Physiological organization of syllables: a review

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The notion that the syllable is a unit of articulatory organization has long had intuitive appeal, although a series of studies spanning more than two decades failed to support this hypothesis (cf. Stetson, 1951; Draper, Ladefoged & Whitteridge, 1959; Kozhevenikov & Chistovich, 1965; Gay, 1978; Kent & Minifie, 1977; Harris & Bell-Berti, 1984). More recently, however, a new approach to this issue – one that considers syllables to be characteristic patterns of articulatory organization (Krakow, 1989; Browman & Goldstein, 1995) – has provided new insights into the nature of syllable organization in speech. This paper reviews the relevant physiological investigations in the literature and presents new data, which together serve to demonstrate that the syllable is, at its core, a physiological unit. The relation between such evidence and phonological patterns is discussed, including cross-language distributional differences between syllable-initial and syllable-final consonants, as well as such notions as ambisyllabicity and resyllabification.

1. Introduction

The idea that the syllable is a unit of physiological organization has long had intuitive appeal. However, years of study resulted in one disappointment after another, as empirical support for this notion was not forthcoming. For example, in work dating back to 1928, Stetson (1951) suggested that pulses of respiratory muscle activity might organize the speech stream into syllable-sized units. Stetson’s own data on pulmonary air pressure and his observations of chest wall movements appeared to support this hypothesis; however, subsequent electromyographic studies by Draper, Ladefoged, and Whitteridge (1959) did not. They found no systematic relation between respiratory muscle activity and syllable organization during speech production.

In the 1960’s Kozhevenikov and Chistovich (1965) emphasized the role of the supralaryngeal articulators, suggesting that the articulatory syllable was coextensive with the temporal domain of coarticulation. Lip protrusion activity associated with a rounded vowel, observed to begin during the first consonant in CₜV (any number of consonants followed by a vowel) sequences, was taken as evidence that the physiological syllable was organized into consonant-vowel units (cf. Boyce, Krakow & Bell-Berti, 1991). However, a large body of work showing asynchronous activity among different articulators and varying temporal domains of coarticulation established the fundamental flaw of this
The speech stream simply cannot be dissected into discrete linearly-ordered units the size of the segment or the syllable. Indeed, the search for boundaries of coarticulation as markers of syllable boundaries failed just as the search for segment boundaries failed years before.

Later work (Gay, 1978; Harris & Bell-Berti, 1984) suggested that syllables might be separated by troughs in the movement pattern of an articulator; that is, similar movements for the two vowels in a vowel-consonant-vowel (VCV) sequence would be separated by a change in the direction of the pattern due to the presence of the intervening consonant. Indeed, there is articulatory evidence showing that lip protrusion activity for the two /u/s in /utu/ is interrupted by retraction of the lips for the /t/. However, such interruptions in the movement pattern between syllables are inconsistently observed. For example, some speakers show sub-phonemic lip protrusion during “unrounded” consonants such as /s/, /t/, /k/, /l/, /h/, and /ʔ/ (Harris & Bell-Berti, 1984; Gelfer, Bell-Berti & Harris, 1989; Boyce et al., 1991), so that troughs may be absent in uCu sequences in which those consonants occur. Similarly, troughs in tongue raising and fronting movements associated with the two vowels in sequences such as /ipi/ fail to occur when the consonant is, instead, /h/ or /ʔ/ (Harris & Bell-Berti, 1984). Nonetheless, there is no question about the presence of two syllables in every one of these examples. Hence, the notion that troughs would consistently mark syllable boundaries did not stand up to empirical scrutiny.

Some researchers appeared to give up on the idea that a physiological basis for the patterns would be found or that it was even worthy of further investigation. For example, in his widely cited dissertation on syllable-based phonological patterns in English, Kahn (1976) stated, “… it is an unfair challenge to require hard physiological evidence of syllable organization from those that specify syllables as phonological domains, since … it is the nature of speech production to obscure abstract and important units of phonological structure, such as the phoneme and the syllable” (pp. 16–17). Boucher (1988) commented, “… the status of syllable boundaries has come under question in a number of studies on coarticulation and some acoustic analyses have even led to outright rejections of the syllable as intuitively given” (p. 303). As noted above, a serious obstacle in much of the work turned out to be the focus on finding syllable boundaries in the speech stream.

Despite the setbacks, the desire to find a physiological basis for the syllable continued to be compelling because of mounting evidence of the role of syllable organization in phonological patterns (Ohala & Kawasaki, 1984). Consider, for example, cross-language evidence of asymmetries in the distribution and behavior of syllable-initial and syllable-final consonants: (1) CV (consonant-vowel) is the most common syllable organization in the world’s languages; (2) Some languages have no syllable-final consonants; (3) Final consonant assimilation, weakening (i.e., lenition) and even loss is common in languages with syllable-final consonants (see Kahn, 1976; Bell & Hooper, 1978; Ohala & Kawasaki, 1984; Ohala, 1990; Manuel, 1991 for further discussion).

Many speech researchers shared the sentiments of Ohala and Kawasaki (1984) concerning these patterns: “… there is good reason to think that these facts are related and that there is an identifiable phonetic basis for them” (p. 115). Starting around the time that Boucher presented his pessimistic view, however, researchers were beginning to take a different approach in the investigation of the syllable (see, e.g., Krakow, 1989; 1993; Tuller & Kelso, 1990; Sproat & Fujimura, 1993; Turk, 1994; Browman & Goldstein, 1994).
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1995; Wang, 1995). For example, Krakow (1989) suggested that syllables might be associated with characteristic patterns of articulatory organization (see also Browman & Goldstein, 1995). In such a view, no boundaries are expected, or sought, in the movement data (or the acoustic outcome). Instead, different intra- and inter-articulatory patterns are predicted to be associated with syllable onsets as compared with syllable offsets. This approach has provided considerable insight into the nature of syllables and the relation between the articulatory patterns, on the one hand, and the phonological asymmetries, on the other.

Of special interest were nasal consonants. The cross-language phonological evidence indicates that vowels are more likely to be affected by nasal assimilation when followed by a syllable-final nasal consonant than when preceded by one. And historically, contrastive vowel nasalization commonly arises through loss of the final oral constriction for the consonant, with nasalization remaining on the vowel (Kawasaki, 1986). Referring to the emergence of distinctive nasal vowels with the loss of the consonant, Schourup (1973) reported that he was struck by the “independence of oral closure” and “nasality.” Such independence, Krakow (1989) supposed, would allow for different patterns of oral-velic coordination for syllable-initial vs. -final nasals, which might contribute to the kinds of phonological asymmetries observed.

The purpose of this article is to review the articulatory evidence concerning nasal consonants and syllable organization along with articulatory evidence for other consonant classes and articulators, since phonological asymmetries between initial and final consonants are clearly not limited to nasals. There is now a fairly extensive literature relevant to this topic that includes data on laterals and stops, in addition to nasals. In fact, taken together, these data provide a largely consistent picture concerning the articulatory organization of syllable-initial and -final consonants. This review is intended to show that the following generalizations can be made: At least in careful speech, syllable-initial and syllable-final consonants are associated with different characteristic articulatory patterns. (Here we review both intra- and inter-articulator patterns for each of these consonant classes.) Moreover, syllable-initial position is a “stronger” position in two senses. It is generally associated with tighter articulatory constrictions and with greater stability. The data also provide insight into such notions as ambisyllabicity and resyllabication.

In what follows, intra-articulator patterns are described first, followed by inter-articulator patterns, for nasals, laterals, and stops. Information on the instrumentation used is provided in footnotes. Note that most of this paper focuses on English, the language for which the bulk of the data is available, although given the cross-language phonological evidence, it is assumed that similar findings would be obtained in other languages for comparable data. When data from other languages are presented, this is explicitly noted.

2. Intra-articulator organization

2.1. Nasals

Evidence that syllable-final nasals are associated with lower positions of the velum than syllable-initial nasals has long been observed in physiological investigations using a variety of instrumental techniques. Such findings have been consistent across languages
The endoscope, inserted through the nose, was used to illuminate the velic region and capture images showing the relative height of the velum during utterances containing nasal consonants in initial and "nal" positions. The Japanese syllable-"nal consonant, represented by the symbol /N/, has the duration of a mora. When followed by a stop, affricate, or nasal, /N/ is produced as a nasal stop and assimilates to the place of articulation of this following consonant (Vance, 1987).

Such data are obtained by inserting hooked-wire electrodes directly into the muscle in order to monitor and record its time-varying electrical activity (Harris, 1970). For example, Henderson’s (1984) data, obtained with a fiberoptic endoscope, showed that the velum reaches a spatially lower position in CVN sequences than in NVC sequences for both English and Hindi. The pattern was consistent for sequences with high, mid, and low vowels.

Ushijima and Sawashima (1972), also using a fiberoptic endoscope, studied velum movement in reiterant Japanese sequences with syllable-initial (in repetitions of /ne/) and syllable-final nasals (in repetitions of /teN/). The final nasal was consistently produced with a lower velum than the initial nasal, despite the requirement of a rapid and extreme rise in velum position from /N/ to the immediately following /t/. Differences between syllable-initial and -final nasals in Japanese are also evident in electromyographic (EMG) data from the levator palatini (LP), the primary muscle of velic raising (Kiritani, Hirose & Sawashima, 1980; see also Ushijima & Hirose, 1974). These data show that there is longer suppression of LP for syllable-final than syllable-initial nasal consonants.

