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# Toward universals in the gestural organization of syllables: A cross-linguistic study of liquids

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**Abstract**

Asymmetries in the relative timing of gestures in English liquids and nasals have provided the basis for the beginnings of an articulatory definition of the syllable, and both perceptually and biomechanically based hypotheses have been proposed to explain these patterns. However, previous studies have not generally considered intergestural timing in languages other than English, making it impossible to distinguish between these hypotheses, or to substantiate claims of universality of these patterns. This paper presents an ultrasound study measuring intergestural timing of liquids in three syllable positions in six languages. Cross-linguistic generalizations in timing patterns among liquids are identified, and specific questions are tested. While much work remains to be done, results at this stage support the view that both perception (recoverability) and biomechanics (jaw movement cycles) are likely playing a role in determining intergestural timing patterns, with possible tendencies for perceptual recoverability to dominate in onsets and jaw movement cycles to dominate in codas.


## 1. Introduction

Recent studies, mostly of American English consonants, have found systematic patterns in the timing of articulatory gestures across a number of segments in different syllable positions (see Krakow, 1999 for an extensive review of previous literature on this subject). These findings have

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not only provided an articulatory basis by which to define the syllable and syllable-based allophonic variation, but have also been of great importance in understanding related synchronic, historical, and developmental phenomena in phonology (Browman & Goldstein, 1992, 1995; Gick, 1999; Gick & Wilson, in press; Krakow, 1989, 1993; Oh, 2002; Sproat & Fujimura, 1993). However, despite an increasing volume of data on this subject, there has been no conclusive explanation as to why these patterns occur, whether the patterns are universal or language-specific, or how the different categories of participating gestures may be characterized. This inability to generalize has stemmed from a lack of breadth in the available data, as studies to date have with very few exceptions focused on one dialect of a single language, American English. Perhaps the main reason for this gap in the available data has simply been the difficulty and invasiveness of measuring synchronous kinematics of multiple articulators. The present paper attempts to begin to fill this gap by using ultrasound imaging to measure intergestural timing between tongue movements in liquid consonants across a number of languages.

Descriptively, previous studies have shown that certain gestures (or types of gestures) tend to occur at syllable peripheries, while other gestures occur nearer the center of syllables. For example, Krakow (1989, 1993) found that the lip closure for American English /m/ occurred later in postvocalic position than the velum lowering, helping to explain the effect of nasalization of a vowel preceding a tautosyllabic nasal consonant. Likewise, a number of researchers (Browman & Goldstein, 1992, 1995; Gick, 2003; Sproat & Fujimura, 1993) have observed a similar pattern for American English /l/, where the tongue tip gesture occurs later than the tongue dorsum gesture in postvocalic position. Sproat and Fujimura (1993) give this effect the term “lag”, as the anterior constriction temporally lags behind the dorsal one. In one of the few non-English studies of this timing effect, Wang (1995) attempted to replicate Krakow’s (1989) results for Cantonese nasals, but found no significant timing lag in initial or final nasals, suggesting that these patterns may not be universal. However, Krakow (1999) suggests that Wang’s lack of positive results may have been due to differences in methods. In any case, it is clear that more languages must be investigated before conclusions may be drawn regarding cross-language tendencies.

Every case of intergestural timing lag studied to date involves multiple physical events, one of which is clearly more anterior than the other. As earlier work has focused on nasals and /l/, this more anterior gesture has typically involved complete closure, while the less anterior gesture is less constricted. It has thus been unclear how to characterize the different types of gestures that participate in timing lag in English. One proposal (Sproat & Fujimura, 1993) suggests that some gestures are [consonantal] while others are [vocalic], based solely on their degree or manner of constriction. In this view, the vocalic gesture occurs more centrally in the syllable (presumably so as to be nearest the vocalic syllable peak), while the consonantal gesture occurs more peripherally. Gick (2003) tested the proposal that these types of gestures are categorized according to constriction degree by studying timing between the lip and tongue dorsum gestures of the glide /w/. Sproat & Fujimura’s proposal predicts that the two gestures for /w/ should show no lag effect, as both gestures are approximant constrictions and therefore [vocalic]. Gick’s results, however, indicate that American English /w/ patterns similarly to /l/, with the lip gesture of /w/ occurring peripherally in the syllable, despite the different degrees of constriction for /l/ and /w/ (though unlike /l/, the lag duration for /w/ is greater in initial than in final position). This leaves anteriority per se, rather than manner, as the determining factor in the organization of these gestures. However, the crucial questions remain as to whether this pattern will hold cross-linguistically, and if so, why it should occur.

To move toward determining the universality of this timing pattern and the factors that may underlie it, the present study measures interarticulator lingual timing between the component gestures of liquid consonants in six previously unstudied dialects and languages: Western Canadian English /l/, Quebec French (Quebecois) /l/, Serbo-Croatian (dark) /l/, Squamish Salish /l/, Beijing Mandarin /r/, and the Korean liquid. Languages were selected to be included in the present study on the basis of two criteria: first, each language had to have at least one liquid appearing in both initial and final position, and second, we had to have access to at least one speaker of the language. Beyond these absolute requirements, languages promising some particularly interesting contribution to the many outlying questions about intergestural timing were preferred (e.g., languages with specific similarities to or differences from American English that might lead to some testable prediction).

Two hypotheses, one perceptually and the other biomechanically based, have offered possible explanations for gestural timing patterns in terms of universal properties of speech that may bear on the present study. The first hypothesis suggests that offsets in intergestural timing are caused by constraints on perceptual recoverability (Byrd, 1994, 1996a, b; Chitoran, Goldstein, & Byrd, 2002; Kochetov, 2002, in press; Mattingly, 1981; Silverman, 1995; Silverman & Jun, 1994; Wright, 1996). The second hypothesis proposes that these asymmetries are linked to physical constraints imposed by the jaw movement cycle (Redford (1999); based on earlier work by Lindblom (1983), Keating (1983), MacNeilage (1998), etc.). These will be referred to henceforth as the "perceptual recoverability" hypothesis and the "jaw cycle" hypothesis.

Several researchers have proposed versions of the perceptual recoverability hypothesis, in many cases based on studies of the timing of consonant clusters. It would of course be desirable, though not a primary goal of this paper, to link timing of segment-internal gestures to these previous intersegmental timing observations. Chitoran et al. (2002) hypothesize that gestures in onset clusters should generally be more overlapped with each other (i.e., closer to simultaneous) than those in other positions, based on the notion that successful recoverability depends on the audible transition into the following vowel. They further suggest that onsets should be particularly influenced by perceptual factors because of the greater importance of onset material in lexical retrieval. Less attention has been given to coda sequences in previous work. However, Kochetov (in press) argues that perceptual recoverability is an important factor in a study of segment-internal timing in Russian palatalized stops. In a Russian–Japanese perception study, Kochetov (2002) shows a dramatic reduction in perceptual recoverability of the tongue body raising (palatalization) gesture of Russian /$p^j$/ in postvocalic position. In a follow-up articulatory study of the component gestures of /$p^j$/ (Kochetov, in press), he attributes this recoverability problem to the finding that, unlike in English /l/, the more posterior tongue body gesture occurs approximately simultaneously with or later than the lip gesture postvocalically. This is consistent with the notion that more anterior constrictions can dramatically reduce the recoverability of less anterior gestures when these are produced simultaneously (Kochetov, 2002 shows that posterior gestures can reduce the recoverability of anterior gestures as well, though to a much lesser degree). These perceptual studies have thus made two predictions: (a) prevocalic gestures should tend toward simultaneity; and (b) postvocalic gestures should have a positive lag (i.e., should occur back-to-front). For example, according to this prediction, the component gestures of an /l/ (or /w/, /n/, etc.) in postvocalic position will be more perceptually recoverable if the more posterior gesture occurs earlier than the more anterior one, and less recoverable if the more anterior gesture occurs earlier than the more posterior one.

