A kinematic study of lingual coarticulation in VCV sequences

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Intra-articulator anticipatory and carryover coarticulation were assessed in both temporal and spatial terms. Three subjects produced VCV sequences with velar stop consonants and back vowels. Pulsed ultrasound was used to examine the vertical displacement, duration, and maximum velocity of the tongue dorsum raising (VC transition) and lowering (CV transition) gestures. Anticipatory coarticulation was primarily temporal for two subjects, with decreases in the duration of the VC transition accompanying increases in displacement for the CV transition. Carryover coarticulation was primarily spatial for all three subjects, with decreases in CV displacement and maximum velocity accompanying increases in VC displacement. It is suggested that these intra-articulator patterns can be accounted for in terms of an interaction between the raising gesture and a vowel-specific onset time of the lowering gesture towards the vowel. The implications of this kinematic characterization are discussed.

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INTRODUCTION

Coarticulation comprises both anticipatory (right-to-left) and carryover (left-to-right) effects. Both effects have temporal and spatial aspects. When different articulators are involved, whose gestures are more or less independent, coarticulatory effects are observed primarily in terms of the timing relations among the articulators. When a single articulator is considered, however, coarticulation may be evident in the extent and timing of individual gestures. The present study aims at a systematic description of coarticulatory effects in a single articulator, the tongue dorsum, with special attention to possible differences in the spatio–temporal characteristics of anticipatory and carryover effects.

Intra-articulator anticipatory effects have been demonstrated in gestures of articulators such as the tongue, the jaw, or the velum. Several studies have shown that tongue gestures in the horizontal plane during an intervocalic stop consonant closure tend to be in the direction of the tongue position for the following vowel (Perkell, 1969; Kent and Moll, 1972a; Barry and Kuenzel, 1975; Butcher and Weiher, 1976; Gay, 1977). These forward–backward gestures of the tongue during closure also affect vowel-to-consonant and consonant-to-vowel transitions, as indicated in the acoustic domain by changes in the direction or frequency of the $F2$ transition (Öhman, 1966; Bell-Berti and Harris, 1976; Fowler, 1981a, b). Examples of other intra-articulator anticipatory effects are reductions in the extent of jaw elevation toward bilabial intervocalic consonants as a function of the final vowel openness in VCV sequences (Sussman *et al.*, 1973), and variations in the extent of velum raising and lowering gestures as a function of either the lingual height of the following vowels or the type (oral versus nasal) of following consonants (Ushijima and Hirose, 1974; Bell-Berti *et al.*, 1979, 1981).

Previous gestures of the observed articulator also affect later movements in the sequence as is shown in the following examples of intra-articulator carryover effects. The tongue position or movement during an intervocalic consonant closure is affected by the lingual position for the previous vowel (Kent and Moll, 1969, 1972a; Barry and Kuenzel, 1975; Butcher and Weiher, 1976). Also, the direction or extent of consonant-to-vowel or vowel-to-consonant lingual gestures varies as a function of previous lingual movements (Öhman, 1966; Gay, 1974; Bell-Berti and Harris, 1976; Gay, 1977; Fowler, 1981a, b). MacNeilage and DeClerk (1969) showed that variations in the EMG amplitude of tongue tip gestures for front vowels depended upon the place of articulation of preceding consonants (see also Bell-Berti and Harris, 1976). Similarly, Sussman *et al.* (1973) showed decreases in the EMG amplitude for jaw depression for the final vowel as a function of the openness of the initial vowel in VCV sequences. The reduction in the EMG amplitude was accompanied by decreases in the extent of the lowering movement, possibly as a result of a reduced jaw elevation for the intervocalic consonant. Carryover effects have also been demonstrated as variations in the extent of velum movements depending upon the lingual height of preceding vowels or the type of preceding consonants (Bell-Berti *et al.*, 1979, 1981).

The above findings suggest that an observed movement of a given articulator is affected by the direction and extent of the preceding and following gestures of the same articulator. Both anticipatory and carryover effects, however, have been described primarily in spatial terms. Thus, taken together, these studies do not offer sufficient information concerning both temporal and spatial aspects of intra-articulator, anticipatory, and carryover effects. Our approach in this paper was to present a detailed kinematic analysis of tongue dorsum coarticulation. The kinematic patterns of tongue dorsum coarticulation may provide some information about the temporal and spatial characteristics of intra-articulator coarticulation which can be tested further with other articulators.