One concern about many studies that compare initial to final consonants, however, is the use of mirror-image pairs (e.g., CVN and NVC, as in Henderson, 1984) or near mirror-image pairs (e.g., CVN vs. NV, as in the two studies of Japanese just reviewed). The problem with such pairs is that the anticipatory contexts are not matched across pairs nor are the carryover contexts. For example, in Henderson’s study, the initial nasal is preceded by an /s/ from the carrier phrase whereas the final nasal is preceded by a vowel; the final nasal is followed by an /s/ whereas the initial nasal is followed by a vowel. Because of a well-known tendency for coarticulatory effects to be asymmetrical (i.e., stronger in one direction than in the other), contextual effects can’t really be separated from syllable effects in such comparisons. Another limitation of mirror-image pairs is that they do not rule out possible effects of sequential position on articulator height. Hence, a nasal consonant occurring earlier in a sequence might simply have a higher velic position than one occurring later (as in NVC vs. CVN) and so the effects attributed to syllable position might be due, partially or entirely, to velic declination over the course of the sequence. (For evidence of declination of velic height in obstruents, see Krakow, Bell-Berti & Wang, 1995).

For these reasons, Krakow (1989) manipulated the location of word boundaries across matched phonetic sequences to ensure comparable coarticulatory contexts and sequential positions for initial and final nasals (as in, e.g., “see more” vs. “seam ore” and “pa made” vs. “palm aid”). Velum movement data were collected using a Velotrace and

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The Velotrace (Horiguchi & Bell-Berti, 1987) consists of three major parts: an internal lever that rests on the nasal surface of the velum, an external lever that remains in full view outside of the nose, and a push rod connecting the two levers. Movements of the velum and, hence, the internal lever are reflected in movements of the visible external lever. A light-emitting diode attached to the external lever of the Velotrace (in the midsaggital plane) is tracked with the use of the optoelectronic tracking system (Kay, Munhall, Vatikiotis-Bateson & Kelso, 1985).

All the words had two full vowels; no reduced vowels were used.

For S1, movement measures on the velum did not include those of "home E," "hoe me," "home Lee," or "homely" because the movements in these sequences were so complex and variable that they could not be segmented in the same manner as those of every other utterance in the study (see Krakow, 1989 for further discussion and illustration). The corresponding lip data did not present any difficulty and, thus, were included in the set of intra-articulator measures considered.

### Table I. Sequences from Krakow (1989)

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Selspot System. Four twelve tokens of each sequence listed in Table I were obtained from two subjects. The subjects were asked to produce the items in the carrier phrase, “It’s — Sid,” using a careful style of speech.

Primary stress was held constant across the rows, its placement determined by the matched single-word comparisons in each row. This meant that, with the exception of “pa made,” “palm aid,” and “pomade,” primary stress fell on the first syllable of a sequence. This was done in order to ensure comparability with the other items in the same row. In this section of our discussion, we focus only on items in the first two columns. (Those in columns 3–5 are addressed below.) However, to ascertain whether initial-final differences were consistent across stress patterns, 12 additional tokens of each sequence containing an intervocalic nasal consonant were obtained from Subject 2 with the alternate stress pattern. This allowed for comparisons such as “see me” vs. “seam E” with stress on the first syllable and the same pair with stress on the second syllable. (Discussion of how movement onsets and offsets were determined in the entire dataset is provided in the appendix.)

Comparisons of initial and final /m/, in the sequences from columns 1 and 2, revealed the following significant differences for both subjects: (a) lower velic positions, (b) longer low velic plateaus, and (c) larger lowering and (d) raising movements for final than initial nasals, whether the items with the alternate stress pattern were included or not. The data shown in Fig. 1 are those of Subject 2, which include all utterances with the stress manipulation.

Remember that, rather than compare CVN to NVC, as is done in studies of mirror-image pairs, CVN was compared to CV#N and N#VC was compared to NVC. (Here, we use ‘#’ to denote a word boundary.) This means that, in the case of velic lowering (Fig. 1C), the larger movement occurs from a consonant-plus-vowel sequence to a nasal within the same syllable whereas, in the case of velic raising (Fig. 1D), the larger movement occurs for raising from a nasal consonant to a vowel-plus-consonant sequence across a syllable boundary. Therefore, the results cannot be accounted for based...
on the presence vs. absence of syllable boundaries, but rather by the location of the nasal consonant in the syllable: syllable-final nasal consonants simply involve larger lowering and raising movements, whether such movements do or do not cross syllable boundaries.

These data also showed a significant interaction between stress and syllable position (Fig. 1B). Velum movements in syllables receiving primary stress and velum movements in syllable-final nasal consonants had longer plateaus. This meant that, on average, the sequences with the shortest plateaus were those with syllable-initial nasals in non-stressed syllables whereas those with the longest plateaus were syllable-final nasals in stressed syllables. Nonetheless, the effect of syllable position was significant for both first- and second-stressed syllables, i.e., the velum remained lowered significantly longer for syllable-final than -initial nasals.

Studies investigating syllable position effects on the velum are not limited to those that compare nasals that are also at the beginning or end of a word. For example, Fujimura...
Phonetically, the medial /H/ is produced as elongation of the preceding vowel. The X-ray microbeam system was designed to reduce the amount of X-ray exposure to subjects and to maximize the efficiency of data collection by focusing very narrow X-ray beams on the pellets fixed to specific locations on articulators in the midsaggital plane. Locating the pellets is a computer-controlled activity as is data collection (Kiritani, Itoh & Fujimura, 1975; Nadler, Abbs & Fujimura, 1987).

The Nasograph (Ohala, 1971) is a device used to determine when the velopharyngeal port opens (or closes) by detecting light coming up through the port. A light source, embedded in a thin flexible tube, is inserted through a nostril and positioned below the port. A light-detector, also embedded in the tube, but positioned above the port, is used to pick up the light as it passes through the open port.

In Portuguese, nasal consonants do not occur in word-final position. (1990) examined velum height in an X-ray microbeam study that included the two Japanese words, /seHmeH/ “declaration” and /seN’eH/ “aggressive.” He found lower velum positions for the syllable-final nasal (/N/) than the syllable-initial nasal (/m/) in the word-medial, as well as word-marginal, positions. Fujimura also included sequences containing the syllable-final nasal immediately adjacent to the syllable-initial one, as in /seNmeH/ (“clear”). For these consonant sequences, he observed a position of the velum intermediate between that of the initial and final nasals when occurring as singletons. He attributed this intermediate position to coarticulation between the adjacent nasals. Similarly, the EMG data of Kiritani et al. (1980) showed that, in /Nm/ sequences, one finds almost complete suppression of levator palatini activity followed by an intermediate level of activity.

Word-medial syllable-initial and syllable-final nasals were also compared by Clumeck (1976), who used the Nasograph to examine differences in the duration of nasalization in Brazilian Portuguese sequences with syllable-initial (/fama/) vs. syllable-final (/samba/) nasal consonants. His results showed that the proportion of vowel nasalization was greater before the syllable-final than syllable-initial nasal.

Thus, taken together, a number of measures (both temporal and spatial) point to differences in the articulation of nasal consonants in syllable-initial as compared to syllable-final positions. The larger velum lowering movement, lower minimum and longer low plateau indicate that a vowel preceding a final nasal is more likely to be affected by coarticulatory nasality than a vowel preceding an initial nasal. Clumeck’s data further support this notion, given the relatively longer duration of velic port opening for final, than initial, nasals. However, by focusing on movements that affect velic aperture, we have so far addressed only one aspect of the articulation of nasal consonants.

Krakow’s (1989) data allow us to consider the corresponding oral articulation. The lip data were obtained by tracking the movement of a light-emitting diode (LED) attached to the lower lip with the Selspot System. This meant that the movement included the contribution of the jaw. In contrast to what was observed for the velum, the lip patterns differed for the two subjects. For Subject 1, tested without the stress manipulation, the results showed that initial bilabials were associated with significantly larger raising and lowering movements and a significantly higher lip maximum than the final bilabials. (Only “seam E” – “see me” was an exception, in that no difference was obtained on these measures.) For Subject 2, a comparison of the same sequences showed that the lip movements were largely unaffected by syllable position. Further testing for the effect of position by adding the sequences with the alternate stress pattern showed significantly larger raising, but smaller lowering, associated with the initial nasals. Again, no significant effect of syllable position was found for the lower lip maximum, but instead a significant interaction between syllable position and stress was obtained: in these

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bisyllables, the presence of stress on the syllable containing the nasal consonant resulted in a significantly higher lip maximum (i.e. CVN#VC > CV#NVC; CV#NVC > CVN#VC), regardless of whether the nasal consonant was initial or final or whether stress fell on the first or the second syllable. In other words, final nasals had the higher lip positions in first-stressed syllables and initial nasals had the higher positions in second-stressed syllables. Thus, for the bilabial nasals, syllable position was more consistently distinguished in the velum than labial articulation. Of course, it is possible that a measure of lip constriction might have provided more consistency than that of lower lip plus jaw. We return to this question when lip movements for initial vs. final bilabial stops are addressed in Section 2.3.