The jaw cycle (biomechanical) hypothesis (Keating, 1983; Lindblom 1983; Redford, 1999), as it has been discussed more commonly in the context of language acquisition, has been explored somewhat less than that of perceptual recoverability with regard to its phonetic implications. As such, the specific predictions for the timing of liquids must be taken as largely conjectural at present. However, it is possible to infer some general predictions. According to this view, the development of humans' speech production capacity begins with cyclical movements of the jaw (see MacNeilage, 1998). At later developmental stages, consonantal closures are introduced into this cycle. Thus, more anterior gestures, being subject to the opening and closing of the jaw, will tend to be restricted to occurring at syllable peripheries (i.e., only during the closed portion of the jaw cycle) lest their goals be at odds with the dominating jaw cycle "frame", while less anterior gestures, being relatively independent of jaw position, are free to occur during the more opened portion of the cycle. It may be drawn from this that: (a) temporal offsets should occur between anterior and posterior gestures in both onset and coda positions, with anterior gestures appearing more peripherally; and (b) sets or clusters of multiple anterior gestures (or of multiple posterior gestures), being similarly affected by the jaw cycle, should tend toward occurring simultaneously. (N.B.: asymmetries in the shape of the jaw cycle observed by Redford (1999) and others may lead to finer-grained hypotheses in the future).

The Korean liquid provides a particularly interesting test case for these hypotheses. Previous articulatory studies have documented the Korean liquid as having two primary constrictions: tongue tip and tongue body (Oh, 2002; Oh & Gick, 2002), with the tongue body gesture creating a constriction in the palatal region. The perceptual recovery hypothesis would treat these as any two gestures where one is anterior to the other, and therefore predicts a timing offset similar to that seen in other liquids. However, as both of these gestures are relatively anterior (and therefore more strongly affected by jaw position), the jaw cycle hypothesis predicts that the two gestures will be closer to simultaneous than those of, say, the American English /l/. While there are many other cases of liquids with palatal components in the world's languages, many of these involve palatalization only as a secondary component (e.g., as part of a more general palatalized series, or only in palatalizing contexts), which may affect gestural timing relationships. Thus, for the purposes of the present paper, constriction degree is not used to determine whether a particular articulation is phonologically "secondary". See Section 5 below for further discussion of the phonological status of measurable physical events.

In addition to the above predictions for timing of gestures, these two hypotheses may make different predictions regarding the spatial aspect (reduction or augmentation) of gestures. However, as there has been very little work bearing directly on this question, the spatial data collected in this paper will be considered independently of the timing hypotheses, and only where a gesture is completely absent, preventing timing measurements between gestures. Similarly unclear are predictions regarding liquids in intervocalic position. Data concerning these points will be reported, but will be discussed only where they are of relevance to previous work, primarily on a language-by-language basis.

Beyond the main questions discussed above, it is a secondary goal of this paper to elucidate other questions regarding the gestural composition, timing, and syllable-based variation of liquids cross-linguistically. For example, "dark" vs. "light" positional variants of English liquids, their phonetic correlates, functions in language change, and so on, have been much discussed in the literature (e.g., Browman & Goldstein, 1992, 1995; Carter, 2003; Gick, 1999, 2003; Giles & Moll, 1975; Hardcastle & Barry, 1989; Tollfree, 1996). However, Western Canadian English postvocalic /l/ sounds impressionistically less dark than that of more commonly studied dialects of American English, while the postvocalic /l/ of Quebecois and other dialects of French seems brighter still. This increase in brightness may suggest the absence of a posterior constriction, or perhaps a reduced timing lag (i.e., less overlap with the peak vowel) in languages with brighter-sounding /l/. Conversely, some languages seem to have a dark-sounding /l/ even prevocalically (e.g., Serbo-Croatian, Squamish Salish, and to a lesser extent, American and Western Canadian English). While data relevant to this and other topics will be presented below, these topics merit further work involving not only kinematics, but acoustic modeling, perception studies, and so on, and must in general be reserved for future research.

## 2. Methods

An ultrasound imaging study was conducted to measure interarticulator timing in liquids in six dialects and languages representing four different language families.

### 2.1. Subjects

Ten speakers participated in this study, two for each of Western Canadian English (WC), Quebec French (QF), Serbo-Croatian (SC), Korean (K), and one for each of Beijing Mandarin (BM) and Squamish Salish (SS). Because of the time-intensive nature of the analysis and the focus on breadth rather than depth, the target number of speakers for each language was limited to two from the outset of the study. While this is by no means a sufficient number for running cross-subject statistics, it is nonetheless (for better or worse) on par with many previously published speech production studies of English only. Development of new methods for collecting and quantifying ultrasound is ongoing, and will allow more extensive studies in the future. Only one speaker of Squamish Salish and Beijing Mandarin participated—SS because of lack of available speakers (there are only a handful of native speakers of this language), and BM because data collected from several additional subjects were unusable (see below for further discussion). All subjects were native speakers of their respective languages, and were living in Vancouver at the time of data collection.

Specific details regarding subjects are as follows. WC: Two female subjects aged 21 and 22; both were undergraduate students at UBC at the time of collection and both are originally from the Vancouver area. QF: One 21 year old male and one 23 year old female; both are originally from the Saguenay-Lac St. Jean region of Quebec and participated in the study during an exchange year at UBC. Neither subject spoke English prior to late adolescence. SC: Two female speakers, ages 22 and 21; both were undergraduates at UBC at the time of the study; note that Subject 2 has been living in Canada since 1996, but continues to speak SC both at home and socially. Korean: Two male native speakers aged 31 and 35; both were graduate students at UBC at the time of the experiment; both subjects lived in Korea until coming to Canada for graduate study; K subject 1 is a speaker of the standard Korean dialect, while K subject 2 speaks the Chunnam dialect of Southwestern Korea. BM: One female native speaker aged 30; she was a graduate student and Mandarin instructor at UBC at the time of the experiments; she lived in Beijing until she came to

Canada to study 3 years ago. SS: One male native speaker in his late 60s; he is literate in both English and Squamish.

One factor limiting the number of subjects was that a relatively large number of potential subjects were screened and rejected, and in some cases unusable data was collected and analyzed for speakers not included in the final study (particularly for Mandarin). The reason for this was that, due to a variety of factors, some subjects' anatomies do not allow for imaging of the entire tongue, from tip to root, as required for several of the languages in this study. First, a very small number of speakers' tongues are too long or too close to the neck surface for the entire length to fall within the range of the transducer; second, some speakers' tongues do not provide clear images in general (about 10%); and third, quite a few subjects' tongue tips do not image well, likely due to a larger sublingual cavity (perhaps 25%). By the end of the study, improved screening methods were developed to avoid time spent attempting to analyze unworkable data.

### 2.2. Stimulus selection and design

Most of the languages selected for this study had only one simple (i.e., with no commonly attested secondary articulations) pulmonic liquid appearing in both pre- and postvocalic position. Omitted from the present study were liquids expected to have only a single gesture in all positions (e.g., QF uvular /r/, SC trilled /r/), liquids commonly described as having secondary articulations (e.g., SC palatalized /l/; Townsend & Janda, 1996), and liquid-like positional variants of nonliquid segments (e.g., WC coronal "flaps"). Liquids previously described as varying in number of gestures across syllable positions were included (e.g., the Korean liquid, which is described as a coronal tap in pre- and intervocalic positions, but a complex liquid in postvocalic position [Oh & Gick, 2002]). WC /r/ was not included in the present study because it has three gestures (lip, tongue tip/body and tongue root), requiring techniques not employed in the present study to measure the lips (e.g., video or optical tracking). See Gick and Campbell (2003) for a study of timing of English /r/ gestures. Finally, liquids were included in the study despite possible language-internal phonological factors which may affect their phonetic behavior (e.g., SC /l/ contrasts with a palatalized /l/ in the same language).