There are several aspects concerning the specific nature of intra-articulator coarticulation in tongue movements that remain unclear. Acoustical rather than kinematic analysis has typically been used to assess anticipatory and carryover effects in lingual vowel-to-consonant and consonant-to-vowel transitions (e.g., Öhman, 1966; Bell-Berti and Harris, 1976; Fowler, 1981a, b). The temporal aspects of the coarticulatory effects have usually been neglected in these intra-articulator studies which focused on the spectral correlates of spatial variations. However, there could be variations in the duration of movements as a function of preceding or following gestures. In addition, while the relationships between lingual velocities and variables such as vowel height, stress, and rate have been examined extensively (Kent and Moll, 1969; Kent and Netsell, 1971; Kent and Moll, 1972a; Kuehn and Moll, 1976; Ostry *et al.*, 1983), the assessment of coarticulatory effects in terms of kinematic parameters such as lingual velocities have received less attention. Also, the relationship between anticipatory and carryover effects in intra-articulator coarticulation remains unclear. That is, in some studies, the carryover effect has been shown to be stronger than the anticipatory effect (Bell-Berti and Harris, 1976; Gay, 1977; Fowler, 1981a, b), while other studies have shown the opposite relationship (Öhman, 1966; Ushijima and Hirose, 1974; Butcher and Weiher, 1976). A more complete kinematic analysis of lingual coarticulation may provide a better understanding of these intra-articulator effects.

In this experiment, the kinematics of tongue dorsum movement were examined during the production of VCV sequences. More specifically, we have examined the displacement, duration, and maximum velocity of tongue dorsum movements from an initial back vowel to a velar stop consonant, and from the consonant to a final back vowel. The anticipatory effect of various final vowels upon the transition from the initial vowel to the consonant (RL effect), and the carryover effect of various initial vowels upon the transition from the consonant to the final vowel (LR effect), have been assessed in both spatial and temporal terms. The relative strength of the effects was also assessed. An explanation based on the interaction between raising and lowering gestures is suggested to account for these effects. Finally, the implications of the kinematic characterization proposed here are discussed.

I. METHOD

A. Instrumentation

Tongue dorsum movements and the acoustic speech signal were simultaneously recorded by a computerized ultrasound system. The tongue dorsum displacement was monitored at a rate of 1 kHz by a single pulsed-echo ultrasound transducer (3.5 mHz) and a Picker model 104 A-scan ultrasound generator and receiver. Ultrasonic reflections from the tongue dorsum were sensed by the transducer which was placed below the mandible. The distance from the transducer to the tongue dorsum was calculated on the basis of the interval between the ultrasound emission and the reception of the greatest-amplitude reflection. A Cromemco CS-2 microprocessor was used for the recording and storage of the data. The computer also sampled and stored the accoustical signal with a 12-bit analog-to-digital converter. This system is described in detail by Keller and Ostry (1983).

B. Transducer placement and measurement axis

The ultrasound transducer was placed externally along the inferior midline of the mandible, about 1-cm anterior to the hyoid bone. The orientation of the transducer was approximately perpendicular to the Frankfurt line, which is parallel to the line between the anterior and the posterior nasal spines (see Zemlin, 1981, Fig. 4-133, p. 388). The transducer was held fixed relative to the cranium by an adjustable lightweight assembly mounted on a helmet worn by the subjects. The head harness and transducer did not significantly affect the extent of vertical jaw movements (Keller and Ostry, 1983). The position and orientation of the transducer for recording were determined such that the measured displacement between the tongue position during the closure for /k/ and the tongue zero-velocity position during /a/ was maximized, and the magnitude of tongue dorsum displacements for the three back vowels, /a, o, u/, corresponded to the traditional order of vowel heights. A simultaneous x-ray–ultrasound recording indicated that this placement procedure directs the ultrasound beam towards the place of closure for velar stops (Keller and Ostry, 1983, Fig. 3).