2.2. Laterals

As with the nasals, the phonological evidence concerning laterals motivates detailed investigation of their production in syllable-initial and -final positions. In a number of languages, including English, initial and final /l/ are analyzed as allophones of the same phoneme, termed ‘light’ and ‘dark’ /l/, respectively. The most commonly cited difference between the two is that dark /l/ involves a more backed articulation, a characterization that is supported by both articulatory (Giles & Moll, 1975; Sproat & Fujimura, 1993) and acoustic evidence (a lower F2 for final as compared with initial /l/; Lehiste, 1960; Maddieson, 1985). Just as oral constrictions have, in some cases, disappeared from nasal consonants, with nasalization remaining on the preceding vowel, tongue-tip constriction for dark /l/ has disappeared in some languages and dialects (e.g., some forms of British English and in Southern American English), whereas the tongue dorsum movement has remained, leaving a high or mid back vowel (Chen & Wang, 1975; Hardcastle & Barry, 1985; Tranel, 1987; Clark & Yallop, 1990).

It is not surprising, therefore, that final laterals, even when preserved, may be produced with a weaker constriction between the tongue and palate than initial laterals. A classic study by Giles and Moll (1975) provided detailed information on the articulatory differences between initial and final laterals in American English using high-speed lateral cinefluorography. The stimuli included mirror-image pairs (where the ordering of phonemes is reversed, as in Henderson’s velum data), as well as minimal pairs (where only the positioning of the word boundary is shifted, as in Krakow’s lip-velum data). Subjects were initially instructed to speak in a casual style.

Consistent with phonetic descriptions of initial and final /l/, Giles and Moll reported that, for all three subjects, the tongue dorsum tended to be further back in the syllable-final than syllable-initial productions. Their data also indicated that, for two of the three subjects, constrictions between the tongue and palate were, indeed, tighter in initial than final positions. Fig. 2 shows tracings of the tongue from one of the subjects when asked to produce each of the phonetic sequences first with the syllable boundary before the /l/, then with the syllable boundary after the /l/.

Giles and Moll also collected data on the effects of a rate change on the production of syllable-initial and -final /l/, using a subset of the original utterances (i.e., those produced

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11This is a technique used for tracking articulator movements over time from motion picture X-rays. In this investigation, three radiopaque markers were attached to the tongue dorsum in the midsagittal plane. Radiopaque paste was spread on the tongue tip to enhance visibility and consistency of measurement positions over time.
at the “casual” speaking rate) when subjects were asked, instead, to speak as rapidly as they could. Fig. 3 compares productions at the two rates for the same subject whose data are shown in Fig. 2. In addition to the initial-final differences just noted, this comparison showed that, whereas tongue tip contact with the alveolar ridge was consistently maintained for initial /l/ at both speaking rates, the contact was sometimes lost for final /l/. In these data, tongue tip contact with the alveolar ridge was usually observed for final /l/ at the conversational rate, but not at the faster rate. In addition to singletons, Giles and Moll also examined clusters containing /l/ (e.g., “pledge,” “help,” “cleft,” “elf”). At conversational rates, tongue tip-palate contact was also often missing in their study when /l/ was part of a final, but not initial, consonant cluster. Naturally, both the very fast rate and the cluster condition put time constraints on movements to the target, which presumably played a role in the loss of contact for the final consonants in those conditions. On the other hand, it is noteworthy that the syllable-initial /l/ remained quite stable in terms of its production in that the contact with the alveolar ridge was never lost, despite the time constraints associated with an increase in rate. Just as we saw with the nasals, Giles and Moll found similar patterns for word-marginal and word-medial laterals (in the less rapid productions), with syllable position being the relevant variable.

X-ray microbeam data collected by Browman and Goldstein (1995) provide additional support for the findings of Giles and Moll. In their study, a pellet was placed on the tongue tip to allow a comparison of positions for syllable-initial and -final /l/. Four tokens of “leap,” “peel,” “lop,” and “Paul” were produced by one Midwestern speaker in the carrier, “Give — buttons.” (In this dialect, the vowel in “Paul” is pronounced [ɔ], providing the appropriate comparison with “lop.”) Tokens with initial /l/ were
consistently produced with higher tongue positions than those with final /l/, consistent with the predominant pattern obtained by Giles and Moll for their measures of tongue height.

2.3. Stops

Just as in the case of nasals and laterals, researchers have found evidence of weakening and/or loss of final stops in a number of languages and dialects. Weakening may involve failure to release stops in final position, replacement of the supralaryngeal consonant constriction with a glottal stop, and/or devoicing of final voiced stops (Chen & Wang, 1975; Locke, 1983; Manuel & Vatikiotis-Bateson, 1988; Kent & Read, 1992). And, as with the nasals and laterals, weakening of the final consonant articulation may, historically, precede its elimination (see, e.g., Chen & Wang, 1975). Data relevant to constriction degree for initial vs. final stops can be found for the three places of articulation in English: bilabial, alveolar, and velar.

Data collected by Macchi (1988) on lip movements for /p/, like those of Krakow (1989) for /m/, showed inconsistent effects of syllable position across subjects. With pellets attached to the lower lip at the vermilion border in the midsaggital plane (and the lower incisor), Macchi used the X-ray microbeam system to examine two subjects’ productions of initial and final bilabial stops in sequences such as “pa potts” and “pop otts.” In addition to a-a, vowel combinations included i-i, i-u, a-i, i-a and a-u, with four repetitions obtained from one subject and two from the other. Based on measures of the second /p/ in each of these sequences, one of the subjects showed a higher lower-lip position (with
jaw) for syllable-initial than syllable-final /p/ whereas the second subject showed the opposite pattern. Because Macchi had collected the jaw movement as well (with the pellet on the lower incisors), she was able to factor the jaw out of the lower lip movement and thus separate the contributions of the two articulators. Her results suggested that, for these subjects, the syllable-based difference in lip position was largely attributable to the jaw position. It is difficult to determine, for either Macchi’s or Krakow’s data, why there are inconsistencies between subjects.

Earlier it was suggested that measures of lip constriction might provide more consistent results regarding syllable position effects. Unfortunately, only one study was found in the literature that examined this same question with measures of lip constriction, and the data were obtained from a single subject. Browman and Goldstein (1995) collected X-ray microbeam data with a pellet on each of the upper and lower lips. The subject produced the sentence, “My pop huddles,” in each of three accent conditions: accent on the target word “pop,” accent on “My” or accent on “huddles.” Five tokens of each sentence in each accent condition were obtained.

The authors calculated lip constriction degree for initial and final /p/ based on the vertical difference between the upper and lower lip pellet positions which, in its raw form, is an indicator of lip aperture. To convert the numbers into constriction measures (for which higher numbers indicate tighter constrictions), they subtracted the aperture values from an estimate of lip aperture in a neutral position, meaning when the lip is not required to be active. In this case, a neutral position was taken to occur during tongue tip constriction gestures for /t/, produced in other utterances that were part of the larger study (as discussed below). The effect of consonant position was statistically significant with lower constriction values finally than initially, observed across the accent conditions (Fig. 4A). Interpretation of the lip data from the different experiments described is obviously made difficult because the methodologies and the results were mixed. And, unfortunately each data set was obtained from only one or two subjects.

In addition to the lip data, Browman and Goldstein collected data from the same subject on tongue tip and tongue dorsum positions (using pellets on each of those positions

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**Figure 4.** Means for vertical positional measures of initial [●] vs. final [ ■ ] stops, including: (A) lip constriction for /p/ (left); (B) tongue tip height for /t/ (center); and (C) tongue dorsum height for /k/ (right). Before = accent on the word preceding the target word, target = accent on the target, and after = accent on the word following the target. (Baselines are best viewed as arbitrary, but consistent, within consonant position: for the lip and tongue tip data, the authors subtracted the values from an estimate of neutral lip and tongue tip constriction, respectively, whereas no special baseline was used with the tongue dorsum; data courtesy of Browman & Goldstein).
on the tongue) in “tot” and “caulk” (pronounced [kak] by this speaker), respectively. The same carrier phrase and accent manipulation were used as with the bilabials. The effect of syllable position was statistically significant for the alveolars (Fig. 4B) and the velars (Fig. 4C), with higher tongue positions occurring initially than finally, regardless of the accent pattern. Again, single-subject data do not make a strong case by themselves. However, there is additional supportive evidence for alveolars based on measures of constriction.

Keating (1995a) examined the production of initial and final alveolars using the Kay Palatometer. This device provides direct information on the consonant constriction by showing the spatial extent of tongue contact with the palate. Contact measures were obtained for eight repetitions from each of two subjects during the initial /t/s in stressed (“timid”) and unstressed (“timidity”) syllables and of final /t/s in stressed (“emit”) and unstressed (“emit”) syllables. Measured, in each case, was the maximum percentage of all electrodes that lit up at a single point in time. Both subjects showed greater peak contact for initial than final /t/ in stressed and unstressed syllables; however, the main effect of position was significant for one subject only. The other subject showed an interaction between stress and position: for that subject, initial-final differences were significant in stressed syllables only.

A second experiment by Keating (1995a) examined palatometer data from a single subject for the voiced alveolar /d/. In this study, contact patterns in the words “deaf” (initial /d/ in a stressed syllable), “demand” (initial /d/ in an unstressed syllable), “fed” (final /d/ in a stressed syllable) and “aphid” (final /d/ in an unstressed syllable) were obtained. The results showed that there was significantly greater contact initially than finally for /d/, and significantly greater contact in stressed syllables than unstressed syllables, whether at the beginning or end of a word. (In addition to the word position and stress manipulations, each test word was embedded in a carrier phrase in each of three different positions: sentence-initial, -medial, -final. Differences in the contact for initial vs. final /d/ were greatest in sentence-initial position.)

