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Articulatory organization of mandibular, labial, and velar movements during speech

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(Received 26 October 1993; accepted for publication 27 March 1995)

It has been shown that articulator movements during speech are adjusted along a number of spatiotemporal dimensions. For example, variations in the extent of lip, jaw, or tongue motion are associated with proportional changes in the respective articulators' peak velocity. Modifications in the timing of lip and jaw actions are apparently constrained, exhibiting relative timing covariation. Syllable prominence systematically affects some combination of the articulator motion parameters, i.e., extent, speed, and duration. The present investigation is an attempt to extend observations of the spatiotemporal properties of articulator movement to include the velum. Lip, jaw, and velar kinematics were recorded optoelectronically and simultaneously with the acoustic signal during productions of the utterance /mɑbnɑb/. The spatial and temporal relations between the lips, the jaw, and the velum were examined and compared across articulators. For movements associated with each syllable, the velum displayed scaling patterns qualitatively similar to those of the lips and jaw. Moreover, velocity–displacement relations were more robust for the lowering than for the raising movements of the velum. There was evidence of interarticulator coupling between the velum and the jaw, and between the velum and the upper lip, although this coupling was not as strong as that observed among the oral articulators. Articulator specific differences in velocity–displacement correlations and degree of interarticulator cohesion for the various movement phases may be related to a combination of aerodynamic and phonetic factors, such as the phonologically noncontrastive nature of nasalization in English. © *1995 Acoustical Society of America.*

PACS numbers: 43.70.Aj

INTRODUCTION

A number of investigations have shown that lip, jaw, and tongue movements during speech are modified systematically across segmental and suprasegmental variations. One of the more robust movement characteristics is the positive linear relationship of an articulator's peak displacement with its associated peak velocity. During speaking, reliable correlations have been observed in the kinematic parameters of various articulators, such as the jaw and the lip (Ohala *et al.*, 1968; Kelso *et al.*, 1985), the vocal folds (Munhall and Ostry, 1985), and the tongue dorsum (Parush *et al.*, 1983; Ostry *et al.*, 1983), to indicate that movement velocity is proportionally scaled to changes in movement extent. Further, this relationship between peak velocity and displacement is reliably observed regardless of movement direction (i.e., raising versus lowering; Kelso *et al.*, 1985; Munhall *et al.*, 1985; Parush *et al.*, 1983; Vatikiotis-Bateson, 1988; Vatikiotis-Bateson and Kelso, 1993). One of the aims of the present study was to examine the relationship between peak velocity and displacement in the velum.

No consistent direction-dependent trends have been noted in these relations in the literature. In a kinematic study of tongue dorsum movement, the peak velocity–displacement correlation for the raising movement toward closure was about the same as that for the lowering movement from the stop release (Parush *et al.*, 1983). For one of the three subjects in that study, the raising movements were slightly faster than the lowering movements, and for another subject the raising movements were slightly larger than the lowering movements. In an analysis of speech kinematics of the jaw and the lower lip, Kelso *et al.* (1985) found that both opening and closing movements showed high correlations between peak velocity and displacement with a trend for the closing movements to display higher (steeper) velocity–displacement slopes than the opening movements. The same finding was also reported by Vatikiotis-Bateson and Kelso (1993), who concluded that, when viewed as a second-order dynamical system, the peak velocity–displacement relationship can provide a sufficient spatial and temporal description of the overall movement behavior. A further aim of the present study was to explore direction-dependent trends in the relations between peak velocity and displacement in the velum, as well as in the jaw and the upper lip.

Stress assignment has been found to produce systematic changes in kinematic variables. Movements associated with stressed syllables are generally of greater displacement, higher velocity, and longer duration than their unstressed counterparts (Gay, 1968; Kelso *et al.*, 1985; Kent and Netsell, 1971; MacNeilage, 1970; Ostry *et al.*, 1983; Ostry and Cooke, 1987; Vatikiotis-Bateson, 1988; Vatikiotis-Bateson and Kelso, 1993). However, examination of the velocity–displacement relationships for various articulators reveals that the scaling of these two kinematic variables displays a consistent pattern in stressed versus unstressed syllables that appears to reflect the varying movement durations. As the movement duration increases for the stressed element compared to the unstressed, there is a notable tendency for the velocity–displacement ratio to decrease (Munhall and Ostry, 1985; Ostry and Cooke, 1987). This trend has been observed for tongue dorsum movements (Ostry *et al.*, 1983; Ostry and Cooke, 1987) as well as for jaw and lip movements (Stone, 1981; Kelso *et al.*, 1985; Edwards *et al.*, 1991; Vayra and Fowler, 1992).

In contrast to the numerous studies of the jaw, lip, and tongue movement, relatively little research has focused on the movement characteristics of the velum. It is not known, for example, whether peak displacement and peak velocity scale in a similar manner for the velum as for the oral and laryngeal articulators, or whether stress prominence effects are reflected on velar raising movements. There is, however, a body of empirical evidence regarding certain determinants of velar position and velar movement. For example, Bell-Berti *et al.* (1979) found velar position to be influenced by vowel quality during adjacent nasal and oral consonants in utterances such as /fipmip/ or /fɑpmɑp/, and /fimpip/ or /fɑmpɑp/. Velar position was lower in the environment of the low, open vowel /ɑ/, than in that of the high, closed vowel /i/. Further, after a nasal consonant, the velum was found to rise sooner and faster for a high vowel than for a low one. Similar findings have been reported by Moll (1962), Kent *et al.* (1974), and Clumeck (1976). Recently, Krakow (1993) reported stress and rate effects on movements of the velum, indicating that the velum may have an active role in the prosodic organization for speech. It was of interest, then, to cast a further glance on nonsegmental variables, such as stress prominence and utterance position, to determine whether their global effect on the kinematic parameters of the raising movements of the velum is comparable to that on lip and jaw kinematics.

In terms of interarticulator cohesion, Krakow (1989) examined the patterns of activity of the lower lip raising and of velum lowering, varying syllable position, and word affiliation. She observed strong effects of syllable structure on the velum, but not on the lower lip. Velar movements showed consistent effects of syllable affiliation, and were generally amplified in syllable-final position. For syllable-initial /m/ the end of the lower lip raising movement preceded the end of the velar lowering movement, whereas for syllable-final nasals, the beginning of the lower lip raising movement preceded the end of the velar lowering movement. Thus Krakow (1989) presented evidence of coordination between the movements of the lower lip and the lowering movements of the velum. McClean (1973) provided comparable observations of velar movements at junctural boundaries using cineradiography. To date there has been no detailed kinematic timing examination of the raising action of the velum with respect to the movements of other articulators. It is not clear whether and to what degree the velar raising movement is coupled to the movements of the jaw or the lips, when all articulators are actively involved in producing sound sequences. The present study aims to investigate these interarticulator timing relations.