Figure 1(a) shows schematically the transducer in place (point A) and the path of the ultrasound beam (dotted line) relative to the Frankfurt line (between points 1 and 2), the hard palate, and the velum. Also shown are two tongue dorsum positions, one during the closure for a velar stop-consonant (dashed tracing), and the other for a back open vowel (solid tracing). Figure 1(b) shows the transducer and the ultrasound beam in relation to traditional tongue dorsum positions for three back vowels /a/, /o/ (diphthongal), and /u/. The ultrasound axis is shown intersecting the tongue dorsum

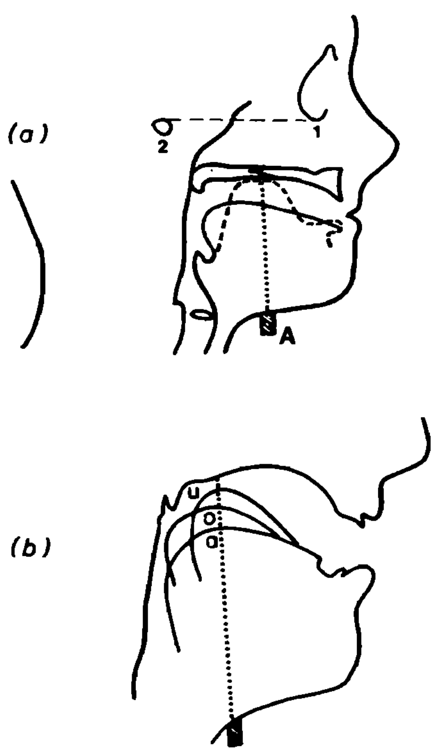

FIG. 1. The ultrasound transducer (A) and the path of the ultrasound beam (dotted line) relative to the cranium and various tongue positions. The top figure shows the tongue position for a low back vowel (solid line) and for a velar stop (dashed line). The Frankfurt line (see text) is indicated by the dashed line between points 1 and 2. The bottom figure shows the traditional tongue positions for the back vowels /a/, /o/ (diphthongal), and /u/.

at points corresponding to the typical tongue pellet positions, in x-ray tracings, for the target positions of the vowels /a/ and /u/ (e.g., Kent and Moll, 1972a, Fig. 1; Gay, 1974, Fig. 2).

The preservation of vowel height order along the ultrasound axis can be seen in Fig. 2 with respect to the recorded tongue dorsum displacements toward the final vowel. In all three records shown in Fig. 2, the initial vowel is /a/ and the stop-consonant is /k/. In Fig. 2(a), the final vowel is /a/, in Fig. 2(b) /o/, and /u/ in Fig. 2(c). It can be seen that the recorded tongue dorsum displacements for the final vowel correspond to the traditional order of vowel heights, /u/ having the smallest downward displacement from the position for /k/, and /a/ the largest. It should be noted that tongue dorsum displacements measured in this fashion correspond to different positions along the axis of the ultrasound beam, and not to changes in the spatial coordinates of tissue points. Consequently, tongue dorsum velocity refers to rates of change along the measurement axis.