The data on alveolar and velar stops seem to be quite consistent with our notion that constrictions are generally tighter syllable-initially than -finally. To add to what we have learned from physiological data, it is worth considering the measures of intra-oral air pressure obtained by Malécot (1955), indicating what he called “force of articulation,” especially as these data provide additional information on bilabials. Much of Malécot’s work in this area focused on comparisons between voiced and voiceless consonants or among manner classes (i.e., stops vs. fricatives vs. nasals). However, he also investigated positional effects, comparing pressure behind the consonant constrictions in CV CVC and CVCVC sequences for ten subjects. In each sequence, all three consonants were the same, but the items produced, taken together, included all the voiced and voiceless stops of English, as well as the fricatives /f s v z/. Smaller peak pressures and smaller pressure impulse values were obtained finally than initially for all consonants, regardless of the stress pattern. Malécot concluded that there is greater articulatory force for initial than

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12 With this technique, the subject wears an artificial palate containing a large number of electrodes, which selectively light up whenever contact between the tongue and palate is detected.
13 Using a catheter coupled with a pressure transducer, inserted through the nose and into the mid-pharynx, Malécot obtained two kinds of pressure measures: peak pressure (measured in mm of water), and pressure impulse. The latter was taken to be “the area (in mm2) contained within the limit of the pressure curve and baseline.” [p. 96]
final stops and fricatives. He also observed a greater force when the consonant preceded a stressed vowel.

Taken together, then, the intra-articulator evidence regarding nasals, stops, and laterals is largely consistent with the notion that there are tighter constrictions in initial than final positions, although the data on the bilabials appear to be ambiguous. The extent to which the data on the rest of the consonants are consistent is noteworthy, especially given the variety of instruments and methods used by the different researchers.

3. Inter-articulator timing

The evidence indicates that, in many instances, coordinative patterns for syllable-initial consonants are distinct from those for syllable-final consonants. However, changes in other aspects of the speech produced, e.g., style or rate change, can result in variability in the syllable-based coordinative pattern. In some cases, the syllable-initial and -final consonants are rendered more, if not entirely, alike. Thus, as we look to find stable patterns of articulatory organization for syllable-initial vs. -final consonants, we note clear evidence of considerable variability, which must be accounted for. This brings us to a comparison of inter-articulator timing patterns for syllable-initial and -final nasals (lip-velum coordination), laterals (tongue tip-tongue dorsum coordination), and stops (lip-larynx coordination). We begin with the nasals.

3.1. Nasals

Krakow (1989) hypothesized that the greater likelihood of vowel nasalization preceding a syllable-final nasal than a syllable-initial nasal was related both to differences in magnitude of velic lowering for initial and final nasals and to differences in the timing of the lowering gesture relative to gestures for the oral tract closure. Fig. 5 provides sample movement patterns for the subjects’ (S1 and S2) productions of word-initial and -final nasals from Table I. (The method for determining movement onsets and offsets involved the use of a noise band around zero velocity. Using this approach, any very slow downward drift following the end of a rapid lowering movement was taken as part of the low velum plateau. See Appendix for further discussion.)

The inter-articulator patterns for the nasals were such that the end of velic lowering appeared, in general, to be closely linked in time either to the beginning (for final /m/) or to the end of lip raising (for initial /m/). The consistency of these syllable-based patterns is especially noteworthy given differences in the trajectories that were related to the segmental makeup of the individual phonetic strings. The timing of the velic lowering movement relative to the activity of the lip in the case of final nasals would be expected to yield significant vowel nasalization, consistent with the phonological evidence that nasal assimilation is most likely to be evident on vowels preceding final nasals (Schourup, 1973).

Note that Fujimura et al. (1977) provide X-ray microbeam data showing velum and tongue movement for nasals in homorganic alveolar clusters with final voiced or voiceless fricatives or stops (e.g., “pens” and “pence”; “pined” and “pint”). While the focus of that study was on the effects of voicing, the traces show that the syllable-final timing pattern described by Krakow (1989) occurs in these NC clusters: the velum reaches a minimum as the tongue blade begins to rise.
Krakow (1989) also included comparisons of word-medial and marginal nasals, holding syllable position constant (Columns 3 and 4 of Table I). Mean data (Table II) showed that, whether measured in relation to lip raising onset or offset, velum lowering ended somewhat later for the word-medial than -final nasals. Nonetheless, the patterns for syllable-final nasals (whether word-medial or -marginal) appeared similar: there was close temporal proximity between the end of velum lowering and the beginning of lip raising and a large delay between the end of velum lowering and the end of lip raising. Mean data for the corresponding word-initial nasals (from Column 1 of Table I) are also shown in Table II. In contrast to the patterns for final nasals, velum lowering offset occurred considerably later than lip raising onset for the initial nasals. The comparison just described was aimed at determining whether, in fact, effects thus far considered syllable-based might instead have been word-based. In addressing this question, Krakow focused on inter-articulator timing, but studies described above in Section 2.1 (Clumeck, 1976 and Fujimura, 1990 on nasals and Giles & Moll, 1975 on laterals) lead to the same conclusion in comparisons of intra-articulator patterns.

Krakow considered another non-segmental manipulation, that of stress, to see how it affected oral-velic timing. In this case, patterns for CVN*VC were compared to those for CV*NVC, and patterns for CV*VC were compared to those for CV*NVC. It was clear that the presence of the nasal consonant (whether initial or final) in the stressed syllable led to earlier velic lowering offset relative to the lip movement. For final nasals,
In these data, the onset of lip contact was determined with the use of a modified electroglossograph and based on the same principle as identification of the onset of vocal fold contact (see Krakow, 1989).

### TABLE II. Coordinative patterns for sequences with medial (VN + IV), final (VN#IV), and initial (V#NV) nasal consonants from Krakow (1989)

<table>
<thead>
<tr>
<th></th>
<th>Velum lowering offset – lip raising onset (ms)</th>
<th>Velum lowering offset – lip raising onset (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td>39</td>
<td>−135</td>
</tr>
<tr>
<td>Final</td>
<td>6</td>
<td>−195</td>
</tr>
<tr>
<td>Initial</td>
<td>183</td>
<td>−27</td>
</tr>
<tr>
<td>S1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td>18</td>
<td>−178</td>
</tr>
<tr>
<td>Final</td>
<td>−5</td>
<td>−235</td>
</tr>
<tr>
<td>Initial</td>
<td>184</td>
<td>−7</td>
</tr>
</tbody>
</table>

The difference in the relative timing of velic lowering offset to the lip movement was not significant. For the initial nasals, on the other hand, it was. In the case of initial nasals followed by a stressed vowel, the end of velic lowering was more closely linked to the beginning of bilabial contact than to the achievement of the peak lip position (i.e., the end of lip raising) for the /m/.14 Across the dataset, contact onset preceded the time of the lip maximum, presumably because of additional compression following initial lip contact and/or the spread of contact along the length of the lips. Thus, it still appears to be the case that, for initial nasals, the end of velum lowering was temporally linked to the target position of the lip whereas, for final nasals, the end of velum lowering was linked to the onset of lip movement toward the target position. Presumably, the fact that final nasals are associated with such early velic lowering in the non-stressed syllables (lowering offset timed to lip raising onset) meant that stress could not induce earlier lowering; the effect would likely be injurious to the articulatory/perceptual integrity of the preceding oral consonant.

Subsequent to the work of Krakow (1989), Wang (1995) investigated lip-velum coordination for syllable-initial and -final nasals in Cantonese. The results appeared to challenge the notion that syllable-initial and syllable-final nasals would differ in a similar manner across languages: her four speakers’ productions of both initial and final nasals generally had relative timing patterns that resembled the syllable-initial productions in English, with lip raising offset and velum lowering offset being closely timed. The difference in results across the two studies is noteworthy since both Wang (1995) and Krakow (1989) used the Velotrace and Selspot System and both tracked velum as well as lower lip (with jaw) movement, and used the same kinds of criteria for determining movement onsets and offsets. However, in addition to the focus on English vs. Cantonese, the experiments differed in two ways: Wang used nonsense sequences, whereas Krakow used real word sequences, and Wang asked her subjects to speak casually whereas Krakow asked her subjects to speak carefully. Here, we pose the question of whether the difference in speaking style or rate might have resulted in the different outcomes between the two studies.

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14In these data, the onset of lip contact was determined with the use of a modified electroglossograph and based on the same principle as identification of the onset of vocal fold contact (see Krakow, 1989).
Both studies provided measures of lip raising and lip lowering duration (movement of a primary articulator toward and away from the consonant constriction). These were used to compare relative utterance durations across the two studies. For the utterances that were phonetically most comparable across the two studies (those in which /m/ was flanked on both sides by the vowel /i/, /si#mi/ and /sim#i/ in English; and /tsi:m#it/ and /tsi:#mi:t/ in Cantonese), lip raising and lip lowering durations were added together to obtain a duration of the lip cycle associated with the vowel-nasal consonant-vowel sequence. The results indicated that Krakow’s two subjects spoke considerably more slowly than all four of Wang’s.