Information about interarticulator cohesion has potential importance for understanding correlates of neuromotor organization for speech in theoretical questions that may be summarized as follows. If the previously observed (Gracco and Abbs, 1986; Gracco, 1988, 1994) consistency in articulator timing among the lips and jaw is found in movements of only that closely coupled group of articulators and did not include more distal articulators such as the velum, this might suggest an articulator organization reflecting local constriction-producing events (i.e., oral, velar, laryngeal). Alternatively and more plausibly, if velar movements are found to demonstrate a degree of coupling with other articulators similar to the coupling observed between the lips and the jaw, that would suggest a control structure reflecting the functional demands of the system for speech production (Gracco, 1991, 1994). However, although a recent finding suggesting tightly coupled timing among the lips, jaw, and larynx during oral opening and oral closing provides some support for the latter position (Gracco and Löfqvist, 1994), no comparable studies extending to the velum currently exist.

In the present experiment we investigated the functional linkages among the jaw, the lips, and the velum, by examining the relative timing relations among raising and lowering actions of the velum, lower lip, and jaw. The hypothesis was that velar movement timing will be adjusted in conjunction with variations in lip and jaw movement timing. In sum, this study focused on the characteristics of velar movements within and across syllables in comparison to concomitant lip and jaw movements, and on the degree of temporal coupling among the velar and oral articulators.

I. METHODS AND PROCEDURES

A. Subjects

The subjects were six females ranging in age from 25–50 yr, with no known history of neurologic, hearing, or speech disorder. Except for BK, the first author, all subjects were native speakers of English and naive to the exact purposes of the experiment. AH, BK, CB, JP, and FE had had formal phonetic training, while LW had no formal phonetic training, but is a fluent speaker of a foreign language. The stimulus utterance obeys English phonotactic constraints. BK is a fluent speaker of English, and her productions were judged appropriate by phonetically trained native speakers of English.

B. Speech stimuli

The stimulus utterance used, /mɑbnɑb/, was selected because, for its production, the velum is expected to reach extremes of its range of movement (low for the nasal consonants and high for the stop consonant; Bell-Berti, 1973, 1976; Krakow, 1989). The velum begins rising from a lowered position for /m/ toward a high position for /b/, followed by rapid velar lowering for /n/, and a final rise for /b/. The vowel /ɑ/ was selected for maximal jaw and lip movements, as well as for maximal velar lowering since the coarticulatory effects of /ɑ/ on the nasal consonant result in a lower velar position than do the coarticulatory effects of other vowels. That is, the velum is at a lower position for /m/ in /mɑ/ than it is for /m/ in /mi/ (Bell-Berti *et al.*, 1979).

The utterance was spoken at a self-selected conversational rate and subjects were instructed to place the primary stress of the utterance on the first syllable. The utterance was modeled for the subjects by the experimenter. As the structure of the utterance was possibly conducive to placement of almost equal stress on both syllables, any of the subjects' productions not conforming to the experimental specifications were discarded. The subjects were then alerted to the required stress pattern and were asked to repeat the token.

C. Instrumentation

1. *The velotrace*

Velar movements were tracked using the Velotrace, a device developed for this purpose by Horiguchi and Bell-Berti (1987). The Velotrace consists of an internal lever connected to an external lever via a push-rod, which rides on a support rod, and is encased in a stainless-steel tube. Part of the support rod rests on the floor of the nose, and part extends outside the nose. The tip of the curved internal lever rides on the nasal surface of the velum, moving with it; the movements of the internal lever are transmitted to the external lever through the push-rod. The external lever is nearly twice as long as the internal lever, and therefore the movements traced from the external lever are about twice as large as the actual velar movements that they reflect. The absolute magnitude of the Velotrace movements may vary across speakers; anatomical differences among subjects may result in differentially optimal positioning of the internal lever of the Velotrace and, consequently, in different absolute displacements of the external lever. Speakers may also differ in the absolute extent of velar movement. The Velotrace is sensitive to even the very rapid movements of consecutive oral–nasal sequences.

2. *The jaw splint*

A custom fitted jaw splint was produced for each subject. A mandibular dental impression was taken and a plaster cast of the subject's mandibular dentition was made and used to mold the jaw splint. An acrylic resin casing of the lower teeth was made. The casing had two wide, stainless-steel wires embedded in its outer edges. The wires were bent to exit the acrylic casing upward, at 45-deg angles, at the level of the cuspids, so as to not interfere with bilabial closure. One of the wires was then bent in a Z shape, close to the chin to allow monitoring of the jaw movement in the midsagittal plane. The other wire was bent horizontally and cut short, in order not to obscure monitoring of the upper lip movements. The jaw splint was kept in place with the help of a commercial dental adhesive.

The experimental setup consisted of an adjustable dental chair, enclosed in an aluminum tubular beam framework, onto which a cephalostat was fixed. (For a more detailed description of this setup see Kelso *et al.* 1984, pp. 814–815.) The Velotrace was then fastened to the stable parts of the cephalostat.

3. *The LEDs*

Infrared light emitting diodes (LEDs) were attached to the subject's lips, jaw splint, and the external lever of the Velotrace in the midsagittal plane, and were tracked optoelectronically using a modified Selspot system.

D. Procedure

The Velotrace was coated with 2% Xylocaine (Lidocaine HCl, a topical anaesthetic) gel, and the subject's nasal cavity was sprayed with 4% Xylocaine spray. Even though no studies addressing the specific effect of topical anaesthetic on movements of the velum exist, studies of the normal behavior of the larynx have revealed no discernible effect of topical anaesthesia (Shipp, 1968; Zemlin, 1969) on laryngeal activity (see also Hardcastle, 1975 for the effects of topical anaesthesia on the tongue). The LEDs were placed on each subject at the following locations: the bridge of the nose (reference LED), the center of the vermilion border of the upper lip (upper lip LED), the tip of the external lever of the Velotrace (Velotrace LED), the external stable portion of the support rod of the Velotrace (Velotrace reference LED), and the point on the arm of the jaw splint closest to the subject's jaw (jaw LED).

The subjects repeated the stimulus utterance at a self-selected, comfortable speech rate following a cuing tone. Each subject produced a minimum of 50 tokens, as follows:

AH:85, BK:69, CB:78, FE:78, JP:137, LW:50.

In the beginning and end of the experiment sustained /s/ and /m/ productions were obtained to view the maximum range of the velar displacement in order to ascertain optimal and functional positioning of the Velotrace. Each subject's data were analyzed separately.