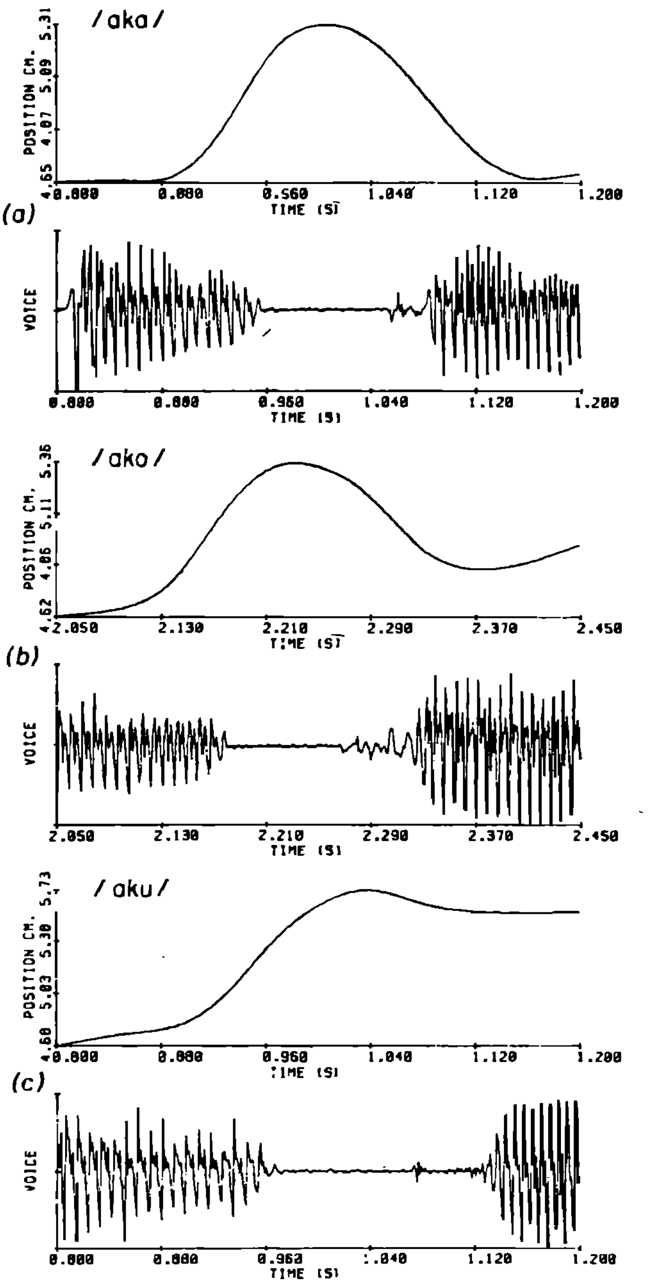

FIG. 2. The vertical displacement of the tongue dorsum in cm and the corresponding waveform plotted against time for the three VCV types: /aka/ (a); /ako/ (b); /aku/ (c). Note that the units on the displacement ordinates correspond to the distance in cm from the transducer to the dorsum of the tongue.

It is not always the case that the ultrasound axis intersects the highest point of the tongue at the vowel position (e.g., for /u/). Nevertheless, the use of a single axis of measurement for vowels such as /a/ and /u/ is justified by both static and dynamic aspects of articulatory and acoustic findings. X-ray tracings show that tongue positions can be accounted for by a single factor in the production of back vowels (e.g., Harshman *et al.*, 1977) The traditional order of vowel heights reported in these studies is preserved in the ultrasound measurement as is shown in Fig. 2. In addition, x-ray tracings of lingual trajectories indicate that there is a comparable forward-directed gesture for vowels such as /a/ and /u/ (e.g., Kent and Moll, 1972a). Acoustically, /a/ and /u/ have similar $F2$ values and different $F1$ values, both statically and dynamically. This indicates that these vowels are distinct in the high–low dimension but similar in the back–front dimension. These findings suggest that the lingual movements in the back–front dimension during the production of these vowels follow similar trajectories, and presumably have comparable effects upon measurements along the vertical axis of the ultrasound beam. Finally, x-ray data (e.g., Perkell, 1969) indicate that the tongue behaves as a semirigid body in vowel production, by assuming a basically invariant shape. Thus movements along the ultrasound axis presumably preserve the dynamic relationships of the movements of specific tissue points, even if the measurement axis is not the exact axis of movement.

C. Speech sample and subjects

The speech sample consisted of 18 different VCV types. This inventory was made up of all possible combinations of the three back vowels: /a/, /o/ (diphthongal), and /u/, varying from low to high, and the two velar stop consonants /k/ and /g/. Each VCV sequence was preceded and followed by the bilabial stop-consonant /p/, and embedded within the sentence "say pVCVp again."

Three adults with normal speech served as subjects. Subjects RF and DO were native speakers of Canadian English (Western and Ontario dialects, respectively). Subject AP was a native Hebrew speaker and fluent in Canadian English. Subject RF was also a fluent speaker of Quebec French. Two of the subjects (RF and AP) produced each sequence 34 times, and the third (DO) 22 times.

D. Experimental procedure

Once a satisfactory transducer placement was achieved and verified by the procedure described above, subjects produced the 18 VCV types in randomized order. The sentences were spoken at a normal rate, with the initial and final vowels in the VCV sequence equally stressed.

The experiment was divided into several sessions, with the transducer placement unchanged during a session. The same placement procedure was employed in each session. Speech samples were recorded in separate trials, each lasting 3.455 s. In each trial, subjects repeated a sentence twice with the same VCV sequence. All 18 VCV sequences were produced and recorded between 4–6 times during each recording session.