One hypothesis that might be considered, then, is that, using a faster speech rate or more casual style, syllable-final nasals are subject to resyllabification, yielding a relative timing pattern that resembles that of the syllable-initial nasals. It was easy to test, in a preliminary way, the hypothesis that the change in rate and/or style can foster a change in the relative timing of the lip and velum movements such that final nasals begin to resemble initial nasals. This was because the data collected by Krakow (1989) included another set of utterances, not analyzed in the original study, i.e., productions by Subject 1 of six tokens each of the utterances with the word-initial and word-final nasals in “see me,” “seam E,” “see more,” “seam ore,” “hell mitt,” “pa made,” and “palm aid,” produced in a casual speaking style. The corresponding data produced “carefully” were described above. Movement onsets and offsets for the casual data were measured in the same way as the carefully produced data (as described in the Appendix).

Fig. 6 shows, for both syllable-initial and -final nasals, the temporal relation between the end of velum lowering and (a) the end of lip raising or (b) the beginning of lip raising. It is necessary to consider the ways in which these data resemble or do not resemble the carefully produced utterances. It is clear that, in the casual speech, the velum reached its low position earlier for final than initial nasals (evident in Figs 6A and B). This pattern is consistent with the careful speech data. Fig. 6A shows that the end of velum lowering for initial nasals is more closely timed to the end of lip raising than it is for final nasals, as we had described for the careful rate data. Furthermore, the attainment of lip and velum targets is roughly synchronous for the initial nasals in the casual speech (as it was in the careful speech), with the exception of “pa made.” In the latter case, we would expect to see the stress coupled with the low vowel make the velum lowering offset occur earlier than in the other sequences, as it did even in the careful speech. However, velum lowering offset in this case appears to be roughly equally spaced between the two lip endpoints (cf. Figs. 6A and B).

In contrast to the evidence that casually and carefully produced initial nasals patterned similarly (compare Figs. 5 and 6A), the final nasals showed a change in the pattern as a function of the style or rate change. Fig. 6B shows that, in the casual speech, one does not generally see the nearly synchronous velum lowering offset and lip raising onset that was observed in the careful speech, although the final nasals show a closer link between these two events than the initial nasals. Instead, the casual final nasals show velum lowering offset that, on average, has moved in the direction of lip raising offset, i.e., in the direction of the syllable-initial pattern. (In three of four cases, it nonetheless remains closer to onset than offset.) Taken together, the results indicate that the syllable-initial pattern is more stable than the syllable-final pattern when the style changes from careful

\[15\] Recall that, for this subject, there was no stress manipulation and that the stress pattern was fixed according to the matched single-word sequences (Table 1).
Figure 6. Mean values for the temporal relation between velum lowering offset and each of the endpoints of lip raising, i.e., (A) lip raising offset and (B) lip raising onset, in casual speech. Means are shown for the four comparisons of sequences with initial (light bars) and final nasals (dark bars) listed at the right.

3.2. Laterals

Two recent studies, Sproat & Fujimura (1973) and Browman & Goldstein (1995), examined the effects of syllable position on tongue tip and dorsum coordination for laterals. Data for both studies were collected using the microbeam system with pellets positioned to casual. Such evidence appears to suggest that the Cantonese data may, indeed, involve resyllabification of the final nasals due to the rapid rate or casual speaking style involved. However, since these are single-subject data, it is important to seek confirmation of the notion that syllable-final consonants may be (partially or entirely) resyllabified in rapid or casual speech. Thus, the same issue will be addressed in the discussions of syllable-initial and -final laterals and stops.
Sproat and Fujimura (1993) describe the # and + boundary types as follows. ".+ is the boundary between (most) latinate affixes and their bases, whereas # is the boundary before the more productive non-latinate derivational and inflectional affixes." (p. 296) This is in contrast to our use of the symbol '.'# earlier in this paper to represent a word boundary.

in the vicinity of the tongue tip and on the tongue dorsum (as well as on the tongue blade in Sproat & Fujimura, 1993).

Five subjects participated in Sproat and Fujimura’s study and produced a set of sentences containing syllable-initial and -final /l/’s. Each sentence was repeated up to four times using a conversational speaking style. Across the list of sentences, final /l/’s were followed by a variety of lexical and phrasal boundary types. Among the dataset were sentences considered to contain “canonical” initial or final /l/ (e.g., the word-initial /l/ in “Mr. B. Likkovsky’s from Madison” and the word-final /l/ before a major intonation boundary in “Beel, equate the actors”). We consider, first, the results for such sentences.

In contrast to the generally-held notion that only final /l/ involves tongue retraction, Sproat and Fujimura observed retraction and lowering of the tongue body for both the initial and final laterals preceding /i/ or /I/; however, these movements were more extreme for final /l/. In addition, tongue dorsum movement occurred considerably earlier in relation to tongue tip movement for final than initial /l/, and this temporal effect was, like the spatial differences, statistically significant. Specifically, the authors reported that, for initial laterals, the dorsal retraction (or lowering) extreme tended to follow the tip forwarding extreme. However, for final laterals, the dorsal extreme tended to precede the tip extreme. This paralleled Krakow’s findings for the bilabial nasals, in that velum lowering occurred considerably earlier in relation to lip raising for final, than initial, nasals. Movement of the velum and tongue dorsum in nasal consonants and laterals, respectively, are articulations that occur in addition to the primary constriction in the vocal tract (i.e., the lip constriction for the bilabial nasals and the tip constriction for the laterals). Apparently, for these consonants, the velic or dorsal components of the articulation vary in their temporal relation to the primary constriction such that syllable onsets are different from syllable offsets.

In related work, Browman and Goldstein (1995) examined the relative timing of tongue tip and dorsum movements for initial and final /l/ in “leap” vs. “peel” as produced by a single speaker. The target words were repeated four times each in a carrier which forced a syllable boundary between /l/ and an adjacent consonant, i.e., “Give leap buttons” and “Give peel buttons.” Browman and Goldstein reported that the end of tongue dorsum retraction was timed to the end of tongue tip raising for initial /l/, but to the beginning of tip raising for final /l/ (Fig. 7). That is, the secondary articulator reached its target at either the end (for syllable-initial laterals) or the beginning (for syllable-final laterals) of the movement of the primary articulator. This is precisely parallel to the difference noted by Krakow (1989) between velum and lip movements as a function of syllable position where the secondary articulator, the velum, reached its target position at the onset (final nasals) or offset (initial nasals) of lip raising.

Returning to the study of Sproat and Fujimura, however, the picture becomes more complex when considering the complete dataset which, as we noted, included a variety of lexical and phrasal boundary types following the syllable-final /l/. The different boundary types were designed, by the authors, to provide a range of durations of the rime (vowel + lateral) in sequences containing the final laterals. Table III lists the boundary types included in this study along with an example of each type. Also listed is the sentence type with initial /l/.\textsuperscript{16}

\textsuperscript{16}Sproat and Fujimura (1993) describe the # and + boundary types as follows. “ + is the boundary between (most) latinate affixes and their bases, whereas # is the boundary before the more productive non-latinate derivational and inflectional affixes.” (p. 296)
Considering the entire utterance list, with the variety of boundaries following the final /l/, the authors described a range of coordinative patterns for final /l/: from the pattern of the “canonical” final /l/ to that of the “canonical” initial /l/ (described above), with many patterning between the two extremes. To illustrate this point, data obtained from one of the subjects are displayed in Fig. 8, which is a plot of the acoustic duration of the vowel-plus-/-l/ sequence by the time difference between the occurrence of the tongue tip extreme and the dorsum extreme. The authors reported that the duration of the vowel-plus-/l/ sequence (i.e., rime duration) accounted for a considerable amount of the variation in the patterning of the final laterals: the longer the rime, the more the pattern resembled that of the canonical final /l/. (Note that the initial laterals are plotted here simply for comparison purposes, and are not factored into the correlations.) Indeed, for three of the five subjects, including the one whose data are depicted in Fig. 8 (R2 = 0.65), rime duration accounted for more than half of the variation in relative timing. There is much left to be explained, however: in no case did rime duration account for more than 65% of the variance in the relative timing pattern. And, for two of the subjects, it accounted for only 25% or less. Sproat and Fujimura provided a hierarchical listing of
TABLE III. Utterance types from Sproat and Fujimura (1993)

<table>
<thead>
<tr>
<th>/l/ Environments</th>
<th>Sample sentences</th>
<th>Plotting characters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before /h/</td>
<td>Mr. Beel Hikkovsky’s from Madison</td>
<td>h</td>
</tr>
<tr>
<td>Major intonational boundary</td>
<td>Beel, equate the actors</td>
<td>I</td>
</tr>
<tr>
<td>VP phrase boundary</td>
<td>Beel equates the actors</td>
<td>V</td>
</tr>
<tr>
<td>VP-internal boundary</td>
<td>I gave Beel equated actors</td>
<td>P</td>
</tr>
<tr>
<td>Compound-internal boundary</td>
<td>The beel-equator’s amazing</td>
<td>C</td>
</tr>
<tr>
<td># boundary</td>
<td>The beel-ing men are actors</td>
<td>#</td>
</tr>
<tr>
<td>+ boundary</td>
<td>The beel-ic men are actors</td>
<td>+</td>
</tr>
<tr>
<td>No boundary</td>
<td>Mr. Beelik wants actors</td>
<td>%</td>
</tr>
<tr>
<td>Word initial</td>
<td>Mr. B. Likkovsky’s from Madison</td>
<td>i</td>
</tr>
</tbody>
</table>

Figure 8. Scatterplot of the relation between the duration of the /l/ plus the preceding vowel (x-axis) and “tip delay” (y-axis). “Tip delay” refers to the interval between (a) the time at which the tongue tip reached its maximum and (b) the time at which the tongue dorsum reached its minimum. The latter also corresponds to the time at which the dorsum reached its most posterior position. Symbols above the dashed horizontal line correspond to cases in which the end of dorsum lowering/backing preceded the end of tip raising. Symbols below the dashed line correspond to cases in which the end of dorsum lowering/backing followed the end of tip raising. (Reproduced from Sproat & Fujimura, 1983, with the permission of Academic Press.)
boundary types according to syntactic principles: “[l > V > P > h > C > # > +]” (p. 296). The plot shows that the relation between boundary strength and the relative timing pattern also leaves much unaccounted for. Certainly other factors are involved here.