Stimuli were designed to be structurally as similar as possible across languages, while controlling for word shape and length, segmental context, and stress. The target liquid segment appeared in either word-initial or word-final position in a nonsensical combination of two monosyllabic words, read within a carrier phrase. The liquid was flanked by maximally similar vowels to minimize interference of V1 with liquid gestures, with only the position of the liquid changing across conditions. A third context (the "final /l/" context, with word-final /l/ preceding a word-initial labial consonant) was included to prevent resyllabification, as shown in (1) below. Vowel-initial words in SS and BM had a strong glottal onset, preventing resyllabification. 10 (or sometimes 11) instances of each sentence were compiled for each position, then randomly ordered and presented visually. The two forms used in this carrier phrase were changed from sentence to sentence in order to prompt a stress pattern in which the two words of the sequence were both stressed, and both to approximately the same degree, eliminating concerns of stress-related effects. Subjects were asked to repeat trials where equal stress was not maintained across the two words; this stress pattern was confirmed impressionistically by experimenters both during and after data collection. A list of language-by-language stimuli is included in Table 1.

$$
\begin{array}{cc}
\text{initial} & \text{final} \\
\ldots V1\#LV1\ldots & \ldots V1L\#(C)V1\ldots \\
 & | \\
 & [\text{lab}]
\end{array}
$$

$$\text{(e.g., English : } \textit{Fay lame} \text{ vs. } \textit{fail (m)aim}\text{)} \qquad (1)$$

## 2.3. Apparatus

For most subjects, articulatory data were recorded to digital video (30 frames/s) from an Aloka SSD-900 portable ultrasound machine (except for the Korean data, which was collected using a higher-end nonportable Aloka SSD-5500 machine), using a 3.5 MHz convex intercostal transducer mounted on a microphone stand at a comfortable height and angle for the subject. This arrangement allowed midsagittal imaging of the tongue from root to blade in most cases, with some cases including a clear tongue tip as well. For two of the earlier subjects (SS, plus one QF subject), the same intercostal probe was hand-held by the subject against his or her own neck, just above the larynx, with probe position monitored using a laser pointer attached to the probe (see Gick, 2002 for further description and illustration of this method). As no correction was made for head movement relative to the probe or for tissue compression, actual distances should not be considered reliable. This should not, however, dramatically affect relative timing measures, assuming head movement to be roughly consistent across tokens. Recent findings (Yehia et al.,

Table 1
Stimuli followed the structure in (1)

| Lang | Carrier phrase | Prevocalic | Intervocalic | Postvocalic |
|---|---|---|---|---|
| WC | He said ____ again | Fay lame | fail aim | fail maim |
| QF | L'enfant a dit ____ immédiatement | mi lit | île Yves | île vie |
| | *The child said ____ immediately* | *half bed* | *island Yves* | *island life* |
| SC | Rekao je ____ i otiS‹ao | vi lim | fil im | fil vim |
| | *He said ____and left* | *you(pl.) aluminum* | *cream-filling them(dat.)* | *cream-filling floor-cleaner* |
| SS | na tsut ta Konrad ___ kwi chelaklh | ti lixw | — | sil im' |
| | *Konrad said ___ yesterday* | *Prox fall-down* | — | *cloth boy* |
| BM | Ta you shuo ____ le | po rou | — | pir en |
| | *He again said ____ (particle)* | *Slope gentle* | — | *skin(dim) kindness* |
| K | Ca ______ hago… | pa lama | pal api | pal mapu |
| | *Let's say ______ and…* | *'pa' lama* | *foot father* | *foot driver* |

Sentences were presented to subjects in their native writing systems, but are given here in romanized form. English glosses are given in italics. Due to restrictions on liquid-vowel combinations, the symmetry in (1) was not completely reproducible in high vowel context in Beijing Mandarin. Vowel initial forms in SS and BM have strong glottal onsets preventing resyllabification.

2002) showed that head movement correlates strongly with f0. Thus, controls on stress and length in the stimulus design were used to control gross head movement. Acoustic data were collected using a Pro-Sound YU34 unidirectional microphone amplified through the built-in pre-amplifier in a Tascam cassette deck, then simultaneously recorded to the same DV tape as the video signal.

### 2.4. Measurement and analysis

Recording sessions for all subjects took place in the Interdisciplinary Speech Research Laboratory (ISRL) at UBC, except for SS, which was collected on-site at the Squamish Nation in North Vancouver, BC. Digitized video signals were transferred to PC using Adobe Premiere software, and material surrounding the target liquids was edited out. Approximately 10–20 frames (about 330–660 ms) were extracted per liquid, during which all apparent movement associated with the liquid took place. Edited video images were measured using Ultrax edge tracking and analysis software, developed at the ISRL by S. Rahemtulla and B. Gick (see http://www.linguistics.ubc.ca/isrl).

Examples of the ultrasound images and measurement methods are shown in Fig. 1. Averaged movement trajectories (e.g., Fig. 2) were created from image sequences by: (1) locating the tongue surface in each frame using graphical edge detection; (2) hand-correcting edge detection errors; (3) fitting a polynomial to the resulting edge; (4) Placing intersect lines across the tongue surface perpendicular to relevant gestures (intersect lines were fixed across repetitions of the same tokens); (5) plotting movement of the approximated tongue surface along the intersect lines over time; (6) temporally aligning repetitions of each token relative to the most prominent event (usually a tongue tip/blade gesture); (7) numerically averaging 7–11 repetitions for each speaker and condition; and (8) approximating the resulting averaged trajectories with a cubic spline. It is important to note here two methodological points relating to the fact that ultrasound does not image the vocal tract beyond the tongue surface during speech. First, the measurement locations described above were determined based on tongue-internal events rather than on actual constriction locations per se; second, the point of reference for measurement is not a fixed part of the anatomy, but the arc where the ultrasound transducer contacts the neck (these issues are discussed in greater detail in Gick (2002)).

Temporal lag was calculated from movement trajectories for each repetition separately. This was done by subtracting the frame number of the achievement of maximum displacement of the less anterior gesture from that of the more anterior gesture (i.e., a "positive" lag is one where the less anterior gesture precedes the more anterior one, as is typical of English postvocalic /l/; these are reversed for a "negative" lag). A gesture was considered as having "achieved" its maximum displacement as of the first frame when the articulator was within one pixel (less than 0.4 mm) of its maximum displacement for that event (i.e., when any remaining movement of that articulator fell below the spatial resolution of the video signal). Number of frames was converted to milliseconds by multiplying by 33.333 (based on a rate of 30 video frames per second). This lag duration could only be calculated in languages and syllable positions where both of the gestures being compared were present. The resulting temporal lag values were subject to two statistical analyses: First, a one-way *t*-test was used to test whether the observed lag was significantly different from a hypothesized mean of zero milliseconds (i.e., no lag). Second, if a language had a

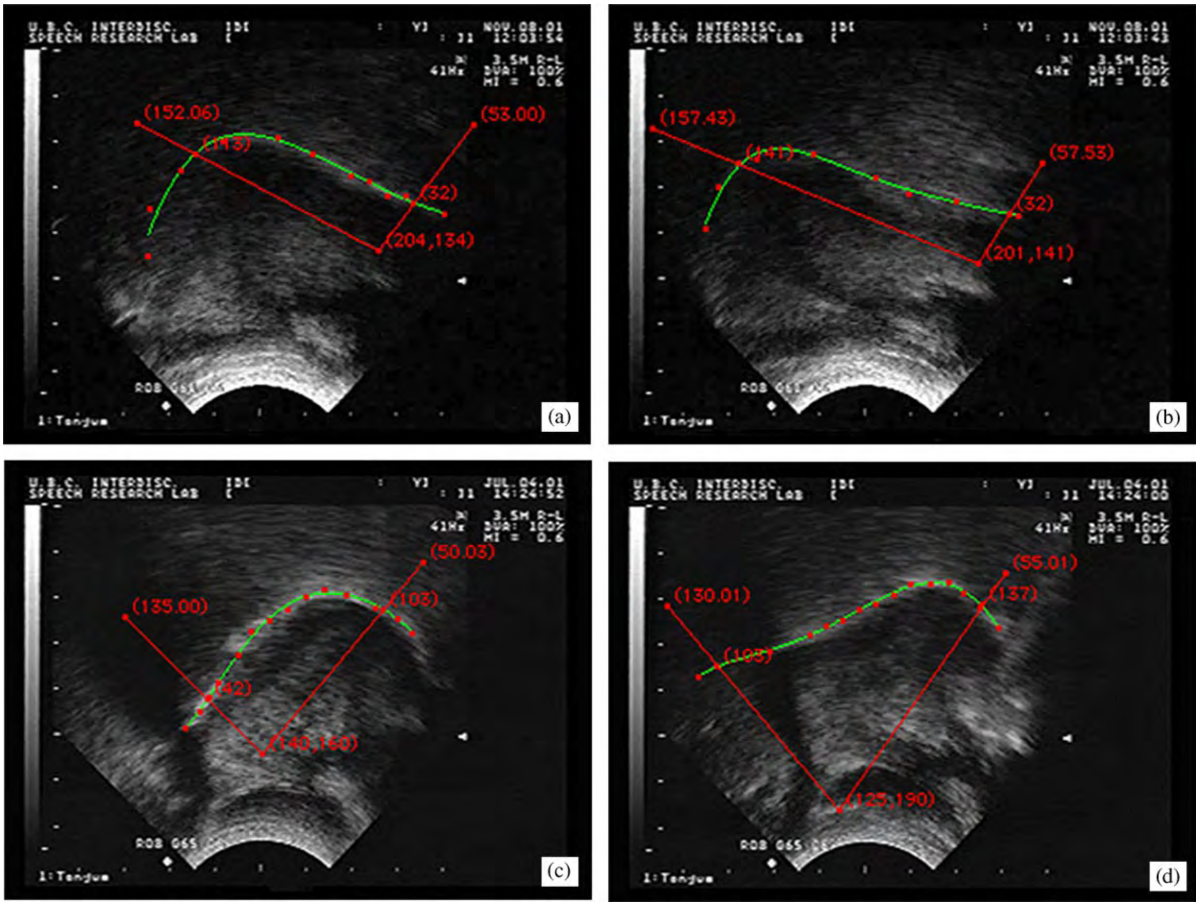


Fig. 1. Illustration of measurement using Ultrax edge tracking and analysis software. A polynomial is fitted to the (hand corrected) tongue edge; measurement lines intersect the tongue surface perpendicular to relevant constriction locations for Western Canadian English /l/ in (a) prevocalic and (b) postvocalic position, and Beijing Mandarin /r/ in (c) prevocalic and (d) postvocalic position.

significant lag in at least one position, and both gestures were present in at least two positions, an ANOVA was used to test whether the difference in lag observed across positions was significant.