E. Data analysis

For the purpose of data analysis, the displacement and acoustic records were transferred to a PDP-11/20 computer. Natural cubic spline functions were employed to reduce nonsystematic variation in the displacement data. These functions are third-degree piecewise polynomials defined over a specified number of intervals. They describe a smooth curve approximating a set of data points (Chambers, 1977; for a detailed discussion of natural splines, see Schumaker, 1981, pp. 309–316). In the analysis of the experiment, the 3.455-s duration of each trial was divided into equal intervals, and the average displacements in the intervals were used as knots (at the interval midpoints) for a spline fitting program (the algorithm used here is from Johnson and Riess, 1977, pp. 200–209). The degree of smoothing of the data is determined by the interval width; greater widths result in smoother curves.

Spline functions have several distinct advantages as an approximating solution. Their piecewise definition leaves them freer geometrically to follow the shape of the curve with no *a priori* assumptions about the overall form of the function. In addition, these specific functions were selected for the ultrasound measurement since they allow missing data points. The approximating curve is differentiable, thus permitting the calculation of kinematic parameters such as velocity and acceleration.

An optimal spline function is one that minimizes the error between the raw data and the spline-fitted curve, while capturing the overall trend of the raw data. Averages of absolute error between the cubic spline and the raw data were calculated over a wide range of interval widths. This procedure indicated that interval widths below 45 ms had no significant effect upon the average difference between the raw data and the spline (Keller and Ostry, 1983, Fig. 4). The choice of 43.2 ms (80 knots) as the averaging interval for calculation of the spline resulted in an average absolute error between the raw data and the spline function of less than 0.03 cm. The points of extreme difference between the raw data and the spline were found mostly at the onset of the consonant closure. (For an example of raw data and the corresponding spline-fitted curve see Keller and Ostry, 1983, Fig. 6).

Instantaneous velocities were calculated as first derivatives of the spline-fitted displacement data. Displacements, velocities, and the corresponding acoustic waveform were then displayed on a videoscreen for the purpose of obtaining numerical values from the records. Values from each of the records were obtained at several points along the time axis and were used to compute six variables for each VCV sequence. The six variables, three for each movement direction, are displayed in Fig. 3.

In Fig. 3(a), the distance from the transducer to the

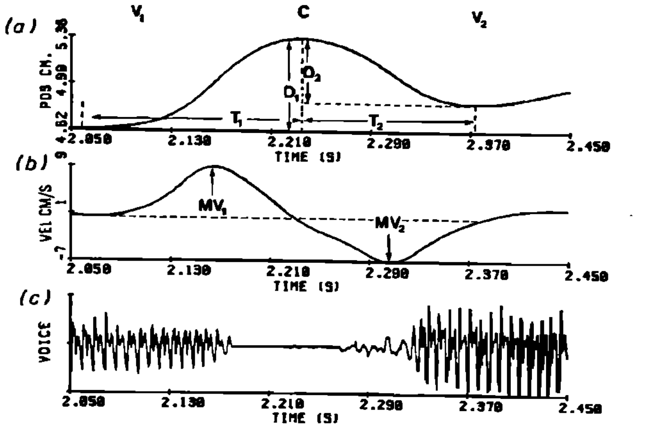

FIG. 3. The vertical displacement in cm (a), maximum velocity in cm/s (b), and the corresponding waveform (c), plotted against time for a single VCV sequence. The zero-velocity line is indicated by the dashed line across the middle panel. Note that the units on the displacement ordinate correspond to the distance in cm from the transducer to the tongue dorsum.

tongue dorsum is plotted against time. The unidimensional displacement of the tongue dorsum from vowel to consonant or consonant to vowel was computed as the difference between tongue heights at the points of zero velocity. *D* 1, the vertical displacement from the initial vowel to the intervocalic stop-consonant, was calculated as the difference between tongue height at zero-velocity during vowel production and the zero-velocity point during the consonant closure. *T* 1, the duration of the transition from the initial vowel to the consonant, was calculated as the time interval between the same two zero-velocity positions. In Fig. 3(b), instantaneous velocities in cm/s are plotted against time. MV1 is the maximum raising velocity of the tongue dorsum during the VC transition.

Vertical displacement, duration, and maximum velocity for the lowering movement are also shown in Fig. 3(a) and (b). *D* 2, the vertical displacement from the consonant to the final vowel, was calculated as the difference between tongue heights at zero velocity during the consonant closure and the vowel. *T* 2, the duration of the consonant-to-final-vowel transition, was calculated as the time interval between these two zero-velocity positions. MV2 is the maximum lowering velocity of the tongue dorsum from the consonant to the final vowel.