One variable found in the sequences containing the final nasals that was not addressed by the authors was the status of the /l/ within the word. Fig. 8 shows that word-medial syllable-final laterals were quite similar in their organization to the initial laterals whereas the word-final laterals were usually quite distinct. Actually, Sproat and Fujimura’s data show a nice continuum in the relative timing pattern that fits well with an analysis that includes word position of the lateral, rather than just syllable position. Word-final laterals have the most extreme “dark” pattern. These include /l/s followed by boundaries that have the symbols DD, V, P (major intonation boundary, verb phrase boundary, verb phrase-internal boundary, respectively). In contrast, the word-medial laterals have a less “dark” and, in fact, rather “light” pattern in these data. These include /l/ followed by derivational and inflectional affixes (represented by # and +, respectively). The laterals that are, in some sense, both word-medial and word-final, i.e., final in the first word of a compound (and represented by C), have an intermediate pattern. (The patterning of the /l/s preceding /h/ appears to be an exception.)

Another factor worth considering is the position of the /l/ in the utterance as a whole. For example, among the word-final laterals, the two that occur in the first word of the utterance (l and V) appear to have the most extreme “dark” /l/ pattern. Additional data will be necessary to address this hypothesis; however, recent work by Fougeron and Keating (1997) indicates that syllable-initial consonant articulations have even tighter consonant constrictions in sentence-initial position than in other positions. Other work by Keating (1995a) shows that differences between syllable-initial and syllable-final articulatory constrictions are greatest when the consonants are in sentence-initial words. Taken together, these facts suggest that syllable-final consonant articulations might also become more canonical or distinct in sentence-initial words. Of course, Sproat and Fujimura’s analysis likewise predicted that the syllable-final laterals in sentence-initial words would yield the “darkest” /l/s, based on the nature of the boundary type that followed; one of these /l/s occurred before a major intonation boundary and the other, before a verb phrase boundary. That is, in these sequences, the location of the relevant word in the sentence (i.e., initial, medial, final) is confounded with its position relative to the immediately following syntactic boundary. Thus, future work should include utterances in which these possibilities are sorted out.

Nonetheless, the studies of lip-velum coordination and tongue tip-dorsum coordination, in careful speech or “canonical” cases, provide consistent evidence concerning articulatory organization of syllables. In both cases, the secondary articulator (the velum for the bilabial nasals and the tongue dorsum for the laterals) reaches its target position considerably earlier than the primary articulator (the lower lip and the tongue tip, respectively) for syllable-final than -initial consonants. In casual (or fast) speech, the pattern characteristic of the final consonant (whether /m/ or /l/) was subject to a shift in the direction of that for the initial consonant. It appears that this shift is more likely to occur when the consonant is word-medial than -marginal. On the other hand, the syllable-initial consonants (/m/ and /l/) remained relatively stable with respect to their inter-articulator timing, regardless of the style or rate of speech.

There is a parallel in Krakow’s (1989) velum and lip data for syllable-final nasals. Relative to the end of lip raising, velum lowering offset occurred later when those nasals were word-medial rather than word-final (e.g., in “seemly” vs. “seam Lee”) much as the
tongue dorsum/mid movement occurred later for the word-medial than the word-final laterals (e.g., in “beelic” vs. “Beel equate”). The difference in relative timing as a function of the word position manipulation was relatively small for the nasals as compared to the laterals; however, in the former case, a syllable boundary was forced after the nasal by the presence of the contiguous /l/. Furthermore, Krakow’s speakers used a careful style and Sproat and Fujimura’s, a casual style.

3.3. Stops

Evidence concerning relative timing for stop consonants provides additional insight into issues of stability and variability in the production of syllable-initial vs. -final consonants. The results support the notion that, in the slower or more careful productions, initial and final stops are associated with distinct coordinative patterns whereas, in the faster speech, initial and final stops may not be distinguishable.

Tuller and Kelso (1990) asked four subjects to produce a series of repetitions of the syllable /pi/ and a series of /ip/, while increasing their rate of speech in four to six steps in each trial. They focused on the relative timing of labial and laryngeal movements for the syllable-initial and syllable-final /p/s. Lip aperture was obtained by taking the difference between the positions of two Selspot LEDs, one each on the upper and lower lips. Glottal opening was obtained using transillumination.\(^\text{17}\)

The authors then determined the phasing of peak glottal opening to the lip cycle (that is, the time from one occurrence of minimum lip aperture, i.e., maximum constriction, to the next). This relation is described in terms of the phase angle of the glottal opening relative to the lip cycle (an entire cycle is 360 degrees). For three of the four speakers, the phase relations for /ip/ and /pi/ were both stable and distinct: peak glottal opening occurred later relative to the lip cycle for initial than final /p/. The fourth subject did not produce stable relative timing patterns for either type of syllable. Focusing, then, on the other three subjects, Tuller and Kelso showed that, as subjects increased their speaking rates, the phase relation for /pi/ remained stable, whereas that for /ip/ became indistinguishable from the pattern for /pi/. They noted that the shift from the final to the initial-type pattern occurred at different speaking rates for different speakers. Hence, for these utterances, lip-larynx coordination for the syllable-initial position appears more stable than for the syllable-final position: an increase in speaking rate at some (speaker-dependent) upper limit fosters a change from syllable-final patterning into syllable-initial patterning. A subsequent perceptual experiment (Tuller & Kelso, 1991) provided evidence of perceptual consequences of the change in coordinative patterns: at the same rates at which the syllable-final pattern was no longer evident, subjects heard only CV syllables.

The tendency for syllable-final stops to migrate to syllable-initial position with an increase in rate was also noted years earlier by Stetson (1951) who compared the relative timing of air pressure peaks (outside the mouth) associated with the vowel to peaks of tongue movement (for /t/) or lip movement (for /p/). He observed that, at a faster rate (i.e., beyond 3.5 syllables per second), “ape” became “pay” and “eat” became “tea.”

\(^{17}\)Transillumination is a technique in which a light source is placed below the glottis and a light detector, above. The amount of light shining through the opening is recorded and used to indicate the magnitude of glottal opening (Baer, Loqvist & McGarr, 1983; this works on much the same principle as the Nasograph does for velopharyngeal port opening, as described above).
Thus, the data on lip-larynx phasing in the production of /p/ add to the data already discussed on relative timing in nasals (lip-velum) and laterals (tongue tip-tongue dorsum). Stable timing relations were observed for syllable-initial consonants irrespective of rate or style of speech whereas characteristic timing relations for syllable-final consonants were only evident in careful or less rapid speech.

4. Uncertain syllable affiliation

Observations of syllable-based articulatory patterns provide an opportunity for comparison with patterns observed for consonants in cases in which phonotactic constraints and word boundaries do not decide between syllabification with the preceding or following vowel. The syllable affiliation of such consonants has frequently been the source of debate among phonologists. Most at issue are those consonants preceding unstressed vowels (cf. Pulgrum, 1970; Hoard, 1971; Anderson & Jones, 1974; Kahn, 1976; Bailey, 1978; Selkirk, 1982).

An approach taken by Krakow (1989) and Turk (1994) to the investigation of this question involved the development of a set of characteristics found in unambiguously syllabified consonants which were then compared to the characteristics of consonants whose syllable affiliation was at issue. The researchers investigated whether each “unclear” consonant better matched the initial or final consonants or whether it appeared as something of a combination of initial or final attributes (i.e., possibly ambisyllabic).