E. Data acquisition

The data were recorded on a multichannel instrumentation recorder at a speed of 3.75 in. per second for storage and subsequent analysis. A highly directional microphone (Sennheiser model MKH816T) was used for audio recording during the experiment. After the experiment, all movement signals were sampled from the tape using a laboratory computer with 12-bit resolution at a rate of 500 Hz per channel; the acoustic signal was low-pass filtered at 4.8 kHz and sampled at 10 kHz. The horizontal and vertical positions of the two reference LEDs and the LEDs placed on the jaw splint and Velotrace were recorded along with the vertical position of the upper lip. For one subject (BK) the signal from the upper lip LED could not be used because the LED was intermittently obscured by one of the outer steel wires of the jaw splint. As a result, no upper lip kinematics were obtained for this subject.

The movement signals were smoothed using a 42-ms triangular window. The reference channels were subtracted from the appropriate kinematic channels to correct for any vertical head movement during the experiment. The resulting upper lip, jaw, and velum signals were then differentiated using a central difference algorithm to obtain the corresponding instantaneous velocities, which were subsequently smoothed using the same 42-ms triangular window.

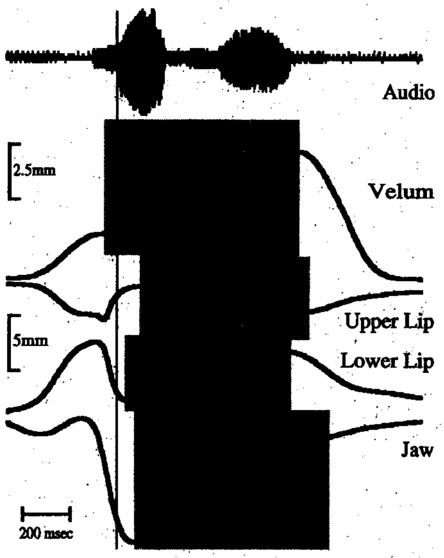

FIG. 1. Acoustic signal for /mɑbnɑb/, with the corresponding velar movement kinematics. The velopharyngeal port is open during production of the nasal consonants /m/ and /n/, and is closed for the production of the bilabial stop /b/. For nasal sounds the velum is at a low position, while for oral sounds the velum is elevated. The first vowel onset is marked (thin vertical line), and the corresponding averaged kinematic traces of the velum, the upper lip, the lower lip, and the jaw for tokens from subject AH. The shaded areas 1 and 2 indicate the first and second closing movements, and shaded area 3 indicates the intervening opening movements.

F. Data analysis

The local maxima and minima of the movement and velocity signals for each token were marked automatically and individually inspected. The onset and offset of the movements were marked based on the zero-crossing values of the corresponding velocity signals. The coordinative timings of the velum, jaw, and lips were also examined. For these measures the time of occurrence for each articulator's peak velocity was identified for each movement phase and referenced to a common line up point depending on the specific movement phase. For the first oral closing movement timing was referenced to the vowel onset in the first syllable; for the subsequent velar lowering/oral opening the occurrence of peak velocity was referenced to the peak jaw closing associated with the first /b/ in /mɑbnɑb/; for the final oral closing the oral articulators were referenced to the second jaw opening peak velocity associated with the onset of the vowel in the second syllable. Shown in Fig. 1 is the acoustic signal for the utterance, along with the kinematic traces for the velum, the upper lip, the lower lip, and the jaw. The different movement phases are indicated by the shaded areas, and the vowel onset is marked.

II. RESULTS

In the present study, we examined the lip, jaw, and velum movement characteristics associated with two contiguous syllables for a group of six subjects.

A. Movement characteristics: Velocity–displacement relations

1. *First closing*

The velar movement for the first syllable was morphologically different from that of the lips and jaw, and different from that of the velar movement for the second syllable. As shown in Fig. 1, the velar motion for the first syllable was a unidirectional movement (raising from a low to a high position, from /m/ to /b/), whereas the lip and jaw movements were composed of two distinct phases (an oral opening for the vowel, /m/ to /ɑ/, and an oral closing for the consonant, /ɑ/ to /b/). For the jaw and the lips, each opening and closing movement had a single associated peak velocity. However, this was not the case for some instances of the velar closing movement. Specifically, even though the velum was raised from /m/ to /b/, the velocity trace sometimes presented two distinct peaks. For all subjects some instances of two distinct velar raising movements were observed, one associated with the raising from the nasal to the vowel /ɑ/, and a subsequent raising for the consonant /b/. These multistep movements were inconsistently present and generally occurred on the longer syllables, i.e., on the slower tokens. Similar multistep movements were observed for velum lowering by Bell-Berti and Krakow (1991; see also Boyce *et al.*, 1990).

Each velar raising step had its associated peak velocity. Since the first raising movement and its associated peak velocity correspond to the raising of the velum from the /m/ to the /ɑ/, and were not identifiable in all of the tokens analyzed, they were not used in the analyses presented here. Instead, the peak velocity associated with the raising of the velum from /ɑ/ to /b/ was used. This second velocity peak was comparable to the velocity peak of the jaw and lip movements for /b/ closure.

However, in these single-step velar raising movements the single velocity peak did not always occur at the same time in the velocity trace as the second velocity peak of the two-step jaw raising movement. Consequently, the temporal interval containing the velar peak velocity was longer than its oral counterpart, and, in fact, longer than the analogous interval for the second velar raising movement, which was invariably achieved in one step.

The first analysis focused on lip and jaw closing and velar raising for /b/. The velocity–displacement characteristics of the jaw closing and velar raising movements in the first stressed syllable were examined. On the left side of Fig. 2 the jaw peak closing velocity and associated maximum closing displacement is presented for two of the six subjects. It can be seen that the peak velocity and displacement covary systematically. The velar peak velocity–displacement relations from the same context are presented on the right side of Fig. 2 for the same two subjects. It is evident that, although the general relationship between velar raising movement velocity and displacement was comparable to that of the jaw, these variables were not as highly correlated for the velum as they were for the jaw. The same was true for the upper lip: movement velocity–displacement correlations were somewhat lower for the velum than for the upper lip, whose kinematic relations were comparable to the jaw's.

