show that the stem-final nuclei, whether consonantal or vocalic, are the triggers for the length of the suffix vowels: the long stem-final nucleus triggers the shortening of the suffix vowel.

(1) (a) Lengthening in genitive plural

srn-a (deer)	*sŕn*	*ran-a* (wound)	*rán*		
jablk-o (apple)	*jablĺk*	*bral-o* (hill)	*brál*		

(b) Lengthening preceding diminutive suffix –ok

vrch (hill)	*vŕš-ok*	*hrad* (castle)	*hrád-ok*		
chlp (hair)	*chĺp-ok*	*sud* (barrel)	*súd-ok*		

(c) Shortening through suffixation

predĺž-i-ť (lengthen)	*predlž-ova-ť*	*zváž-i-ť* (think)	*zvaž-ova-ť*		
vykŕm-i-ť (feed)	*vykrm-ova-ť*	*zníž-i-ť* (lower)	*zniž-ova-ť*		
dĺžk-a (length)	*dĺžk-ach*	*dĺžk-am*	*lúk-a* (meadow)	*lúk-ach*	*lúk-am*

(d) Rhythmic law

Word	Gen.Pl.	Dat.Pl.	Word	Gen.Pl.	Dat.Pl.
srn-a (deer)	*srn-ách*	*srn-ám*	*ryb-a* (fish)	*ryb-ách*	*ryb-ám*
vln-a (wave)	*vln-ách*	*vln-ám*	*ruk-a* (hand)	*ruk-ách*	*ruk-ám*
vŕb-a (willow)	*vŕb-ach*	*vŕb-am*	*tráv-a* (grass)	*tráv-ach*	*tráv-am*

Pouplier and Beňuš (2011) analyzed Slovak liquids in all three syllabic positions: onsets, nuclei, and codas. They designed triplets of words such as *mrak* ("cloud"), *mrk* ("wink"), and *park* ("park"). Then they compared pairwise the articulatory characteristics of onset /r/ in *mrak* and its coordination with /m/ in the onset cluster with the articulatory characteristics of nucleus /r/ in *mrk* and its coordination with onset /m/. Similarly, they examined the articulatory features of coda /r/ in *park* and its coordination with another coda consonant /k/, and compared this with nucleus /r/ in *mrk* and its coordination with coda /k/. The first question they asked was if consonantal nuclei are more vowel-like compared to their onset/coda counterparts. More specifically, they tested the hypothesis that when liquids are in the nucleus position, they resemble vowels articulatorily more than when they are in the onset or the coda position. Analyzing kinematic measures of the liquid tongue tip gestures such as plateau duration, peak velocity, or stiffness, they did not find any systematic evidence to support this hypothesis. However, they observed a relatively small overlap in consonant sequences and a tendency to an epenthetic schwa (open transition; Catford 1977). Testing for the effect of syllable affiliation on the timing of liquids showed that the overlap with adjacent consonants was greater for the onset-coda liquids than for the nucleus ones. Hence, Pouplier and Beňuš (2011) proposed that the syllabicity of liquids relates to the coordination patterns of liquids with the gestures of the consonantal onsets and codas. In other words, they extended the arguments for the importance of both inter- and intra-syllabic gestural coordination patterns and, in general, provided additional evidence for conceptualizing gestural coordination as a defining principle behind the syllable.

Finally, Beňuš (2011) included syllabic liquids together with vocalic nuclei in examining the articulatory strategies for signaling length, both phonemically and non-phonemically as speech rate modulations. The data for this study included nonsense words in the form of *pNpa*, in which N represented all 14 possible nuclei in Slovak: [i], [e], [a], [o], [u], [r], [l], [iː], [eː], [aː], [oː], [uː], [rː], [lː]. The reported results that are relevant for the current study include these:

- syllabic and vocalic liquids did not differ in the realization of acoustic duration, and this applied to both phonemic quantity and speech rate differences;
- the major articulatory signature of nucleus duration was the coordination between the two labial movements in *pNpa*. The nucleus type (vocalic vs. consonantal) affected various measures of this coproduction either minimally or not at all;
- robust kinematic differences between the tongue tip gesture of the syllabic liquids and the tongue body gesture of the vowels were reported, for example, in peak velocity or stiffness. Similarly, robustly greater lag (i.e., more open transition) between the gesture for the first /p/ and the syllabic liquid than the vocalic nucleus was reported.