Krakow (1989) used the carefully produced word-medial nasal consonants in “homey,” “seamy,” “Seymour,” “pomade,” and “helmet” and compared them to the patterns observed for the matched sequences with word-initial and word-final nasals, described above (compare columns 5, 1, and 2 of Table I). In these data, various measures were used to develop a profile of the medial nasals in order to determine the syllabification of those consonants. These measures included: the relative timing measures described above (velic lowering offset in relation to lip raising onset and offset), the duration of the low velic plateau, as well as a measure of velic height at the midpoint of the vowel preceding the nasal consonant and at the onset of the nasal consonant.\(^1\)

No doubt, these data must be viewed as suggestive because of the limited number of sequences involved coupled with variability across and within subjects. Nonetheless, in most cases, the nasal consonant appeared to affiliate with the syllable carrying primary stress: for both subjects, the nasal consonants in “homey” and “seamy” appeared syllable-final, whereas, in “pomade,” the nasal consonant appeared initial. Similarly, in S2’s data, the nasal consonant in “helmet” appeared syllable-final. Data inconsistent with the prediction that such medial nasals will affiliate with the syllable carrying primary stress included S2’s productions of “Seymour,” in which the /m/ appeared syllable-initial and S1’s productions of both “helmet” and “Seymour,” for which the results were mixed. For “helmet,” S2’s productions were split between those that appeared to contain a final nasal and those that appeared to contain an initial nasal. There was also such a split for

\(^1\)The latter measure was obtained because of the difficulty of getting movement measures from S1’s productions of the sequences, “homey,” “home E,” and “he me.” Hence, for S1’s productions of these 3 sequences, only the acoustically based measures of velum height were used in this analysis (see footnote 6). For the rest of the sequences, the acoustically based measure was used in addition to the other measures described here.
this subject’s productions of “Seymour,” however another subset of the tokens appeared more like a combination of initial and final attributes. Krakow proposed that the two sequences showing a deviation from the stress-based syllabification were cases in which specific conditions might have led to an alternative organization. In “helmet,” for example, the presence of the consonant sequence may have prompted a syllabification in which the /lm/ consonant sequence is divided across syllables rather than affiliated with the stressed vowel. In “Seymour,” the presence of secondary stress on the second syllable may have attracted the nasal consonant to that syllable. Although it appears that stress-based syllabification accounts well for most of these data, it is not entirely clear how to account for the exceptions. Still, data from another study on lip movements provide some support for the hypothesis that primary stress tends to attract the medial consonant.

Turk (1994) used the X-ray microbeam system with a pellet on the upper lip. In this case, the focus was on oral bilabials and the measurements were of upper lip movement (specifically, vertical displacement and peak velocity) in the productions of three subjects. The sequences of interest were those containing intervocalic consonants preceded by a stressed vowel and followed by an unstressed vowel, as in “rabble” and “leper.” Of course, these consonants follow lax vowels in stressed syllables and, as such, must terminate the syllables. But some researchers have suggested that such consonants might, at the same time, affiliate with the following syllable (i.e., function as ambisyllabic; see Kahn, 1976).

Turk used discriminant analysis to determine how such consonants patterned in relation to bilabials in contexts in which syllabification was unambiguous, e.g., the syllable-initial consonants in the “repair” and “rebel (v.)” vs. the syllable-final consonants in “captor” and “object (n.)”. In particular, she suggested that evidence of ambisyllabicity might be found by looking separately at movements toward and movements away from the consonant in question. Turk found that the intervocalic consonants preceding an unstressed vowel generally patterned as though syllable-final, both in their closing and opening movements.

The two studies just described provide evidence that physiological data are likely to be useful for determining syllable affiliation in cases in which other kinds of evidence fail to provide an answer. Both the studies of velum-lip coordination and of upper lip movement patterns appear to support the hypothesis that, in just those cases in which syllable affiliation has been most debated (in intervocalic position before an unstressed vowel), the consonant is usually affiliated with the preceding vowel. At the same time, given the data examined in previous sections, it is worth speculating that these consonants may, in fact, be quite susceptible to partial or complete resyllabication in speech produced casually or rapidly, since they are necessarily word-medial.

5. Summary and discussion

The purpose of this review was to determine whether the notion that syllables correspond to characteristic patterns of articulatory organization is a viable one when one considers a variety of speech sounds and articulators. The evidence from nasals, laterals, and stops indicates that, in careful or non-rapid speech, one typically does observe distinct intra- and inter-articulator patterns for syllable-initial and syllable-final consonants. Given the assumption that careful and/or non-rapid speech provides the best
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evidence concerning speakers’ tacit knowledge of the articulatory patterns for particular lexical items, it seems reasonable to conclude that there are characteristic patterns of articulatory organization that distinguish syllable onsets from syllable offsets.

Specifically, for the three classes of consonants, the intra-articulator data were largely consistent with the notion that tighter constrictions are found initially, based on measures of velum, tongue tip, and dorsum height, and of bilabial and lingua-palatal constriction. One might suppose that, if a final consonant constriction is weaker than an initial consonant constriction, the listener may fail to detect that final consonant even when the constriction is present. Moreover, as discussed by Ohala (1981), what is not detected in the spoken output, whether actually present or not, may not be included when the listener next becomes speaker. Of course further weakening or loss of the constriction may instead (or in addition) have an articulatory basis. For example, a relatively weak consonant constriction, evident in careful speech, may be further weakened in more rapid or casual speech such that contact does not occur at all.

Investigation of the inter-articulator timing patterns showed that, in the careful, non-rapid, or ‘canonical’ productions of nasals, laterals, and stops, there was a closer temporal relation between the velum and lip for /m/, the tongue tip and dorsum for /l/, and the lip and larynx for /p/ when the consonants were initial rather than final. When we consider all the data evaluated so far, it seems fair to state that syllable-initial position is a stronger position; first, based on the evidence of tighter constrictions which presumably involve greater articulatory effort and second, based on the relative stability of the patterns (both intra- and inter-articulator) for syllable-initial consonants. For example, changes in rate and/or style had qualitative effects on the production of final consonants; i.e., they appeared unstable, perhaps too difficult to retain, at very rapid rates and/or in casual styles of speech. As noted, one outcome of an increase in rate or change to a more casual style was loss of the primary consonant constriction. A second outcome for the three classes of consonant (nasals, laterals, stops) examined was a change in the coordinative pattern for the final consonants such that the relative timing pattern shifted in the direction of that for the corresponding initial consonants: sometimes the pattern remained clustered with those of other canonical/careful final consonants; other times, the pattern appeared intermediate between those of the distinct initial and final consonants; and still other times, the pattern for the syllable-final consonant appeared to indicate a complete shift to syllable-initial organization. By what principle(s) did these changes occur?

First, as noted, increasing the rate of speech or changing the style to a more casual style was found to influence the articulatory organization of syllable-final consonants. Other factors influencing the inter-articulatory timing pattern and/or the degree of consonant constriction included: the position of the final consonant in the word (medial position was less stable), the nature of the following syntactic boundary (final consonants before weaker boundaries were less stable), the occurrence of the consonant as part of a final cluster vs. singleton (final nasals, laterals, and stops were less stable in clusters) and, possibly, the location of the relevant word in the utterance (consonants in utterance-initial words may be more stable). Indeed, it seemed that one could begin to predict the extent to which a syllable-final consonant would resemble the more “canonical” or “careful” production by seeing how many of these factors conspired to render that organization unstable. Thus, for example, a final consonant produced as part of a cluster in casual speech would be quite unstable; more so than the same consonant produced as a singleton under the same conditions. And, a word-medial syllable-final consonant
produced casually would be more unstable than a word-final consonant produced under the same conditions. Even in careful speech, the patterns of syllable-final consonants in word-medial position were less stable than those in word-final position. And, the more rapid the speech, the more unstable final consonants became, all other things being equal.

Still, we clearly need to have a better understanding of the set of factors that together influence the intra- and inter-articulatory patterns for the syllable-final consonants. It is certainly the case that rate, style, word position, syntactic/prosodic position, presence of a cluster vs. singleton all have an effect, but it is not precisely clear how these factors combine to shape the articulatory organization for the different kinds of consonants, or what other factors play a role.

Certainly, taken together, the results of the studies discussed support the notion that syllables are organized articulatorily. Adopting the notion of characteristic movement patterns for beginnings vs. ends of syllables (Krakow, 1989; Browman & Goldstein, 1995) appears to provide the first clear and consistent picture of how syllables are organized and of the relation between the articulatory organization and the phonological patterns described in the literature. The results, showing both tighter constrictions and greater stability for initial than final consonants, appear also to provide a link to the cross-language preference for CV syllables, in which a tight consonantal constriction alternates with the open position of a vowel. The relatively weaker constriction of syllable-final consonants makes them less distinct from an adjacent vowel than is the case for initial consonants. Further weakening of the final consonant constriction, e.g., due to an increase in the rate of speech or change to a more casual style, renders the consonantal contact subject to loss. The relative timing patterns (for the nasals and laterals) also indicate that there is considerable temporal overlap between a syllable-final consonant and a preceding vowel, which also reduces the contrast between the two. This brings us to the question of what happens when that final consonant becomes extensively overlapped with the preceding vowel due to particular speaking conditions; that is, what happens when the syllable-final organization becomes very unstable?

The data reviewed here suggest that one possible outcome is loss of the consonant constriction for the final consonant, with other aspects of its production remaining on the vocalic portion of the syllable. For example, the evidence from the laterals indicated that, in very rapid speech or when produced casually as part of a syllable-final cluster, the final consonant constriction was sometimes lost (Giles & Moll, 1975). Since we also know that tongue dorsum retraction often preceded tongue tip raising by a considerable amount of time, it seems reasonable to suppose that the vocalic portion might retain the retraction gesture. Indeed, phonological evidence supports this notion. Historically, in French, the constriction for dark /l/ was lost in words like “chevals” (horses). In this and similar words, dark /l/ first became the back vowel, /u/, forming a diphthong with the preceding /a/. The vowel sequence was then simplified to /o/ (modern “chevaux”). Other examples of French words that have undergone /l/ vocalization include “paume” (palm), “loyauté” (loyalty), and “faute” (fault) (see Tranel, 1987; Clark & Yallop, 1990). A similar process of /l/ vocalization occurs in some dialects of British and American English, as described by Hardcastle and Barry (1985), for final clusters in British English and by Ohala (1974) for children’s speech.