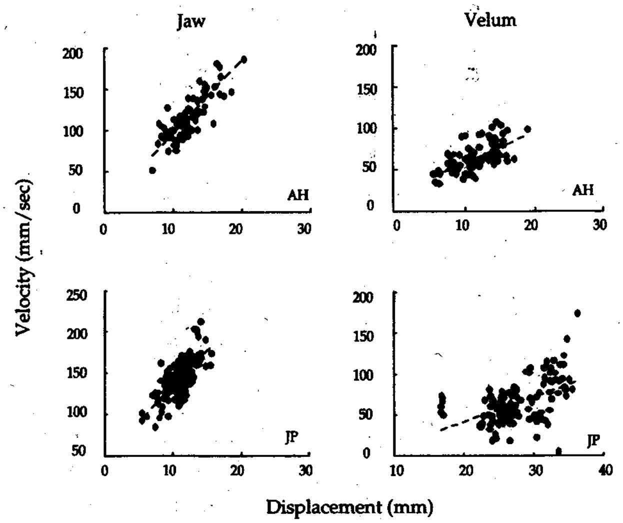

FIG. 2. Peak closing velocity–maximum displacement correlations for the first closing movement (/mɑb/), for the jaw and the velum for two of the six subjects. Peak closing velocity is plotted as a function of the displacement of the closing movement. Movement displacement is in mm and peak velocity in mm/s.

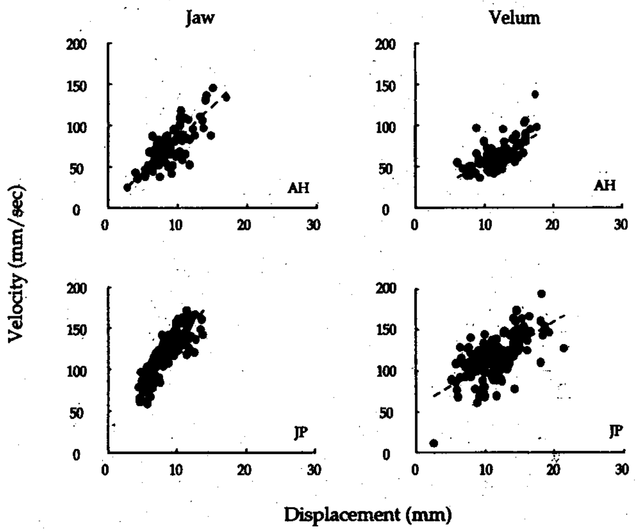

FIG. 3. Peak closing velocity–maximum displacement correlations for the second closing movement (/nɑb/), for the jaw and the velum for two of the six subjects. Movement displacement is in mm and peak velocity in mm/s.

The increased variability in the velocity–displacement relations observed in the velum may be specific to the morphology of the first velar raising movement as discussed above. The trend for more variable velar velocity–displacement relations for the velum compared to the lip or jaw was seen in the data for all subjects. Presented in Table I are the velocity–displacement correlations for the upper lip, jaw, and velum for all subjects. The correlations for the upper lip and jaw ranged from $r=0.734$ to $r=0.940$. For velar raising, the correlations between peak velocity and peak displacement for the six subjects ranged from $r=0.138$ to $r=0.773$. All lip, jaw, and velar correlations were significant at the 0.01 level with the exception of the correlations in the velar movement for subject BK (see Table I).

2. Second closing

We next examined the correlation between the peak velocity and displacement for the second closing movement of the jaw, the velum, and the upper lip. The second syllable and hence closing movement differed from the first in terms of utterance position, phonetic context (/mɑb/ vs /nɑb/), and stress prominence. Unlike the velum movements of the first syllable, the kinematic profile of the velum for the second syllable included both a lowering and a raising movement, thus rendering its morphology comparable to that of the jaw and lip. Moreover, in contrast with the first syllable, the velum raising movement in the second syllable was always achieved in a single-step movement, even though this movement also involved raising of the velum for two separate "targets:" from /m/ to /ɑ/ and from /ɑ/ to /b/. However, as a result of the single-step movement, only one evident velocity peak was associated with velar raising.

Figure 3 shows the peak closing jaw and velar velocity plotted as a function of the displacement of the closing movement for the /b/ in the syllable (/nɑb/) for two subjects. As shown in the figure and summarized for all subjects in Table II, the velocity–displacement correlations for the velum were higher for the second closing than for the first closing. All correlations were significant ($p<0.01$) except as noted. The upper lip and jaw velocity–displacement correlations for the second oral closing movement were comparable to those for the first closing movement except for LW's upper lip second closing movement. In this respect, and unlike the velum, the upper lip and the jaw showed similar velocity–displacement relations for the two closing movements, regardless of utterance position, phonetic context, or stress prominence.

TABLE I. Velocity–displacement correlations for the first closing movement ($p<0.01$).

Subject	Velum	Jaw	Upper lip
AH	0.625	0.827	0.734
BK	0.138 NS	0.881	···
CB	0.350	0.770	0.800
FE	0.773	0.891	0.746
JP	0.494	0.748	0.940
LW	0.305	0.925	0.753
Mean	0.485	0.853	0.815

TABLE II. Velocity–displacement correlations for the second closing movement ($p<0.01$ except where marked).

Subject	Velum	Jaw	Upper lip
AH	0.627	0.772	0.835
BK	0.308 $p<0.02$	0.916	···
CB	0.634	0.761	0.753
FE	0.885	0.916	0.601
JP	0.621	0.857	0.900
LW	0.875	0.887	0.341 $p<0.02$
Mean	0.707	0.865	0.735

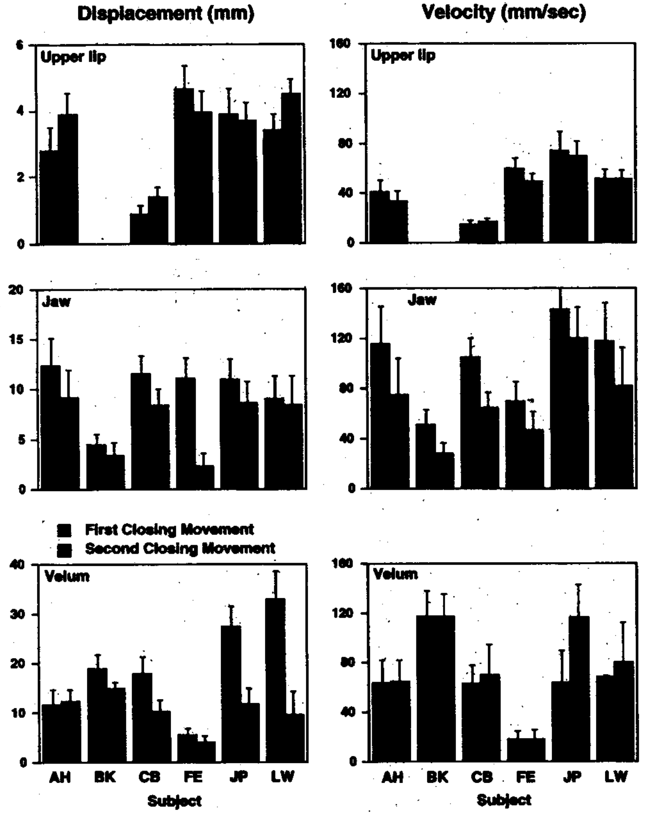

FIG. 4. Mean /b/ closing displacements and velocities of articulator movements for the two syllables of /mabnab/ for the six subjects. The darker bars indicate the values for the first syllable, and the lighter bars the values for the second. The upper lip movement values are on the top panels, the jaw values in the middle, and the velum ones on the bottom panels. For the jaw, the first syllable is /mab/ and the second /nab/, while for the velum, the first syllable begins at the acoustic onset of the first vowel (/ab/), and the second begins at the offset of the stop closure (i.e., onset of the nasal: /bnab/). Displacements are in mm and velocities are in mm/s.