It should be noted that the necessarily limited conditions of data collection for Squamish Salish affected the quality of the data for that language, forcing a somewhat different analysis approach. In particular, as the data were collected from an elder in a field situation, head and transducer movement were substantially less controlled than for the other languages. First, this caused sporadic imaging of the tongue tip; second, it made producing a clear trajectory prohibitively time-consuming. Therefore, although intervocalic data were collected for Squamish Salish, this was not included in the present study. For the remaining Squamish data, only the times of achievement of these gestures (rather than the full trajectories) were measured. Times were calculated for Squamish as follows: (1) The frame showing achievement of gestural maximum was normally visually evident within a frame or so; three trained analysts independently viewed all of

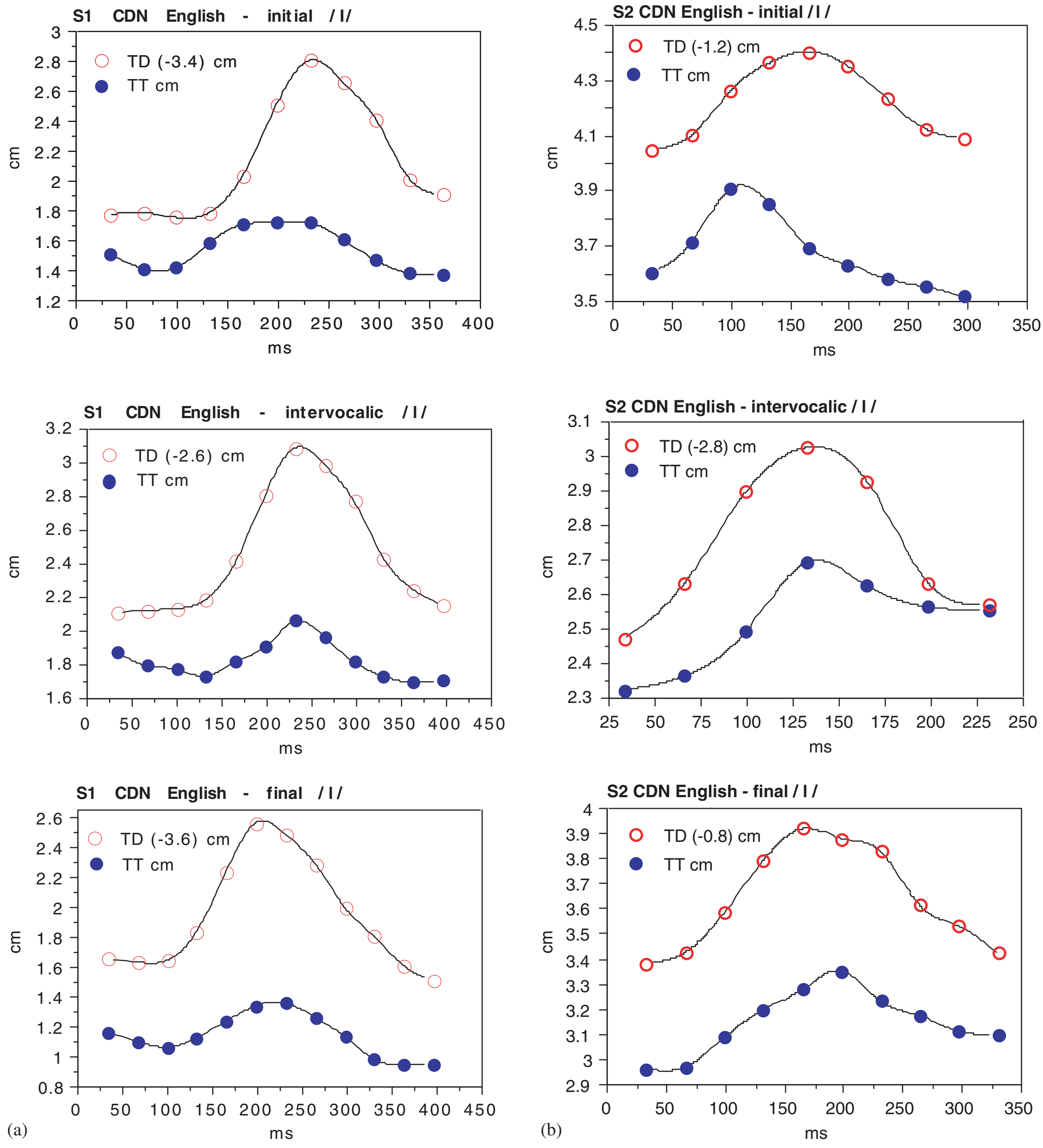


Fig. 2. Averaged movement trajectories showing gestures for Western Canadian English /l/ in prevocalic, intervocalic, and postvocalic positions, as produced by (a) WC subject 1 and (b) WC subject 2. TT and TD refer to tongue tip and tongue dorsum movements, respectively.

the SS data frame-by-frame, marking the frame numbers corresponding to the achievement of each of the two apparent gestures. (2) These frame numbers were subtracted from each other as for the other languages, giving a lag value for each token. (3) The resulting lag values were compared token-by-token across analysts, and values agreed upon by two or more analysts were included in the final analysis (i.e., if none of the analysts agreed on the lag value for a particular token, it was discarded). (4) The remaining lag values were used in the statistical analysis. Given the relatively low temporal resolution of the tools involved and the relatively long timecourse of the events being measured, timing differences below an arbitrary cutoff of 10 ms were considered to indicate simultaneity.

## 3. Results

Results for each language are first presented separately, then tabulated and viewed across language in the remainder of this section.

### *3.1. Language-specific results*

#### *3.1.1. Western Canadian English*

Results for WC /l/ suggest a similar but not identical pattern to that previously reported for American English /l/ (Browman & Goldstein, 1995; Gick, 2003; Sproat & Fujimura, 1993). As in previous studies, a tongue tip raising and fronting gesture and a tongue dorsum backing gesture were present in all syllable positions. Fig. 2 shows averaged tongue tip and tongue dorsum trajectories for each of the two speakers of WC.

While previous studies found a relatively long positive lag in postvocalic position and a relatively short negative lag (often nearly simultaneous) in prevocalic position, these two speakers showed a greater prevocalic negative lag than their postvocalic positive lag. Both subjects exhibited a significant positive lag in prevocalic position, no significant lag in intervocalic position, and a significant negative lag in postvocalic position (based on 1-sample t-tests with a hypothesized mean of 0, WC subject (1) prevocalic lag $-52.4$ ms ($p < .01$), intervocalic lag $< 10$ ms ($p > .05$), postvocalic lag 26.7 ms ($p < .001$); WC subject (2) prevocalic lag $-57.6$ ms ($p < .0001$), intervocalic lag $< 10$ ms ($p > .05$), postvocalic lag 18.2 ms ($p < .05$)).

The relationship between positions can be more easily seen in Fig. 3, which shows the mean values from an ANOVA comparing lag in pre-, inter-, and postvocalic positions. The overall effect of the factor Position is significant for both speakers (WC subject (1) $F\,(2, 30) = 35.986$, $p < .0001$; WC subject (2) $F\,(2, 23) = 33.145$, $p < .0001$); posthoc tests (Fisher's PLSD) indicate a significantly greater negative lag in prevocalic position vs. both inter- and postvocalic position for both speakers ($p < .0001$ for all comparisons), as well as a significantly greater positive lag in post- vs. intervocalic position for WC subject 2 ($p < .02$) but not for WC subject 1 ($p = .0606$).