Beňuš (2011) concluded that stable coordination between the two consonants (in this case the two /p/ sounds in *pNpa*), irrespective of the nucleus type of N, may facilitate the similarity in the phonological behavior of vocalic and consonantal liquids in Slovak, despite great kinematic differences and other coordination patterns related to these two types of nucleus. Hence, Beňuš argued that these results are in line with the approach outlined in Section 1 that construes the syllable as a set of timing gestural requirements.

1.2 Motivation for the Current Study

The papers reviewed in the previous subsection addressed the articulatory characteristics of syllabic liquids primarily by analyzing their tongue tip gestures. Pouplier and Beňuš (2011) kept liquids stable and varied their syllabic affiliation. Beňuš (2011) kept the syllable affiliation stable by analyzing only nuclei but varied the nucleus type (liquid vs. vowel). These studies analyzed the kinematic and coordination patterns of the more "consonantal" liquid gesture of tongue tip raising. However, as already mentioned in Section 1, the production of liquids also requires a more "vocalic" gesture of tongue dorsum retraction and the coordination of these two gestures defines the onset-coda affiliation of liquids. Given the importance of gestural coordination for syllables and the absence of information about the vocalic tongue dorsum retraction gesture, this paper asks if the "vocalic" gesture of liquids can fulfill the coordination requirements for the syllable nucleus. More specifically, the question addressed is if the "vocalic gestures" of liquids are timed with consonantal onset gestures in a similar way to vowel gestures. Hence, this paper addresses the question of how a phonetic consonant with a significant obstruction in the vocal tract may function phonologically as a vowel, and why the syllabicity of liquids, as in Slovak, is more marked cross-linguistically than the syllabicity of vowels. In other words, we ask how the structural properties of syllables and their constituents relate to the phonetic realization and thus to the practical use of language.

2. Methodology

The data for this study represent a partial overlap with the data analyzed in Beňuš (2011). Two datasets will be examined. In the quantitative analysis we analyze nonsense words in the form of *pNpa*, in which N represents all 14 possible nuclei in Slovak: [i], [e], [a], [o], [u], [r], [l], [i:], [e:], [a:], [o:], [u:], [r:], [l:]. We will refer to this dataset as *pNpa*. In the limited qualitative analysis we also complement this dataset with similar data including the coronal and dorsal flanking consonants: *tNta* and *kNka*. We refer to this larger superset as *CNCa*.

The procedure for recording both datasets is described in detail elsewhere (Beňuš 2011). Briefly, five native speakers of Slovak produced target nonsense words embedded in the prompt sentence *Čítame* ___ *pyšne* ("We read ___ proudly.") Each speaker produced five repetitions of each sentence at both normal and fast speech rates totalling 2100 tokens (5 speakers × 14 nuclei × 2 rates × 3 consonants × 5 repetitions) for the entire *CNCa* dataset and 700 for the *pNpa* subset.

Both articulatory and acoustic data were recorded. We used electromagnetometry (Hoole and Zierdt 2010; Beňuš 2012) to collect the kinematic trajectories of sensors attached to the active articulators. This technology allows up to five-dimensional kinematic data of articulatory movements to be collected with high temporal and spatial resolution. An example of data from the target word [pr:pa] is illustrated in Figure 1. The x-axis represents time in milliseconds. The first panel shows the oscillogram for the entire prompt sentence with the rectangle of the zoomed target interval. The second and third panels show the oscillogram and spectrogram for this zoomed target sequence. The bottom four panels show the vertical or horizontal trajectories of the sensors most relevant for this study: vertical movement of the tongue tip, horizontal and vertical movement of the tongue dorsum, and vertical movement of the lower lip.

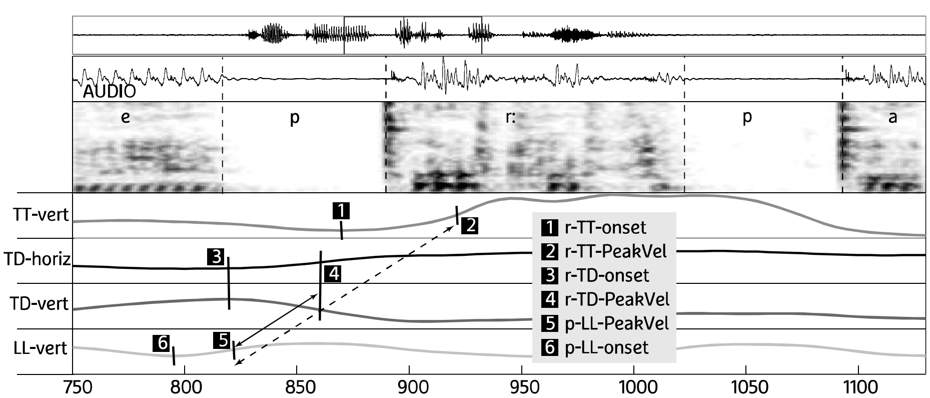

Figure 1. *Example of acoustic and articulatory data collected. See text for explanations.*