3. Comparisons of the two closing movements

Consistent with previous studies, in all articulators the closing movements for the stressed first syllable were larger compared to those of the second syllable. Figure 4 shows the average displacements for the first and second closing movements. For five of the six subjects, the movement displacements for the first syllable were significantly greater than those for the second syllable for the jaw and the velum ($p < 0.01$). For the upper lip, the results were less consistent. As shown in Fig. 4, the peak velocities also differed between the first and second closing movements for the jaw and the upper lip, and less consistently for the velum. The jaw and upper lip closing peak velocities were generally higher for the first syllable. For the velum, the trend was for the raising velocity to be equal or higher in the second syllable.

4. Opening movement

As mentioned above, for the first syllable (/mab/) the utterance began with the velum at a low position. For this reason we could examine only one velar lowering movement flanked by the first and second raising movements. Figure 5 presents plots of the peak velocity–peak displacement for the jaw and the velum lowering movements for two subjects.

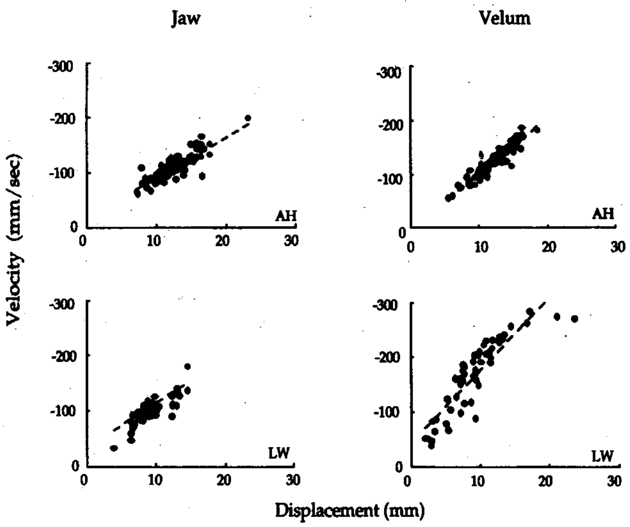

FIG. 5. Peak lowering velocity–maximum displacement correlations for the opening movement for the jaw (/bna/) and the velum (/bn/) for two of the six subjects. Movement displacement is in mm and peak velocity in mm/s.

The jaw and velum lowering movements behave quite similarly as evidenced by the magnitude of their respective correlations. The peak opening velocity–displacement correlations for the jaw, the velum, and the upper lip for all subjects are presented in Table III. All correlations were significant ($p < 0.01$).

To evaluate the possibility that the high peak velocity–displacement correlations observed in the velar lowering movement might reflect a mechanical effect related to the mass of the Velotrace rather than an active lowering action, we obtained the coefficients of variation for the lowering movement of the jaw and the velum. The reasoning was as follows: If the mass of the Velotrace was the major determinant of the lowering movement, then the characteristics of that movement (duration or velocity) would be extremely consistent, and, unlike the jaw lowering movement, would exhibit only a small degree of variability. We found, however, that the coefficients of variation (CV) for the lowering movements of the two articulators were relatively large. Moreover, the duration and velocity of the velar lowering movement was more variable than that of the jaw. The CV for the opening movement displacement ranged from 9.5 to 17.2 mm (mean 13.1) for the jaw, and 13.2 to 23.4 mm (mean 18.3) for the velum; peak velocity CVs ranged from 15.5 to 33.8 mm (mean 26.4) for the jaw, and 12.4 to 40.3 mm (mean 27.4) for the velum. It appears then, that the

TABLE III. Velocity–displacement correlations for the opening movement /bna/ ($p < 0.01$ for all correlation coefficients).

Subject	Velum	Jaw	Upper lip
AH	0.942	0.884	0.462
BK	0.695	0.906	0.734
CB	0.851	0.762	0.781
FE	0.934	0.914	0.775
JP	0.891	0.866	0.611
LW	0.895	0.945	0.565
Mean	0.885	0.890	0.670

TABLE IV. Slopes of the regression equation of x on y, x=displacement and y=peak velocity. Regressions were significant at the 0.01 levels unless marked otherwise.

	Closing 1			Opening 1			Closing 2		
Subject	velum	jaw	u. lip	velum	jaw	u. lip	velum	jaw	u. lip
AH	3.7	8.8	9.7	10.4	6.4	6.5	4.4	7.9	10.5
BK	1.1 NS	10.2	···	13.6	8.3	···	4.4	6.7	···
CB	1.5	6.3	11.1	11.5	7.1	10.4	6.4	4.5	8.0
FE	5.9	10.4	9.0	12.2	9.5	14.7	5.5	10.7	6.1
JP	3.1	8.6	19.4	16.0	9.9	8.5	5.2	9.8	20.4
LW	1.3	12.4	11.4	13.2	6.2	9.4	6.0	9.1	5.3
Mean	2.8	9.5	12.1	12.7	7.9	9.9	5.3	8.1	10.1

systematicity observed in the lowering movement characteristics of the velum is not an artifact of the presence of the transduction device.

5. Comparisons of movements in sequence

The velocity–displacement relations of the two closing movements were next compared to the velocity–displacement relations for the intervening opening action. Regression slopes were obtained from a simple least-squares analysis relating the peak velocity and the displacement for each of the movement phases for the jaw, the velum, and the upper lip. In a simple sense, the slope measurements can be viewed as indicators of each articulator's movement frequency (see also Kelso *et al.*, 1985). As such, it was possible to examine the global effects of variables such as utterance position, stress prominence, and movement direction by comparing the slope changes within and across articulators. Table IV presents the slopes obtained from the regression analysis. The velum showed the most consistent pattern across subjects, with the first closing movement having the lowest frequency, and the opening movement having the highest. The second closing movement was faster than the first, but slower than the opening.

For the jaw the opposite was true: The first closing was the fastest, and the opening movement was the slowest; the slope for the second closing tended to be lower than for the first closing, but this was not consistent across subjects. For the upper lip the results were not as systematic across subjects as they were for the jaw and the velum. For three of the five subjects the slopes of the closing movements were reduced from the first to the second syllable, while for the remaining two subjects (AH, JP) the slopes increased in the second syllable.