#### *3.1.2. Quebec French*

Two gestures were present for QF /l/: a tongue tip fronting and raising gesture and a tongue dorsum backing gesture. Although the dorsum gesture was evident in post- and intervocalic positions, this gesture was not present in prevocalic position. For this reason, no prevocalic

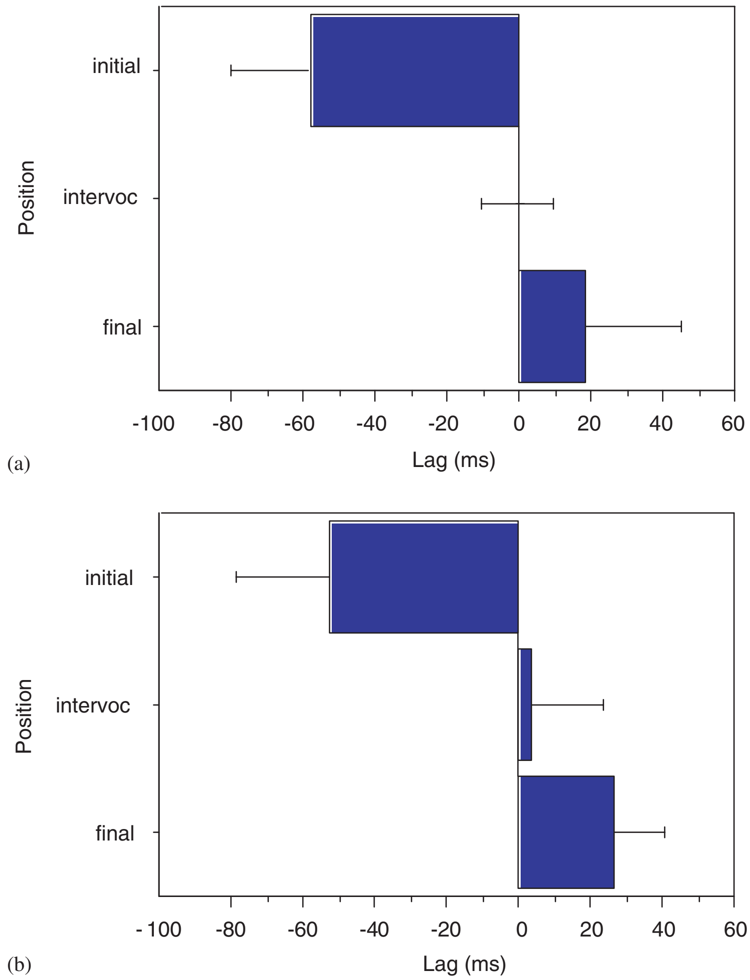


Fig. 3. Mean temporal lag between gestures in /l/ for (a) WC subject 1 and (b) WC subject 2. Error bars show ±1 standard deviation.

trajectory is shown in Fig. 4, and a statistical comparison of lag across positions could not be calculated for this language. It can be seen in Fig. 4 that the postvocalic variant does exhibit the expected lag for QF subject 1 (44 ms, significantly different from a hypothesized mean difference of 0 in a 1-sample $t$-test ($p < .05$)). However, the results for QF subject 2 show no significant postvocalic lag, and an apparent but not significant lag in intervocalic position ($p > .05$).

### 3.1.3. *Serbo-Croatian*

Results for SC /l/ were consistent across both speakers, showing two gestures: a tongue tip raising and fronting gesture and a tongue dorsum backing gesture. These two gestures occurred simultaneously in all positions for both subjects (according to 1-sample $t$-tests, no lags were significantly different from a hypothesized mean of 0; mean lag duration for all positions was $< \pm 10$ ms). The overall effect for an ANOVA on the factor Position was not significant ($p > .05$)

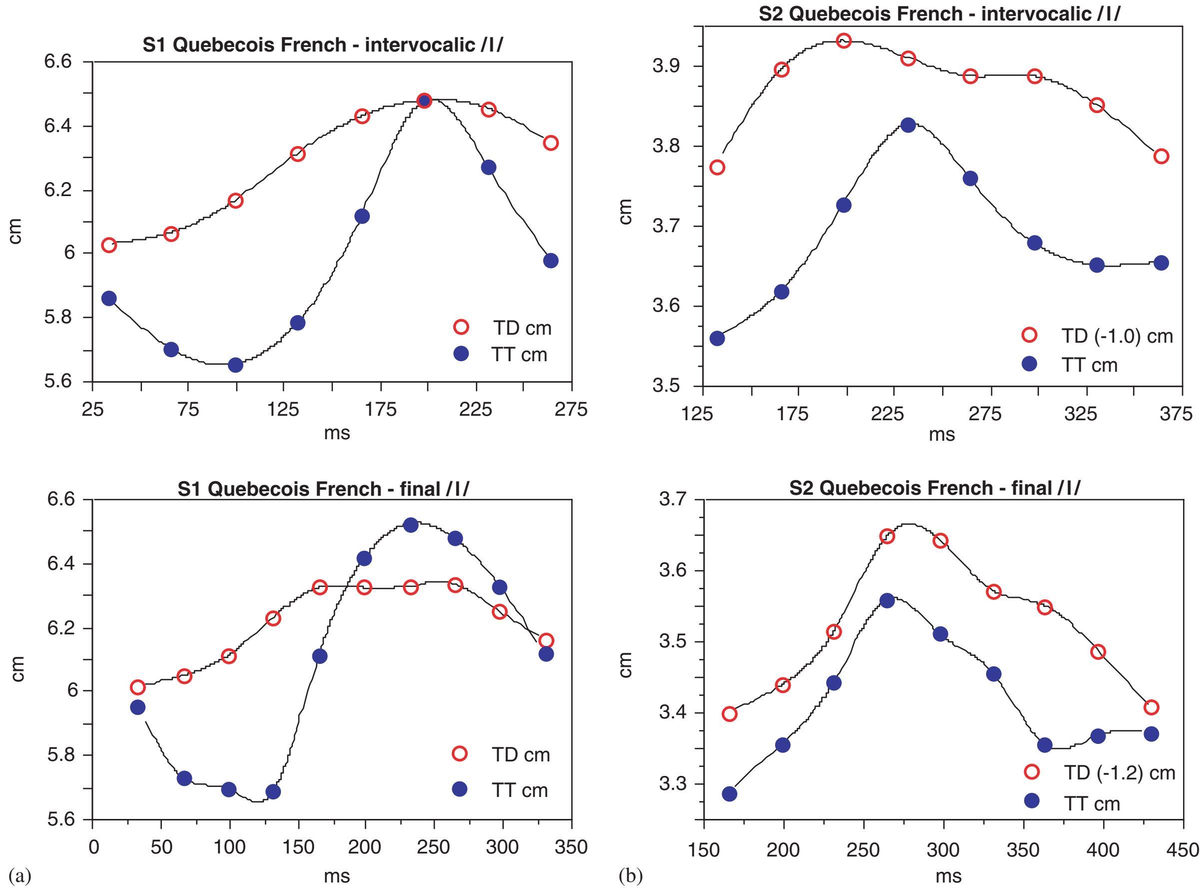


Fig. 4. Averaged movement trajectories showing gestures for Quebec French /l/ in intervocalic and postvocalic positions, as produced by (a) QF subject 1 and (b) QF subject 2.

for either speaker. Additionally, although spatial measures are not the focus of this study and should not be considered conclusive (see above), it is interesting to note that neither speaker shows an apparent dramatic reduction in magnitude for either gesture in any position (Fig. 5).

### 3.1.4. *Squamish Salish*

Results for Squamish Salish /l/ show a tongue tip raising and fronting gesture and a tongue dorsum backing gesture. Both of these gestures were present in all three positions (though, as discussed above, only pre- and post-vocalic positions were analyzed). Also as discussed above, because of the less-controlled circumstances of data collection for this language, movement trajectories were not calculated from image data.

Based on 1-sample *t*-tests with a hypothesized mean of 0, the SS subject exhibited a significant positive lag in postvocalic position (mean = 23.8 ms; $p < .01$), but no significant lag in prevocalic position ($p > .05$).