For the complete *CNCa* dataset, an independent experienced annotator labeled the acoustic intervals for all consonantal closures using the cessation of the formant structure for the preceding vowel as the consonant onset and the discontinuous increase of energy associated with the burst as the consonant offset. These labels are shown with vertical dashed lines in the spectrogram in Figure 1. For the *pNpa* subset, another experienced annotator (the author) used a semi-automatic Matlab procedure developed by Mark Tiede for identifying gestural targets on the basis of velocity landmarks, thus labeling the gestures of articulatory phonology (e.g., Goldstein and Fowler 2003). The labels for the onsets and peak velocities of articulatory movements resulting from this labeling are depicted in the four bottom panels of Figure 1.

The two double arrows in Figure 1 – one solid and one dashed – show the crucial dependent variable for this study. It measures the interval between peak velocities as the most stable articulatory landmark. The dashed arrow depicts the peak velocity lag between the consonantal onset /p/ and the tongue tip raising for the syllabic nucleus. The solid arrow shows the lag between /p/ and the vocalic tongue body retraction (and lowering). Hence, we will examine how consonantal nuclei are coordinated with their onset consonants by analyzing both the consonantal and vocalic gestures of syllabic liquids and the vowel gestures. The hypothesis that we will test with this dependent measure is that peak velocity lag in the vocalic tokens *pVpa*, in which V corresponds to all vowels, is similar to the lag of the vocalic movement in *pLpa*, in which L corresponds to the two liquids.

3. Results

We start with descriptive observations of the kinematic movement of the tongue tip and tongue dorsum during syllabic liquids. Figure 2 shows the vertical trajectories of the tongue tip (top row) and the horizontal trajectories of the tongue dorsum (bottom row) in *pr(:)pa* (left), *tr(:)ta* (middle), and *kr(:)ka* (right) for short (black) and long (red/gray) /r/. These data come from a single subject and because of space limitations we do not sho w all ten figures (five subject and two syllabic liquids). Importantly, all trajectories are time-normalized so that the time point 50 on the x-axis corresponds to the acoustic release of the onset consonant preceding the nucleus and the time point 150 to the acoustic closure of the consonant following the nucleus.

The analysis of these ten figures suggests the following observations. First, both /l/ and /r/ display both tongue tip raising and tongue dorsum retraction. Crucially, the former consistently follows the latter. This can be observed by comparing the onset of the tongue tip raising in the top row, commonly at or slightly later than the leftmost vertical line at 50 units of the x-axis. This applies to the *prpa* and *trta* tokens, with *krka* starting a bit earlier. The onset of the tongue retraction in the bottom row starts well before this vertical line for *prpa* and *trta*. Again, the pattern for *krka* is slightly different, which relates to the tongue dorsum closure needed for the flanking /k/ sounds. The second observation is that long liquids show slightly greater displacements but similar temporal coordination to short liquids. Additionally, both tongue tip and tongue dorsum movements seem to show greater overlap with the preceding onset consonants for the long liquids than for the short ones. This can be assessed through the distance between the leftmost vertical dashed line at 50 and the onset of the target gesture (major vertical movement of the plots). Finally, when /r/ and /l/ are compared, these patterns are more robust and visible for /r/ than for /l/; nevertheless, they are all, at least partially, observable for /l/ as well. Hence, the patterns shown in Figure 2 are in general symptomatic of the entire corpus and applicable to all five subjects.