B. Interarticulator timing: Jaw–velum–upper lip coordination

The second analysis focused on the relative timing relations among the velum, the jaw, and the upper lip for the first and second closing movements, as well as for the intervening opening movement.

1. Articulatory ordering

It is known that articulators cooperating in the same motor task demonstrate a high degree of temporal coupling to each other. As a first step to establishing whether there is any degree of temporal coupling between the velum and the jaw, we looked at the order with which the upper lip, the lower lip, the jaw, and the velum achieve peak position for closure. Generally the lips attained peak closing position first and the jaw and the velum followed. Beyond that, however, a more specific or stable ordering of the closure events was not observed. Regarding the order with which the same articulators arrived at peak position in the subsequent (/bnɑ/) opening movement, the only consistent observation was that the jaw reached peak opening position last, while the other articulators showed no systematic ordering pattern.

2. Relative timing: Comparisons between velar–oral and oral–oral articulator pairs

Previous studies have revealed a number of consistent kinematic relations among the movements of functionally related articulators. It has been shown, for example, that the lips and the jaw are coupled in their relative timing for oral closing (Gracco and Abbs, 1986; Gracco, 1988; McClean *et al.*, 1990; DeNil and Abbs, 1991). By analogy, we expected that, in the present study, the upper lip and jaw would demonstrate consistent relative timing of their kinematic landmarks and that the velum might assume a consistent relationship to them. Thus, in order to explore interarticulator cohesion, we examined the patterns of covariation exhibited in the kinematic behavior of the three articulators. The specific variables we examined were the times of attainment of peak velocity and peak position for the jaw, the upper lip, and the velum for the different movement phases. The degree of correlation between these variables was considered an indicator of interarticulator cohesion.

a. First closing movement. For the first /b/ closing movement, the times of arrival at peak velocity and peak position were measured relative to the acoustic onset of first vowel in /mɑbnɑb/. As expected, a high degree of correlation between the timing of the jaw and the upper lip for the attainment of peak velocity was observed (see Table V). The relation between the corresponding intervals for the velum and jaw showed greater variability than between the upper lip and jaw. One possibility for the apparently reduced cohesion among the velum and the jaw may relate to the particular velocity trace of the first raising movement, as was discussed in Sec. II A, earlier. A second possibility is that the relative timing for attainment of peak velocity for closure is not an important coordinating variable. Instead, a different temporal

TABLE V. Times of peak position and peak velocity for the first /b/ closing movement: Correlations for velum–jaw and upper lip–jaw. Correlations were significant at the 0.01 level. The /b/ closing time is measured from the time of the first vowel onset.

	Time of peak position			Time of peak velocity		
Subject	velum–jaw	upper lip–jaw	velum–upper lip	velum–jaw	upper lip–jaw	velum–upper lip
AH	0.85	0.62	0.78	0.32	0.97	0.30
BK	0.78	···	···	0.54	···	···
CB	0.77	0.87	0.71	0.13 NS	0.94	0.13 NS
FE	0.59	0.74	0.69	−0.01 NS	0.91	0.03 NS
JP	0.36	0.67	0.51	0.43	0.91	0.50
LW	0.65	0.89	0.73	0.37	0.95	0.41
Mean	0.695	0.781	0.694	0.306	0.941	0.284

variable for the three articulators might demonstrate greater stability as an indicator of interarticulator coordination.

In order to examine this latter possibility, the relative timing of peak jaw, upper lip, and velar positions were obtained for the first closing movement. Overall, the relative times of peak position rather than the times of peak velocity showed a higher correlation for the velum–jaw and the velum–upper lip closing movements. Interestingly, this was not the case for the upper lip–jaw relations. The relative timing results using peak position and peak velocity are presented in Table V. In general, it seems that the relative timing of the closing events for the velum with the jaw and with the upper lip are related, but not as consistently as for the oral articulators with each other (i.e., the upper lip with the jaw).

b. Second closing movement. For the second closing movement, the referent used for measuring the times to peak velocity and peak position was the time of jaw peak velocity at /ɑ/ opening for /nɑb/. Examination of the closing movements for the second syllable showed a high correlation between the times of the attainment of peak closing velocity for the jaw and the upper lip (see Table VI). We found that the relative timing based on the attainment of peak position was somewhat better for the velum–upper lip pair than for the velum–jaw pair.

For subjects AH, BK, and FE the relative times of peak position for closure between velum–jaw and velum–upper lip were found to be more highly correlated than the relative times of their respective peak velocities. This was also true for subject CB in the timing relations between velum and upper lip. However, in the case of the velum–jaw relative timing the opposite was true for CB. Similarly, subject JP exhibited a higher degree of correlation in the relative timing between articulator peak velocities than between peak positions for velum–jaw and for velum–upper lip. For subject LW the timing of peak position for the velum did not correlate with either the time of peak position of the jaw, or with that of the upper lip. The relative timing results for peak position and peak velocity are presented in Table VI.

Overall, it seems that the relative timing of the velum for the second closing movement demonstrates some degree of temporal coupling with the oral articulators, particularly with the upper lip. For the second /b/ closing movement, the degree of coupling (as indicated by the correlations in the peak velocity times) among velar–oral articulators was not as high as that observed among the oral articulators (upper lip and jaw). However, the degree of coupling in the peak position times among velar–oral articulators was comparable to that observed among the oral articulators.

c. Opening movement. The relative timing between the velum and the jaw for the oral and velar opening movement in the second syllable was examined next. The intervals to peak position and peak velocity were measured from the peak jaw position at /b/ closure in /mɑb/. As noted earlier, velar lowering appears to be an actively controlled gesture.

TABLE VI. Times of peak position and peak velocity for the second /b/ closing movement (for /nɑb/). Correlations for velum–jaw, upper lip–jaw, and velum–upper lip. /b/ closing time is with respect to the time of jaw peak velocity for /ɑ/ opening in /nɑb/. Correlations are significant at the 0.01 level, unless otherwise indicated.

	Time of peak position			Time of peak velocity		
Subject	velum–jaw	upper lip–jaw	velum–upper lip	velum–jaw	upper lip–jaw	velum–upper lip
AH	0.47	0.40	0.86	0.35	0.92	0.30
BK	0.63	···	···	0.56	···	···
CB	0.33	0.54	0.72	0.46	0.91	0.44
FE	0.29 $p<0.05$	0.61	0.64	0.28 $p<0.05$	0.95	0.30
JP	0.51	0.70	0.76	0.73	0.90	0.82
LW	0.13 NS	0.67	0.24 NS	0.69	0.73	0.48
Mean	0.405	0.592	0.685	0.531	0.900	0.505

TABLE VII. Times of peak position and peak velocity for the /bna/ opening movement: Correlations for jaw–velum and jaw–upper lip. /bna/ opening *re*: time of jaw peak position for /b/ closing for /mab/. $p<0.01$ except where marked otherwise.