The comparison of lag measures across pre- and postvocalic syllable positions, given in Fig. 6, showed a pattern similar to that described for American English in previous studies (positive lag

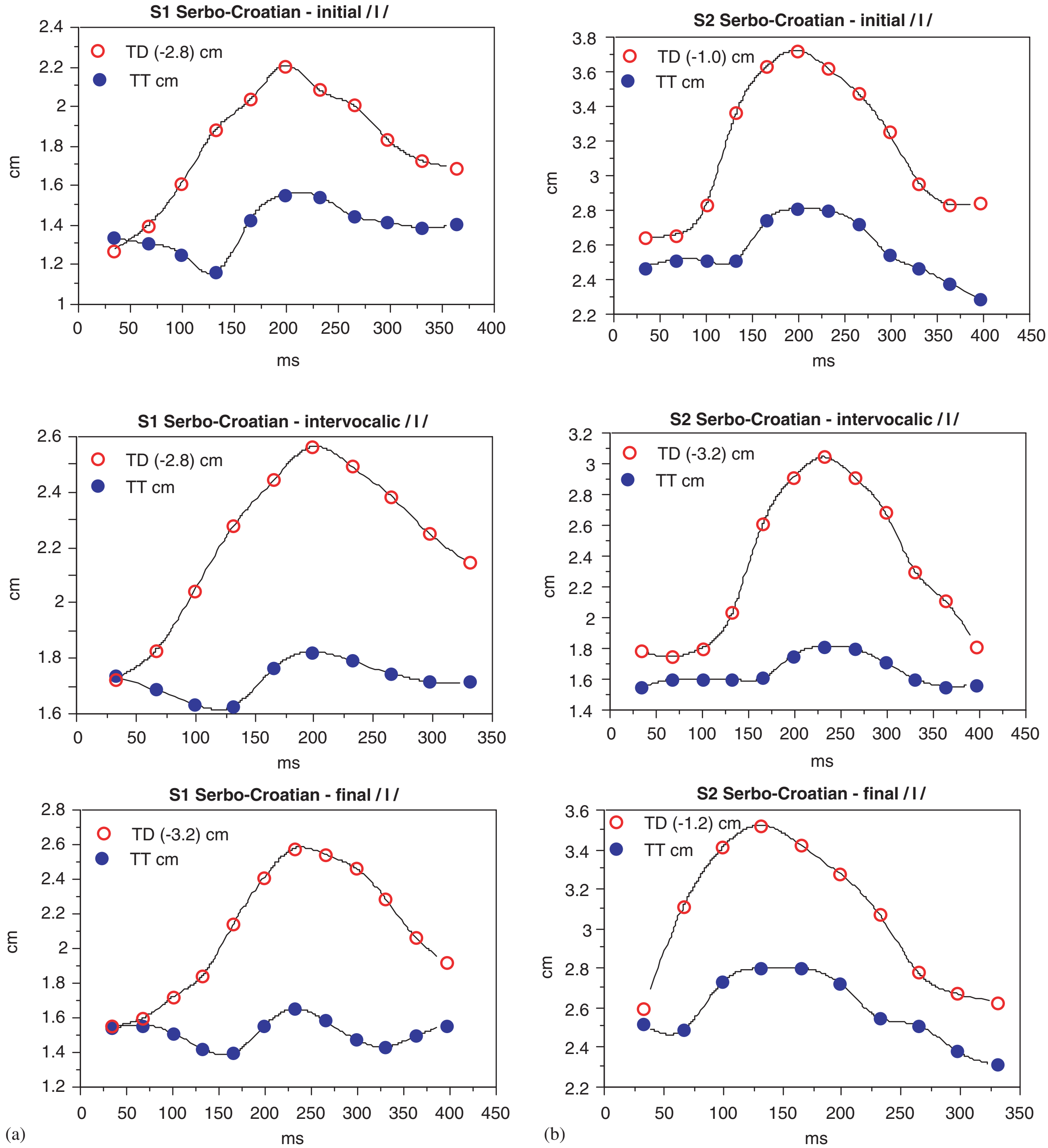


Fig. 5. Averaged movement trajectories showing gestures for Serbo-Croatian /l/ in prevocalic, intervocalic and postvocalic positions, as produced by (a) SC subject 1 and (b) SC subject 2.

postvocalically, very small negative or no lag prevocalically). Results of an ANOVA on the factor Position (testing lag effect in pre- vs. postvocalic position) shows a significantly greater positive lag (24 ms) in post- vs. prevocalic position ($F(1, 12) = 13.5$; $p = .0032$).

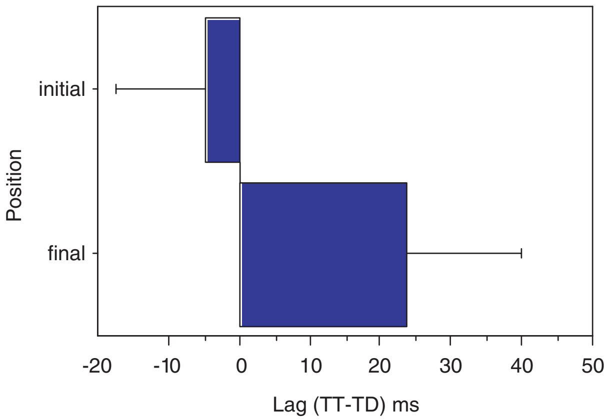


Fig. 6. Mean temporal lag between gestures in Squamish Salish /l/, calculated by subtracting the frame number of the achievement of the tongue dorsum gesture from that of the tongue tip gesture. Error bars show $\pm 1$ standard deviation.

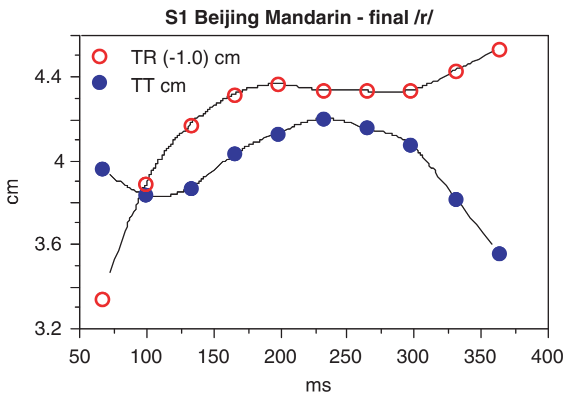


Fig. 7. Averaged movement trajectories showing gestures for Beijing Mandarin /r/ in postvocalic position. TR refers to tongue root movement.

### *3.1.5. Beijing Mandarin*

Results for BM /r/ showed two active gestures: a tongue anterior raising gesture and a tongue root backing gesture. The more posterior of the two gestures (tongue root backing) was not present in prevocalic position, so that movement trajectories and statistical comparisons of lag could not be calculated for this position, and no comparison could be made across syllable positions. For the postvocalic position, however, it can be seen in Fig. 7 that there is a positive lag (33 ms) between the two gestures, significantly different from a hypothesized mean difference of 0 in a 1-sample $t$-test ($p < .01$).

### *3.1.6. Korean*

As in previous studies (Oh, 2002; Oh & Gick, 2002), the Korean liquid was found to comprise a tongue tip closure gesture and a raising and fronting gesture of the tongue body. The tongue body gesture, however, did not appear in the pre- and intervocalic positions (which were realized as coronal taps), and therefore no movement trajectories or statistical comparisons were calculated for these positions. The postvocalic trajectories in Fig. 6 show a negative lag for subject K1 (−21 ms, significantly different from a hypothesized mean difference of 0 in a 1-sample $t$-test ($p < .05$)), and no significant lag (< 10 ms; $p > .05$) for subject K2 (Fig. 8).