A numerical procedure was used to assess the effect of different degrees of smoothing (i.e., different interval widths for the spline function) on the estimated points of movement onset and offset (zero-velocity points). These points were obtained by varying the spacing between knots for a given VCV sequence from 27.6 to 49.3 ms. The analysis indicated that within this range different degrees of smoothing had no systematic effect on the estimation of onset or offset points. The standard error of 12 movement onset point estimates was 0.6 ms; the standard error of an equal number of offset point estimates was 1 ms.

II. RESULTS AND DISCUSSION

A. Kinematics in symmetric VCV sequences

The kinematics of the vowel-to-consonant and consonant-to-vowel transitions were first examined in the sym-

TABLE I. Means and standard errors (SE) for the displacement (D; in cm), duration (T; in seconds), and maximum velocity (MV; in cm/s) in symmetric VCV sequences.

Subject	Direction	Variable	/a/ Mean	/a/ SE	/o/ Mean	/o/ SE	/u/ Mean	/u/ SE
RF	Raising	D	0.8	0.015	0.6	0.019	0.3	0.016
		MV	10.8	0.3	7.8	0.2	4.0	0.2
		T	0.130	0.003	0.140	0.004	0.145	0.006
	Lowering	D	0.8	0.016	0.6	0.020	0.3	0.010
		MV	8.6	0.2	6.9	0.3	3.9	0.3
		T	0.180	0.005	0.144	0.004	0.120	0.008
AP	Raising	D	0.8	0.017	0.7	0.012	0.4	0.020
		MV	8.3	0.2	7.2	0.2	4.6	0.2
		T	0.183	0.005	0.214	0.005	0.140	0.004
	Lowering	D	0.8	0.016	0.7	0.012	0.3	0.014
		MV	8.4	0.2	8.3	0.2	4.0	0.2
		T	0.192	0.005	0.149	0.002	0.137	0.004
DO	Raising	D	0.9	0.040	0.8	0.030	0.5	0.040
		MV	8.9	0.6	8.4	0.5	5.1	0.5
		T	0.167	0.004	0.165	0.005	0.193	0.011
	Lowering	D	0.8	0.040	0.7	0.020	0.3	0.020
		MV	8.9	0.3	8.6	0.4	4.3	0.3
		T	0.167	0.006	0.136	0.005	0.140	0.006

metric VCV sequences. The purpose of this analysis was to verify that known kinematic relationships were preserved in the ultrasound measurement. The means and standard errors of displacement, duration, and maximum velocity of the raising and lowering movements of the tongue dorsum are displayed in Table I. In order to simplify the presentation of the results, the data are pooled across both consonants in all the tables and figures that follow.

A three-way ANOVA (3 vowels $\times 2$ movement directions $\times 2$ consonants) was performed on each of the kinematic variables. The analysis enabled the examination of differences in displacement, duration, and maximum velocity as a function of the vowel, the movement direction in the symmetric sequence, and the consonant. Overall, highly significant differences ($p < 0.001$) in the tongue dorsum displacement and maximum velocity were obtained for the different vowels. Figure 4(a) shows the mean displacement for the vowels /a/, /o/, and /u/ for both raising and lowering gestures in the symmetric VCV sequences. It can be seen that the mean displacement for both the raising and lowering gestures decreased as the vowel shifted from low to high.

These effects were accompanied by an interaction between the displacement for the vowel and the movement direction (raising versus lowering), $F(2,218) = 7.69, p < 0.01$; $F(2,396) = 4.04, p < 0.05$; $F(2,116) = 4.10, p < 0.05$, for subjects RF, AP, and DO, respectively. The interaction between the vowel factor and the movement direction is also shown in Fig. 4(a). Lowering movements from closure toward the vowels /o/ and /u/ tended to have less displacement than the raising movements from the same vowels toward closure. However, for the open vowel /a/, raising and lowering movements were different in terms of their vertical displacement only for subject DO, and similar for subjects RF and AP. The interaction is thus indicated by the increasing difference between the mean displacement of the raising and lowering gestures as the vowel shifted from low to high.