	Time of peak position			Time of peak velocity		
Subject	velum–jaw	upper lip–jaw	velum–upper lip	velum–jaw	upper lip–jaw	velum–upper lip
AH	0.74	0.45	0.53	0.83	0.67	0.62
BK	0.51	···	···	0.59	···	···
CB	0.42	0.06 NS	0.10 NS	0.40	0.13 NS	0.05 NS
FE	0.13 NS	−0.14 NS	0.12 NS	0.42	−0.12 NS	0.27 $p<0.02$
JP	0.53	0.64	0.56	0.78	0.37	0.47
LW	0.39	0.40	0.16 NS	0.46	0.36	0.21 NS
Mean	0.475	0.306	0.310	0.614	0.306	0.340

Therefore, the time of the peak velar lowering movement from /b/ to /n/ should covary with that of the jaw lowering from /b/ to /a/ in the /nab/ context. Here, it was the timing of peak velocity across articulators (rather than of peak position as in the first syllable) that resulted in higher correlations. Moreover, the velum and jaw displayed the most consistent relations across the six subjects with all correlations being significant ($p<0.01$). The correlation of the time of peak velocity between the velum and the jaw averaged $r=0.61$ across subjects, ranging from $r=0.40$ to $r=0.83$. However, only two upper lip–velum correlations reached our significance criterion ($p<0.01$) and another approximated it ($p<0.02$). The times of peak velocity for the jaw and the upper lip were quite variable, with correlation coefficients ranging from $r=-0.12$–$r=0.67$ across subjects (see Table VII). Similar findings have been reported previously (e.g., Gracco, 1988).

III. SUMMARY AND DISCUSSION

The purpose of this investigation was to examine the movement characteristics of the velum in a specific phonetic environment, across syllables and across concurrently active oral articulators, and to assess oral–velar interarticulator cohesion. Overall, the movement and relative timing characteristics of the velum were found to be similar to those of the jaw and the upper lip, although some consistent differences were seen in the velar raising motion. As has been previously observed for jaw and lip movement, the correlations between peak velocity and peak displacement were consistently high. For the velum, the peak velocity–displacement correlations for the two raising movements were statistically significant, but lower than the correlations observed in the oral articulators. In contrast to the raising movement, the lowering movement of the velum displayed higher velocity–displacement correlations than did the corresponding lowering movements of the lip and jaw. In terms of interarticulator cohesion, lip and jaw timing were found to covary as in previous studies of oral articulator coordination. In terms of remote articulators' intergestural cohesion, oral–velar closing movements showed a different pattern than oral–velar opening movements. The relative timing between the velar raising movements and the lip or jaw closing movements indicated less tight coupling than either oral–oral closing movements or oral–velar opening movements. The velar lowering movement, which displayed the most robust velocity–displacement correlations, also showed tight temporal coupling to the jaw lowering movement. The significance of these findings is discussed below.

A. Movement characteristics

1. Experimental considerations

Before addressing the results of the present study, certain issues regarding the transduction technique and the methods used in the present study should be discussed. One of the findings of this investigation indicates that the movement and relative timing of the velum can be considered qualitatively similar to those of oral articulators such as the lips and jaw. In contrast to previous studies of lip and jaw movement and of relative timing, the movement characteristics of the velum were less consistent. One possibility accounting for the observed difference is that the presence of the device (the Velotrace) modified the velar movement patterns in a significant manner. Previous investigation of the characteristics of the device, however, suggests otherwise (Horiguchi and Bell-Berti, 1987). Horiguchi and Bell-Berti (1987) showed, for example, that the movements of the velum obtained with the Velotrace are qualitatively similar to comparable data obtained endoscopically from various subjects using the same speech material and that movement data obtained from simultaneous Velotrace and cineradiographic recordings are quantitatively similar. Specifically, they compared vertical velar movement measurements obtained cineradiographically to movement measurements of the tip of the internal level of the Velotrace. These movements were highly correlated ($r=0.90$ and higher).

Another possibility is that the device, which only transduces velar motion in a plane, may not be capturing the complexity of the changes in velopharyngeal port area. While linear motion does not allow for accurate extrapolation to area measures due to the nonlinear relationship between planar movement and changes in area, it is improbable that measures of velar movement and area measures are unrelated. In fact, the displacement of the velum and fiber-optic measures of changes in port size have been shown to be highly correlated (Zimmermann *et al.*, 1987). Specifically, Zimmermann *et al.* (1987) found correlations of $r=0.78$ and

$r = 0.89$ between photodetector outputs, indicating changes in port size, and displacement of the velum from the pharyngeal wall, measured cineradiographically. By analogy, a single point transduced at the midline of the lips or jaw does not allow for direct information on the position of all parts of either structure. Admittedly, reduced kinematic descriptions have certain limitations, yet results based on such simplified descriptions may, nonetheless, provide important information on articulator control principles.

2. Context effects

Despite the observed intra- and intersubject variability, several generally consistent trends were evident in the data. Perhaps one of the most significant factors pertaining to velar and oral articulator differences is related to the morphology of the observed movements. For the oral articulators, the pattern of movement alternated as a function of the phonetic composition of the utterance. That is, the jaw started at a relatively high position for /m/, lowered for the first vowel, raised for the /b/ and /n/, lowered for the second vowel, and raised for the final /b/. As detailed in the previous section, the velum started low for the /m/ and raised continuously through the first vowel, reached a peak for /b/, lowered for the /n/, and raised again for the second vowel and the final consonant. For the lip and jaw movements, the oral closing motion was always achieved in a single step, and was associated with a single phonetic segment. In contrast, the velar motion during the same interval progressed through two contiguous phonetic units.

The movement characteristics associated with velar raising were more variable than those observed for the lip and jaw, since the velar raising movement reflected a compound motion combining two velar gestures associated with two phonetic segments. Each segment was associated with a distinct velar position, with the position for the bilabial stop being higher than the position for the preceding vowel. This explanation is consistent with data and interpretations offered by previous investigators (Bell-Berti, 1976; Bell-Berti and Hirose, 1975; Bell-Berti *et al.*, 1979; Fritzell, 1969; Kent *et al.*, 1974; Lubker, 1968; Krakow, 1989; Boyce *et al.*, 1990) that position of the velum is not specified simply in a binary manner (open versus closed port), but in a continuous one, with the intermediate positions between maximally open (low) and maximally closed (high) being dependent on phonetic identity. Moreover, for the velar lowering movement associated with the single phonetic segment /n/, the velocity–displacement relations of the velum were comparable to those of the oral articulators. These findings underscore the contributions of contextual manipulations to investigations of articulatory characteristics.