### 3.2. General results

Tabulated results for all languages are shown in Table 2. One somewhat surprising result is that liquids in all of the languages investigated—even those with a "brighter" sound—have two lingual gestures in postvocalic position. However, as Table 2 indicates, only half of these (WC, SC, SS) have both gestures present in prevocalic position (in all cases it is the anterior gesture that is present in both pre- and postvocalic positions). Of the three languages having both gestures present in prevocalic position, only one (WC) exhibits a lag greater than 10 ms. This lag appeared for both speakers, and it was in the negative direction (i.e., with the anterior gesture preceding the

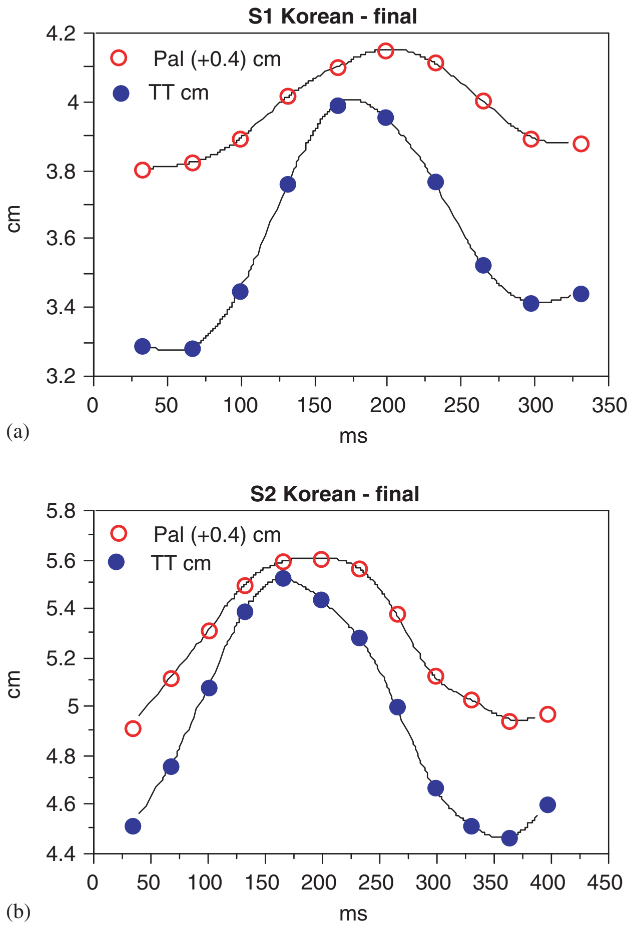


Fig. 8. Averaged movement trajectories showing gestures for the Korean liquid in postvocalic position, as produced by (a) K subject 1 and (b) K subject 2.

Table 2
Tabulated results for three syllable positions in five languages showing presence of posterior gesture and duration of lag (*t* anterior minus *t* posterior; a positive lag indicates that the posterior gesture precedes the anterior, a negative lag indicates that the anterior gesture precedes the posterior)

| Language | WC | QF | SC | SS | BM | K |
|---|---|---|---|---|---|---|
| Segment | /l/ | /l/ | /l/ | /l/ | /r/ | /l$^j$/ |
| Posterior gest present in prevoc pos | yes | no | yes | yes | no | no |
| Prevoc lag (ms) | −55 | — | NL | NL | — | — |
| Intervoc lag (ms) | NL | NL | NL | — | — | — |
| Postvoc lag (ms) | 22.5 | 22 | NL | 24 | 33 | −11 |

WC, QF and SC are averaged values from two speakers. '—' indicates no available value due either to absence of a gesture (QF, BM, K) or to systematic avoidance of resyllabification (BM, SS). 'NL' indicates no lag (not significantly different from zero). N.B.: For lack of a specific IPA symbol, /l$^j$/ is used here to represent the Korean palatal-alveolar lateral, however this should not be taken as an implication that the palatal component is secondary.

posterior gesture). Postvocalically, four languages exhibited a positive lag greater than 10 ms (WC, QF, SS, BM), and one speaker of one language (K) exhibited a negative lag. Of the three languages for which intervocalic data were available, only one speaker of one language (QF) showed an intervocalic lag greater than 10 ms. All of these results are discussed further in the following section.

## 4. Discussion

This section first presents a brief discussion of language-specific results. Second, more general cross-language observations are made, and these findings are used to evaluate the hypotheses presented in Section 1.

### *4.1. Language-specific discussion*

#### *4.1.1. Western Canadian English*

The two notable differences between the WC pattern observed here and previous results for American English are: (1) A relatively greater negative lag was seen in prevocalic position, and a smaller lag in postvocalic position, than observed in previous studies (Browman & Goldstein, 1995, Gick, 2003; Sproat & Fujimura, 1993), showing a pattern more like that previously observed in /w/ for four American English subjects (Gick, 2003); and (2) an intermediate timing pattern was seen in intervocalic position, with a duration between those in the pre- and postvocalic positions. This is contrary to Gick's (2003) previous findings, where the intermediate effect was only seen in gestural magnitude.

Given the small number of subjects in this and previous studies, as well as the generally large variation between subjects within and across previous studies, it is impossible to know whether these differences are speaker-dependent, or whether they indicate more general dialectal differences between WC and American English. In any case, it is apparent from these results that: (1) the timing differences previously observed between /l/ and /w/ are not fixed, even within

North American English; and (2) intergestural timing is at least in some cases a phonetic correlate of ambisyllabicity/resyllabification.

#### 4.1.2. Quebec French

The relatively "bright" quality of French initial /l/ does seem to find a correlate in our data—namely that the tongue dorsum gesture does not occur in prevocalic position. The pattern for QF subject 1 is qualitatively consistent with what we have seen with other QF subjects included in pilot versions of the present study (i.e., no tongue dorsum backing gesture in prevocalic position, some lag in postvocalic position, no apparent lag in intervocalic position). While the absence of a posterior gesture for QF subject 2 follows the typical pattern, this subject is unusual in having no significant lag in postvocalic position.

#### 4.1.3. Serbo-Croatian

As mentioned above, the SC nonpalatalized /l/ considered in this study sounds quite dark in all positions. It must be presumed that the articulatory correlate of this is the large dorsum backing gesture observed above in all syllable positions. Timing lag, however, does not seem to be an indicator of this, as the two gestures are simultaneous in all positions. This across-the-board simultaneity in all environments for both subjects differs markedly from the patterns seen in the other languages in this study, particularly in post-vocalic position, and may indicate a counterexample to an otherwise relatively consistent cross-language tendency (see Section 4.2). However, an important consideration regarding SC is to recall that this language has a second, palatalized /l/, omitted from the present study (Townsend & Janda, 1996; see Section 2.2). In view of this, it is worth considering whether the dorsal constriction in the dark /l/ of SC might also be a secondary articulation, or in any case whether the properties of the nonpalatalized /l/ may be directly influenced by its contrast with the palatalized /l/. Future studies with greater focus on the timing of secondary articulations may help to clarify this issue.

#### 4.1.4. Squamish Salish

SS showed a positive lag in the postvocalic /l/. Also, like WC and SC, SS retained its posterior gesture in prevocalic position. The possible interaction of these factors with darkening is discussed in the general discussion below. The overall timing pattern observed for SS is very much like that observed for American /l/ in previous studies (Browman & Goldstein, 1995; Gick, 2003; Sproat & Fujimura, 1993). While it is conceivable that this similarity could relate at least in part to the subject being a fluent speaker of both Squamish and English—the details of phonetic interference across bilingual speakers' languages is not yet well understood—Squamish is typical of native languages of North America in that, of the very few remaining speakers, none are purely monolingual.

#### 4.1.5. Beijing Mandarin

With its tongue body raising gesture and tongue root backing gesture, the lingual characteristics of the BM postvocalic /r/ are surprisingly similar to those of American English /r/ (e.g., Delattre & Freeman, 1968; this striking similarity is currently being pursued in other articulatory studies, e.g., Honorof et al., 2003), and the positive lag in postvocalic position is consistent with that seen in English /l/ (and other languages). The absence of the posterior (tongue root backing) gesture in prevocalic position is consistent with patterns seen in QF and Korean above. Although data for other BM subjects were not of sufficient quality to include in this paper (see above), their general patterns were consistent with those observed here.

#### 4.1.6. Korean

As with QF and BM, the posterior (tongue body raising) gesture of the Korean liquid is absent in prevocalic position. Korean is unusual, however, in that the posterior gesture is also absent in intervocalic position. As for timing lag in postvocalic position, results show that these two gestures are simultaneous for one subject and that there is a negative lag between the gestures for the other subject (this is the only case of postvocalic negative lag among speakers and languages). That there is a difference between these two speakers is not surprising, as they speak two quite different dialects. The general implications of these results will be discussed in the following section.

### 4.2. General discussion

Perhaps the clearest finding of this study is that there is no single timing generalization that applies across all languages. While this is contrary to Krakow's (1999) position, it should perhaps not be surprising, especially if it is indeed true that there are multiple factors whose influences affect these timing relationships. This paper has explored two of these factors: perceptual recoverability and the jaw cycle—and there are surely other influences not considered here, both in the perceptual and biomechanical realms as well as in other realms (sociolinguistic, developmental, phonological, etc.). That said, there are certain tendencies that appear across languages that may help to indicate which of the factors considered in this paper may tend to dominate in which environments.