The ANOVA also indicated that there were significant interactions between the duration of the raising and lowering transitions and the vowel factor. These interactions are sum-

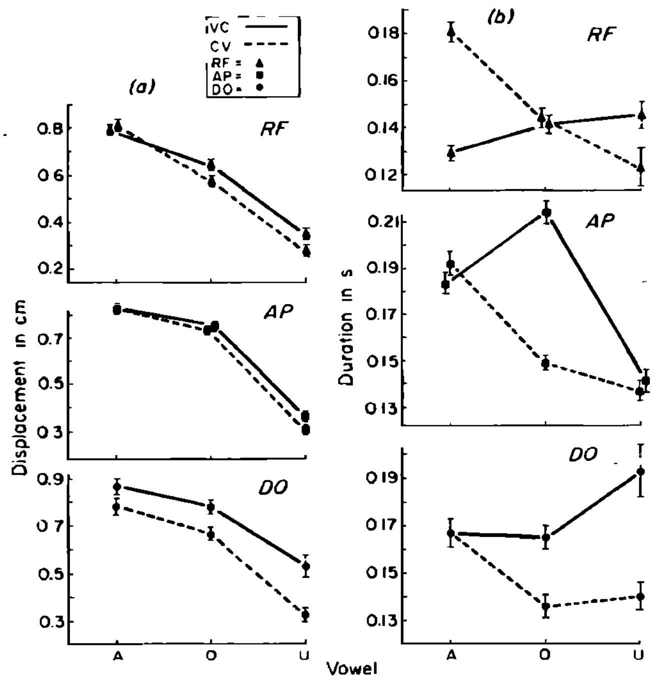

FIG. 4. The mean displacement (a), and duration (b) of the raising (VC) and lowering (CV) transitions shown for the three symmetric VCV types: /aCa/, /oCo/, and /uCu/. The means are pooled across both consonants.

marized in Fig. 4(b). This figure shows the mean durations of the raising and lowering gestures for each of the vowels in the symmetric VCV sequences. It can be seen that the mean duration of the lowering movement decreased as the final vowel shifted from low to high. However, there was no consistent pattern across subjects to the interaction between the movement direction and the vowel.

The results indicate that the ultrasound measurement preserves the traditional order of back vowel heights for both the initial and the final vowels in the symmetric VCV sequences. In addition, there are differences in the extent of tongue dorsum raising and lowering movements, with greater differences for /o/ and /u/ than for /a/. Several studies have shown that the raising and lowering movements of the tongue in symmetric VCV sequences describe a roughly circular or elliptical trajectory, having horizontal and vertical components (Perkell, 1969; Kent and Moll, 1972a; Gay, 1977; Alfonso and Baer, 1982). The asymmetry between the raising and lowering gestures observed here for /o/ and /u/ could perhaps be attributed to such effects. One possibility is that the vertical displacement of specific tongue dorsum tissue points was similar for both raising and lowering gestures for all vowels, but there was a greater horizontal component in the elliptical trajectory for /o/ and /u/ than for /a/. This could result in less displacement for the lowering gestures for /o/ and /u/ along the measurement axis, which captures only the vertical component of the movement. However, this possibility is not compatible with x-ray findings which indicate that the forward-directed gestures for /a/ and /u/ are comparable (Kent and Moll, 1972a). Another possibility is that the vertical displacement of specific tongue dorsum tissue points is not similar for the raising and lowering gestures (e.g., Kent and Moll, 1972a, Fig. 6). Such asymmetry could result from the interaction between the horizontal component and the vertical extent of the lowering gesture.

The intervocalic consonant had some effect upon the displacement, $F(1,396) = 12.02$, $p < 0.01$, for subject AP, and the maximum velocity, $F(1,218) = 6.08$, $p < 0.05$; $F(1,116) = 4.08$, $p < 0.05$, for subjects RF and DO, respectively. There was less displacement and maximum velocity for the gestures to and from /k/ as compared to /g/. Kent and Moll (1969), and Ostry *et al.* (1983) report similar tendencies. A possible explanation is that the depression of the hyoid bone for the voiced stop may pull the mass of the tongue downward. Consequently, greater displacement may be required in order for the tongue to reach the vowel target position. It is not clear, however, whether this explanation can account for the raising gesture too.