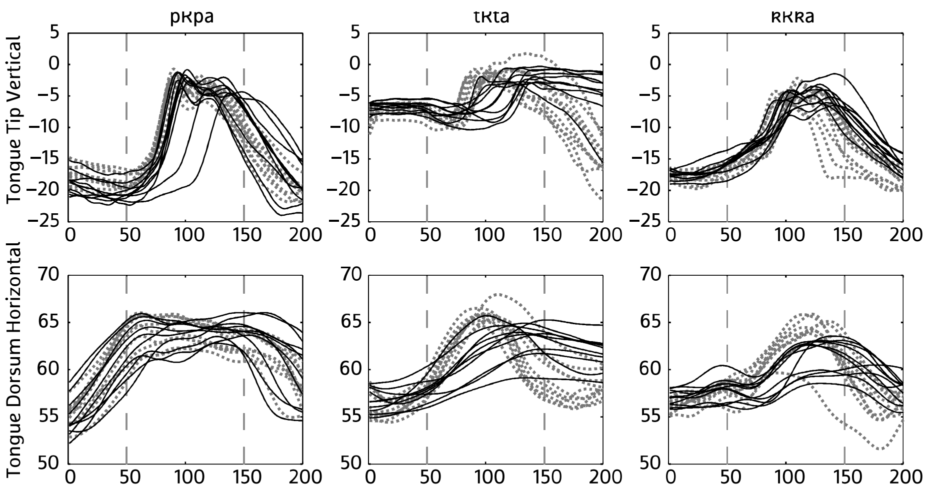

Figure 2. *Trajectories of two sensors: vertical movement of the sensor placed on the tongue tip in the top row (TT-y, up means tongue is moving up) and horizontal movement of the sensor placed on the tongue dorsum (TD-x, up means tongue dorsum is moving back). All trajectories are time-normalized with respect to the acoustic release of the C1 (left-hand dotted vertical line at 50) and acoustic closure of C2 (the right-hand dotted vertical line at 150). Black trajectories represent short rhotics, and red/gray dotted ones their long counterparts. The data are from a single subject.*

We next move to quantitative examination of the coordination between the two movements for liquids with the labial movement of the *pNpa* dataset. Figure 3 shows the data. The y-axis shows the lag between the peak velocities (peak velocity lag; see discussion of Figure 1); the greater the value, the less overlap there is, i.e., the more open the transition is. The white boxes (on the left in each panel) show the lag for the vocalic nuclei. The light gray boxes in the middle of each panel illustrate the data for /l/, the solid ones for the consonantal tongue tip raising, and the striped ones for the vocalic tongue dorsum retraction. Finally, the dark gray boxes on the right of each panel illustrate the data for /r/: the solid ones are for the tongue tip and the striped ones for the tongue dorsum.

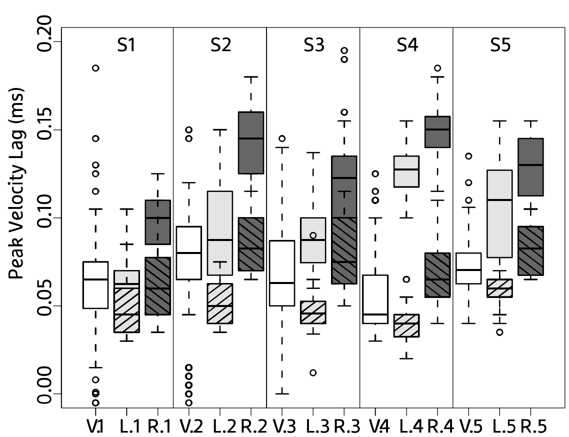

Figure 3. *Peak velocity lag in ms. for vocalic nuclei (V, white boxes), lateral (L, light gray), and rhotic (R, dark gray). The solid boxes show the tongue tip gesture and the striped ones the vocalic gesture of liquids.*

We first report the patterns observable in the figure, followed by the results from the quantitative statistical testing. We employed mixed-models tests in the lme4 package of R that allow multiple factors to be filtered and thus to be treated as random, and used Monte-Carlo simulations for determining *p*-values (Baayen 2008).

The first observation is that *consonantal* tongue tip gestures of syllabic liquids start significantly later than vowel gestures. In a mixed-model test with SUBJECT, TEMPO (fast vs. normal) as random factors, the factor NUCLEUS TYPE (vowel vs. /l/ vs. /r/) showed a significant effect on the lag measure ($F = 227.1$, $p < 0.001$). Phonemic quantity affected gestural coordinations less robustly ($F = 5.3$, $p = 0.02$) so that the lags were slightly shorter for short nuclei, especially for vowels and /r/, than the long ones. The interaction was not significant. In the crucial Welch t-tests, /l/s started later than vowels with respect to preceding /p/ ($t = 8.8$, $p < 0.001$) and the same, and more robustly, applied to /r/ ($t = 20.8$, $p < 0.001$). Hence, the coordination of the consonantal tongue tip gestures of the syllabic liquids with /p/ is significantly different from that of vocalic gestures.