Chitoran et al. (2002) and others discussed in Section 1 predicted that gestures in syllable onsets should be simultaneous in response to perceptual recoverability factors. The jaw cycle hypothesis, however, predicted that onsets would show a negative timing lag similar in magnitude to that seen in codas. Of the languages observed, only WC showed a timing lag in prevocalic position. This pattern differs from that of American English /l/, the gestures of which have generally been observed to occur simultaneously in onset position in previous studies. Other languages in this study either had no posterior tongue gesture in prevocalic position (QF, BM, K) or exhibited simultaneity (SC, SS). Thus, it appears that perceptual recoverability is exercising a strong influence on gestural timing in onset position cross-linguistically. In addition, as pointed out by one reviewer, the absence of the posterior gesture in QF, BM, and K is particularly notable, as the constriction location of the posterior gesture is different in each language (TD, TR and TB, respectively). This observation supports the contention of this paper that the relative anteriority/posteriority of gestures is important to gestural coordination.

Both hypotheses predicted a positive temporal lag in postvocalic position for most languages. Results for WC, SS, BM, and one speaker of QF supported this prediction (see Section 4.1.3 above for discussion of results for SC). However, the predictions of the two hypotheses differed for Korean. The perceptual recoverability hypothesis predicted that the postvocalic liquid in Korean should show a positive lag pattern similar to the other languages, while the jaw cycle hypothesis predicted no lag. Results for Korean showed no lag for subject 1 (a speaker of

Standard Korean) and a negative lag for subject 2 (a speaker of the Chunnam dialect). These results conflict with the perceptual recoverability hypothesis for both speakers, but are consistent with the predictions of the jaw cycle hypothesis for only speaker 1. It thus appears that perceptual recoverability may be a less important factor in determining timing patterns in syllable codas, and that biomechanical influences may be stronger in this position. These results for postvocalic position, however, are neither completely consistent nor statistical, and must be taken only as indicative of trends to be confirmed in future studies. The study of additional speakers of these dialects and of other languages with palatal liquids will confirm whether these patterns continue to hold.

Regarding the results for intervocalic position, in every case where there were two gestures present in intervocalic position, they occurred simultaneously. There are arguably multiple factors supporting simultaneity in this position. This conspiracy of factors may itself explain the strong tendency toward simultaneity here. First, it is possible that both gestures are coordinated relative to both flanking syllables (Browman & Goldstein, 1992), thus reinforcing simultaneity regardless of the relationship between the two gestures per se. Further, if the position of Chitoran et al. (2002) is correct, then recoverability for both gestures is improved in intervocalic position, as acoustic information may be carried by vowels on both sides of the liquid.

Finally, Section 1 posed a question about the articulatory correlates of "darkness" of liquids. The present results suggest (not surprisingly) that the presence of a posterior gesture in prevocalic position in SS, WC and SC corresponds exactly with these languages having a "darker" sounding initial /l/ than other languages. The role of relative timing in this darkening effect is less clear. However, it should be noted that the two gestures of prevocalic /l/ in SS and SC are essentially simultaneous (as has been the case with American /l/ in several previous studies—see above) while the two gestures of WC /l/ are offset by 60 ms. Impressionistically, the /l/s of SS and SC, as well as American English, are decidedly darker than that of WC, suggesting that darkness may be more effectively conveyed with simultaneous movements in prevocalic /l/. An additional factor in phonetic darkness not raised in the present paper is the reduction or absence of the anterior gesture previously observed in postvocalic position for some dialects of English (Ash, 1982, Hardcastle & Barry, 1989; Gick, 1999; Giles & Moll, 1975; Narayanan, Alwan, & Haker, 1997, p. 1070). This relates to previous observations for other languages such as Brazilian Portuguese (Feldman, 1972), which appear to have lost their anterior component entirely in postvocalic position. While an anterior gesture was present in liquids for Western Canadian English (and other languages) in the present study, pilot ultrasound data collected for other dialects of English, as well as for Brazilian Portuguese and Bulgarian, have confirmed the absence of this gesture. These languages should be considered in future studies of darkness in liquids. It is hoped that the articulatory data in this paper will help to inform future acoustic and perceptual analyses of darkness in liquids.

## 5. Conclusions

The present results support the proposal that syllable positions may be distinguished and characterized articulatorily (e.g., Krakow, 1999). However, although languages thus far studied use only a very small subset of the logically possible arrangements of gestures, there is no single pattern that characterizes syllable positions across languages. Thus, language-specific patterns, though apparently influenced by universal phonetic factors, must nonetheless be to a large extent specified language by language. This said, the present paper has identified some strong cross-linguistic tendencies in intergestural timing in the liquids studied to date, including that: (1) postvocalic liquids always have a measurable dorsal constriction; (2) patterns of gestural timing and magnitude in liquids are almost always different (asymmetrical) in pre- vs. postvocalic positions; (3) multiple gestures are simultaneous in intervocalic/resyllabified position; and (4) intergestural timing tends to follow a sonority-like hierarchy corresponding largely to anteriority, such that when a timing offset does exist, more anterior constrictions occur more peripherally while less anterior constrictions occur more centrally in syllables.

Two hypotheses were evaluated in view of these patterns—one based on perceptual recoverability and one based on jaw movement cycles. Results favor the view that perceptual factors dictate intergestural timing in prevocalic (onset) position. Results for postvocalic position are less clear, but findings from Korean favor biomechanical causes over perceptual ones for codas. This is consistent with the prediction of Chitoran et al. (2002), who argue that perceptual recoverability is more important in onsets to facilitate lexical retrieval.

Two final points to consider regarding the cross-linguistic study of gestural timing involve the phonological status of the physical events being measured, and the comparability of these events across languages. That is, first, what exactly are the criteria for considering a particular event to have phonological status; and second, if, as we have found, different languages show different patterns of timing and even differences in presence vs. absence of gestures, can a meaningful cross-linguistic comparison of gestures (or features or segments) ever be made? According to Browman and Goldstein's (1992) Articulatory Phonology, there is essentially no difference between a phonological gesture and its physical instantiation. However, while it is inconceivable that every observable physical event should be categorized as a "gesture", the criteria for determining under exactly what circumstances an observed physical event should be considered phonologically real have been vague in the previous literature on Articulatory Phonology (and essentially absent from most other prominent models of phonology). From a phonetic point of view, regardless of one's choice of phonological framework, the intergestural timing generalizations observed experimentally here and in previous studies of English /l/ merit consideration whether they are the result of language-specific phonological specifications or universal phonetic forces. For it is only through collecting phonetic data of this kind that we can begin to observe and gain insight into whatever cross-linguistic generalizations may exist, from which we may draw our own conclusions about phonetic universals or phonological status. For example, the very fact that a measurable posterior (phonetic) gesture was present in every language studied in this paper suggests possible universal effects not previously considered. Thus, while some languages may indeed treat tongue dorsum backing as an independent gesture, it may be that others employ a different gesture for /l/, e.g., active lateral compression of the tongue (McDowell, 2004), which could result in a consistent but small nonphonological tongue dorsum backing, simply as the result of volume displacement. To return to the question of phonological status, then, it may be that a less pronounced tongue dorsum movement such as that observed in Quebec French /l/ is a phonetic by-product of some other event, and thus has no phonological status, while the more substantial movements seen in English /l/ and Beijing Mandarin /r/ may be considered phonological. Likewise, the observation that the two gestures of Serbo-Croatian /l/ are always present and always simultaneous may be linked to a greater need to maintain contrastivity (SC being the only 3-liquid system in this study). These questions, posed here at the level of individual gestures, extend equally to systems comprising features or segments. Without clear phonetic criteria for defining and categorizing physical events, phonological categories (such as /l/ or [+lateral]) can only be meaningfully compared across languages at the most abstract level. While the primary goal of the present paper is not to determine the phonological status of the events observed in this study, nor whether they are phonologically comparable across languages, it is hoped that these findings will add to the available data on intergestural timing, so that their phonological status and the role of universal phonetic principles in their patterning may be better evaluated.

While this study provides new data, it raises more questions than it answers. It will of course be desirable to further test the hypotheses explored here in future perceptual and biomechanical experiments. It is surely the case that both perception and biomechanics, as well as a variety of other factors, contribute to the control of speech production. A better understanding of cross-linguistic patterns in gestural coordination may help to understand these factors and their specific effects.

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