Examination of effects such as utterance position and stress prominence on the articulators' closing movements indicated that they affected not only lip and jaw movements, as was expected, but also velar raising movements. As shown in Table IV, the slopes of the velocity–displacement correlations for the velar raising movements differed across syllables, apparently reflecting the degree to which the two steps of the raising movement are uncovered. In the first syllable, movement durations were somewhat longer, uncovering the two raising steps and resulting in weaker velocity–displacement correlations. In the second syllable, the raising movement was invariably achieved in one step, and the velocity–displacement correlations were higher than those seen in the first raising movement.

Certain direction-dependent trends were observed in the relations between peak velocity and displacement in the velum, as well as in the jaw and the upper lip. The movement frequency, as indexed by the slope of the velocity–displacement correlation, was higher in the closing movements than in the opening one for the jaw. The opposite was true for the velum: the movement frequency was higher in the opening movement than in the closing ones. It is possible that the difference observed between the jaw and velum trends is related to the morphology of the velar raising movements outlined earlier. As noted, the velocity–displacement correlations for velar lowering were generally higher than for the velar raising. While it seems possible that the velum motion was influenced by the mass of the lever of the Velotrace, subsequent analyses indicate that a mechanical interpretation of the findings is not tenable. The conclusion is, then, that velar lowering, like velar raising, is the result of controlled neuromuscular action, purposefully adjusted to the requirements of the phonetic environment, and velar activity timing is regulated along with other concomitant articulatory actions. This is consistent with interpretations offered by Bell-Berti and Krakow (1991).

B. Interarticulator timing: Upper lip–jaw, velum–jaw

The relative timing between upper lip and jaw movements for oral closure was highly consistent. This result is similar to findings of previous studies of lip and jaw temporal coordination (Gracco and Abbs, 1986; Gracco, 1994). The variations observed in vowel duration during the first and second syllables effected proportional changes in the timing of the two oral articulators. These changes, apparently aimed at maintaining a high degree of interarticulator cohesion, were observed only in the closing movement; the opening movement displayed no evidence of strong interarticulator coupling for lip and jaw timing (see also Gracco, 1988, 1994). A number of findings regarding the coordination of the velum with the oral articulators is discussed below.

The relative timing relations of the velum with either of the oral articulators (lip or jaw) were somewhat weaker than those among the oral articulators. As outlined earlier, for the raising movements of the velum, the low velar–oral interarticulator correlations most likely reflect the differences in the movement pattern for the specific phonetic configuration. Given that the raising movement was a blending of two adjacent movements, the resultant velocity profile was not necessarily associated with a single segment. Instead, the velocity profile reflected the combined movement trajectory. Perhaps as a result, the time of peak velocity showed greater variability than the time of peak position, reducing the strength of the interarticulator correlations. Support for this explanation comes from the observation that, for the velar raising movements, higher correlations were found for the attainment of peak positions (rather than peak velocities) across the contributing articulators. In the case of peak positions, the intervals of interest were associated with the same phonetic target.

Overall, the velar–oral (velum–upper lip, as well as velum–jaw) correlations were somewhat lower than those found among the lip and jaw in this and previous studies. Comparisons of time of peak position versus time of peak velocity across articulators demonstrated certain articulator- and parameter-specific differences. Velar–oral comparisons showed higher correlations for the timing of peak position than for the timing of the peak velocity. In contrast, for oral–oral (upper lip–jaw) comparisons higher correlations were found in the timing of peak velocities than in the timing of peak positions. Within the oral–oral closure framework, one explanation that may account for the relaxed oral–oral peak position timing relations compared to the peak velocity timing relations is that, for local constriction-producing events, like oral closing, the timing of lip and jaw movement toward closure (better indexed by the timing of peak velocity) is more critical than the timing of movement offset (better indexed by the timing of peak position). In that case, the time of peak velocity is the measure more critically associated with the coordination of multiple articulators. For phonetic events such as velar–oral closure—given the morphological differences of the articulatory movements—the relative timing conditions may allow for a broader critical time frame of action constraint than for local events, thus providing an explanation of the observed patterns.

Consistent with this notion are the results from the oral–velar opening interactions for /bnɑ/; the stop closure is followed by a nasal consonant and low vowel requiring velum lowering and oral opening. It is reasonable to assume that the velar lowering for the nasal and the jaw lowering for the vowel should be tightly coupled in this context. For this portion of the second syllable the oral–velar interactions were indeed very strong. This was further evidenced in the higher correlations found in the times of peak lowering velocity compared to the times of peak lowering position. Recent findings from a study of the relative timing of the lips and larynx provide additional support for this notion (Gracco and Löfqvist, 1994). Therefore, as interarticulator timing becomes more or less critical, the parameters that are indicative of coupling may also adjust: peak velocity relations may be more illustrative of critical or constrained timing relations while peak position timing relations may reflect a less constrained coordinative coupling.

In terms of contextual influences, a possible account for the somewhat relaxed peak position timing across velar–oral articulators is that vowel nasalization is not phonologically contrastive for any of the languages spoken by the subjects. Had vowel nasalization been controlled as a phonologically contrastive variable, the temporal interactions between velar and oral articulators would have been more highly constrained in order to maintain the contrast.

Examining these effects across syllables, it appears that oral–oral timing decreases from the first to the second closing movement, to the intervening opening movement, with respect to peak position and peak velocity times. The oral–velar correlation pattern in peak position was nearly the reverse from that seen in peak velocity. Oral–velar peak velocity timing was less tightly constrained for the first than for the second closure, where the velum–lip and velum–jaw relative timing relations were more robust. Again, the reduced oral–velar peak velocity temporal cohesion for the first syllable is most likely related to the difference in the movement pattern for the first compared to the second syllable. For the opening movement, the oral–velar timing correlations were rather variable, but they were at least as high as the oral–oral timing correlations.

The general direction-dependent trends of interarticulator cohesion found in the data indicated that for closure events oral–oral cohesion was higher than oral–velar cohesion. For opening actions, however, oral–velar temporal coordination was better than oral–oral coherence.

In summary, the present investigation demonstrated that the kinematic characteristics of the velum are similar to those of the lips and the jaw. Velar velocity was scaled with velar displacement and the relative timing of velar actions showed adherence to the actions of the lips and the jaw. While there was a tendency for the timing covariation in the kinematic variables for the velar closing action to be less robust than that observed for the lips and jaw, the significance of this difference should be further explored in varying phonetic contexts.

ACKNOWLEDGMENT

This work was supported by NIH Grants No. DC-00121 and No. DC-00594 to Haskins Laboratories.

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