Let us recall that the main hypothesis of this work predicted that the vocalic gestures of syllabic liquids would be coordinated with the onset consonants in a similar way to the vocalic nuclei. The factor NUCLEUS TYPE showed a significant effect on the lag between the onset and *vocalic* gestures (for vowels and liquids) in a mixed-model test with SUBJECT and BLOCK (fast vs. normal) and QUANTITY (short vs. long) as random factors ($F = 87.5$, $p < 0.001$). Welch t-tests showed that vocalic gestures for /l/ have a significantly shorter lag than vowel gestures ($t = -6.5$, $p < 0.001$), which is shown with the white and light gray striped boxes in Figure 3. Vocalic gestures for /r/, shown with dark gray striped boxes, have a significantly longer lag than vowel gestures ($t = 4.1$, $p < 0.001$).

4. Discussion and Conclusion

In this paper we started with the proposal of Pouplier and Beňuš (2011) that open transitions between the onset consonant and the tongue tip gesture of the nucleus in words like *mrk* facilitates the syllabicity of liquids. This work stems from much recent work about the syllable and its underlying articulatory coordination patterns. The main goal of the current paper was to test an extension of this general proposal, namely, that Slovak liquids have both the "consonantal" tongue tip gesture and the "vocalic" tongue dorsum gesture, and if that is the case, then the "vocalic" gesture fulfills the coordination requirements for the syllable nucleus. More specifically, we wanted to compare the timing of the syllabic liquid's "vocalic gestures" with syllable onsets and hypothesized that this temporal coordination would be similar to the coordination of vowels with syllable onsets.

The answer to the first question, whether Slovak syllabic liquids have both consonantal and vocalic gestures, is convincingly affirmative. The descriptive analysis of normalized sensor trajectories shows distinct retraction (and lowering) of the tongue dorsum at or before the movement of the tongue tip. The difference between these two gestures was also clearly visible when their timing with the onset consonant was examined with the measure of peak velocity lag.

The answer to the second question, whether the "vocalic" gestures of the liquids function as the vowel gestures in vocalic nuclei, is less clear. On the one hand, "vocalic" gestures of the tongue dorsum of syllabic liquids coordinate with the onset in a more similar way to vowels than the consonantal tongue tip gestures. This could be seen by looking at Figure 4, as well as by the lower F and t values in the reported statistical tests. Hence, the presence of the vocalic gesture of the tongue dorsum and its coordination with the onset might facilitate the syllabicity of liquids. On the other hand, the vocalic gestures of the syllabic liquids were still timed significantly differently with the onset compared to the vowel gestures of vocalic nuclei. Moreover, the directions of these differences were opposite for the two liquids. These two results suggest that the coordination patterns of the vocalic gesture of syllabic liquids cannot, on its own, explain the phonological behavior of Slovak syllable liquids since they pattern together, and also form a natural class with vowels.

There are several avenues for future research, given these results. First, it seems that subject variability plays a role. The statistical tests filtered this variability as we were interested in the general pattern, but Figure 3 showed significant differences among the subjects. For example, when vowels with syllabic /l/ (white with light gray boxes) are compared, the data from subjects 1 and 2 display similarities between vowels and the consonantal tongue tip gestures of /l/ (light gray solid boxes), while the data for subjects 3–5 show similarities to the vocalic gestures of the tongue dorsum (light gray striped boxes). The comparison between the vowels and /r/ was, however, remarkably stable among the subjects. This stability might be related to the other aspects worth pursuing in the future: the Slovak syllabic liquids /l/ and /r/ differ in their acoustic and aerodynamic properties and requirements. While /l/ is relatively unproblematic, /r/ displays severe aerodynamic, and possibly also acoustic, limitations on its production. Specifically, before the contact between the tongue tip and the palate the vocal tract needs to be open and the airflow must reach a certain threshold for the canonical production of the trill. Hence, the two gestures for a trill /r/ must be coordinated with greater precision than is assumed for /l/. In future research, we plan to examine whether these "mechanistic" requirements and differences between /l/ and /r/ are sufficient to explain the observed patterns reported in this paper, and how these phonetic aspects relate to the stable phonological behavior of syllabic liquids in general.

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