Similarly, distinctive nasal vowels have commonly arisen through complete loss of the consonantal constriction with nasality maintained on the vowel (Schourup, 1973; Kawasaki, 1986). The weaker oral tract constriction for final than for initial nasals coupled
with the extremely early velic lowering movement sets the stage for this common sound change. In addition, as with the evidence concerning laterals, developmental data show cases in which young children delete final nasal consonants but retain nasality on the vowel, even in languages that do not have distinctive vowel nasalization (Locke, 1983).

In contrast to the evidence that syllable-final consonants are, under the right conditions, subject to loss of the primary consonant constriction, it was also shown that, in some cases, rather than losing the consonant closure, the inter-articulator organization associated with a syllable-final consonant was altered such that the final consonant became more, if not entirely, like the organization of an initial consonant. Evidence of changes in relative timing was observed for all three consonant classes: nasals, laterals, and stops. However, given that loss of the consonant constriction is a qualitatively different process than a reorganization of the relative timing pattern in the direction of that for the initial consonant, how do we predict which outcome is most likely? Across the studies examined here, the evidence showed that the final consonant constriction was subject to loss when there was no immediately following vowel. On the other hand, in the context of an immediately following vowel, the final consonant was subject to resyllabification (partial or complete). In both cases, the change is one that results in, or, at least, moves toward the establishment of CV organization (whether [CVC → CV] or [CVC + V → CV + CV]; here we use “ + ” to denote a syllable boundary. We would, of course, also expect that, under the right circumstances, the final consonant would resyllabify, rather than disappear, in CVC + CV sequences in which the two consonants can together initiate a syllable). This fact, coupled with the finding that the initial consonant is resistant to weakening despite changes in rate and style, is consistent with the hypothesis that the CV unit provides an alternating articulatory pattern beginning with a tight constriction and ending with an open vocal tract in a kind of rhythm that may somehow be easier for the speaker as well as the listener. It is especially interesting to note, in this regard, that across languages that have closed syllables, stops (i.e., the consonant class involving the tightest constrictions) are favored in initial position but disfavored in final position (Locke, 1983).

In addition to the preference for CV syllables evident in cross-language phonological inventories, it is well known that, in early babbling, CV syllables predominate, even in those languages that have syllable-final consonants. Moreover, up to age three, normally developing children often continue to leave out the final consonants of words (Vihman, 1996). Older children who produce CVC words without a final consonant (whether consistently or inconsistently) are considered to have a phonological disorder, albeit a common one (Weismer, Dinnsen, & Elbert, 1981). Furthermore, it is interesting to note that some children who delete syllable-final consonants in word-final position retain them when morphological processes position them in word-medial intervocalic position. For example, a child who omits the final consonants in hop, dog, pig, and bake may produce those same consonants in hopping, doggie, piggie, and baker, respectively (Weismer et al., 1981). In the latter series of words, the consonant is positioned precisely where it would be a candidate for resyllabification from final to initial position, as described above.

Long before researchers had much information on the articulatory organization of syllables, the syllable was proposed as a basic unit of speech production (Stetson, 1951; see Kelso & Munhall, 1988; Kent & Minifie, 1977), perception (see Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967), and synthesis (Mattingly, 1981). The positive outcome of studies seeking stable patterns of articulatory organization has helped to promote the development and/or modification of a number of current theories of speech
production, among them, the Converter-Distributor (C/D) Model (Fujimura, 1994, 1995, 1997) and Articulatory Phonology (Browman & Goldstein, 1986, 1992, 1995).

The C/D model is a model of phonetic implementation in which sequentially ordered syllables function as the basic segmental units. The linear string of syllables has intervening syntactically motivated phonological boundaries of varying strengths. Attached to the linear string is the metrical tree that specifies the prosodic organization. Features are attached directly to the syllable components (e.g., onset, nucleus, coda, and affixes, if present) and then converted to articulatory gestures. Gestures differ systematically, both in their spatial magnitude and in their relative timing, as a function of a variety of variables, including location within the syllable as well as prosodic conditions. This allows, among other things, for the kinds of differences observed for canonical or careful syllable-initial and -final consonants as well as instances in which the syllable-final consonants begin to resemble (more or less) the initial consonants.

Another model, Articulatory Phonology (AP), has been modified to take into account the articulatory evidence of syllable organization reported by Krakow (1989), Sproat and Fujimura (1993), Browman and Goldstein (1995), and others. In contrast to the C/D model, AP posits gestures, rather than syllables, as the basic units. Gestures, corresponding to constrictions and releases within vocal tract subsystems (i.e., lip, tongue tip, tongue body, velum, glottis), are directly represented in the lexicon and, as such, function as units of phonological contrast. While gestures have intrinsic time, they vary in their patterns of temporal overlap as a function of a variety of variables, including speaking rate and syllable position. Gestural units are organized over time by means of a gestural score, which then serves as input to a task-dynamic model (Saltzman & Kelso, 1987), and results in the actual articulatory movements. In contrast to the C/D model, then, which preserves the distinction between phonology and phonetics, AP considers gestures to be both physically real events and phonological entities; syllables are particular patterns of gestural coordination. As is the case with the C/D model, many of the details of AP have yet to be worked out. For example, Keating (1995b) has argued that AP has no mechanism for capturing some articulatory variation which is not lexically specified (i.e., variation that is not due to lexical stress, position in word or syllable), although the model does allow for phasing variation as a function of different combinations of adjacent lexical items.

In this regard, Fougeron and Keating (1997) reported that lingual constrictions for initial consonants are strengthened (have more extensive palatal contact) at the beginning of prosodic domains (phonological phrase, intonational phrase, utterance) and that, generally speaking, the higher the prosodic domain, the greater the strengthening. As noted by the authors, these effects on gestures cannot be lexically specified. Moreover, the same study showed that, in the type of CV sequence investigated, most vowel articulations have weakened constrictions at higher prosodic levels of organization. Thus, the contrast between C and V was enhanced as the prosodic level increased. We have already suggested that the CV unit is preferred because it provides an alternating articulatory pattern beginning with a tight constriction and ending with an open vocal tract and, as such, results in a kind of rhythm that is especially suited both to the production and perception mechanisms. The work of Fougeron and Keating indicates that the magnitude of constriction difference between an initial consonant and a following vowel in the CV unit is further enhanced at higher levels of prosodic organization. Additional work is clearly warranted to understand better the relation between the kinds of effects reported by Fougeron and Keating and those reported in this review. Further
investigation will, no doubt, also go a long way in facilitating the continued development of models such as C/D and AP, which have enhanced our understanding of phonological, as well as articulatory, organization.

In light of the research available today on syllable organization in speech and the clear link between the articulatory and phonological patterns, there is no question that we have come a long way since 1979 when Kenstowicz and Kisseberth commented that “... the syllable is probably the most elusive of all phonological/phonetic notions” (pp. 255–6).

Appendix

In Krakow (1989), the method used for determining movement onsets and offsets was derived from the (commonly used) approach in which movements are taken to begin and end at the time when the velocity function passes through zero. However, because it was often the case (especially for the velum) that the velocity hovered just below or just above zero before or after passing through zero, while the associated movement appeared to have effectively ceased, strict use of zero-crossings seemed inappropriate for these data. Thus, for each articulator, a velocity noise band around zero was defined. When velocity exceeded this band, movement was considered to have begun. When the band was entered, movement was considered to have effectively ceased. The noise bands were defined as follows. For both articulators, peak velocities of raising and lowering movements were obtained across all of the utterances in the experiment. Then, for the velum, the noise band was defined as 10% of the highest peak velocities of each of the velic raising and lowering movements. For the lower lip, the noise band was defined as 5% of the highest peak velocities of the raising and lowering movements. This procedure was done separately for each of the subjects and required a stronger indication that a “real” movement had begun for the velum than lip, taking into account the fact that the Velotrace external lever magnifies the movement of the velum roughly two-fold.

Using the algorithm just described, a velic lowering gesture, a low velic plateau (between the end of lowering and the beginning of raising), and a velic raising gesture were identified. The position of the velum at the end of the low plateau was taken to be the velum minimum; the velum was usually lower at this time than at the beginning of the plateau because of additional drift or movement following the end of the large lowering movement. For the lower lip, a raising movement and lowering movement were identified as well as a lip maximum. While the procedures employed produced independent markings of lip raising offset and lip lowering onset, the two points often coincided or fell within 5–10 ms of each other and the difference was, therefore, not considered to be different from 0.

It is important to note that the displacements were examined visually in order to define the regions in which automatic velocity criteria were to be applied. In many cases, there were two-stage lowering movements associated with the nasal consonants, with a relatively small movement preceding the more extreme movement, which was closer in proximity to the acoustic onset of the nasal murmur. Work by Bell-Berti and Krakow (1988) suggests that the earlier movement is movement for the vowel, independent of the nasal consonant. Hence, the onset and offset of the larger movement were marked in such cases. In some cases, I noted the occurrence of a shallow movement that followed the large movement for the nasal consonant. This shallow movement was also excluded from
the measure of velic lowering. In most cases, the movement appeared as drift and fell within the velocity criterion for movement offset.

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