Relationships among kinematic variables were also assessed, for each subject, by a set of correlations. The average correlation between displacement and maximum velocity for the three subjects was 0.89 for the raising movement, and 0.92 for the lowering movement ($p < 0.001$). Significant correlations were not found between either displacement or maximum velocity and the duration of the movement. These patterns, observed for all three subjects, follow previous findings indicating a strong relationship between displacement and velocity and no systematic relationship between either displacement or maximum velocity and the duration of the gesture (Kent and Moll, 1969, 1972a; Kent and Netsell, 1971; Kuehn and Moll, 1976; Ostry *et al.*, 1983).

B. Anticipatory and carryover coarticulation in asymmetric VCV sequences

The assessment of anticipatory and carryover coarticulatory effects was performed in two steps. First, the effects of the vocalic context, in either the initial or final transition, upon the kinematic characteristics of the opposite transition were examined with two-way ANOVAs (3 initial vowels $\times 3$ final vowels). Second, stepwise multiple regression was employed to assess the specific nature of the effect for each vowel separately. This second analysis was different from the ANOVA in several respects: (a) while the ANOVA indicated the overall pattern of variations, the regression analysis allowed the assessment of coarticulation in the conventional way of having one vowel constant and varying the vowels across the intervocalic consonant; (b) the stepwise procedure enabled the identification of the kinematic parameter of a given VC or CV transition which was most affected by different vowels in the opposite transition; (c) the displacement to or from the vowel was used as a quantitative measure of vowel height as opposed to the use of vowels as nominal variables in the ANOVA; (d) the regression analysis provided some indices of the relative strength of the various effects.

1. Anticipatory effects

a. Overall vocalic context effect. Previous studies (e.g., Öhman, 1966; Sussman *et al.*, 1973; Fowler, 1981b) have found that the identity of final vowels in VCV sequences has some effect upon the movement, of either the tongue or the jaw, from the initial vowel to the consonant. To assess the effects of different final vowels upon the initial transitions, the displacement, duration, and maximum velocity of the VC transition were used as dependent variables in a two-way ANOVA. If different final vowels affected the kinematic parameters of the VC transitions, then there should have been significant differences between the means of these parameters as a function of the final vowels. The overall F values were all significant ($p < 0.01$) except in the case of the VC duration for subject DO and maximum velocity for RF.

Figure 5 shows the mean duration, displacement, and maximum velocity of each of the three VC transitions, plotted for each of the three final vowels. Overall, it can be seen that the means of all three parameters of the initial transition tended to increase as the final vowel shifted from low to high. This trend was particularly clear when the initial vowel was /a/ (solid lines). In other words, the identity of the final vowel had an effect upon the kinematics of the transition from the initial vowel to the consonant, although the relative strength of these effects differed among the specific measurement parameters. The observed displacement differences, although small, are similar to the pattern reported by Sussman *et al.* (1973) in which the extent of jaw elevation from the initial vowel to the consonant was progressively reduced as the final vowel shifted from high to low. It is not clear whether the displacement differences observed here were be-

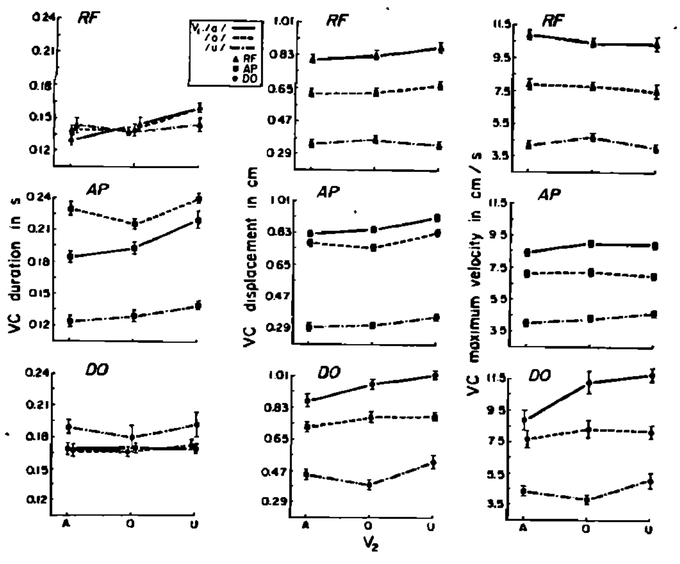

FIG. 5. The mean duration, displacement, and maximum velocity of the three VC transitions shown for each of the three final vowels. The means are pooled across both consonants.

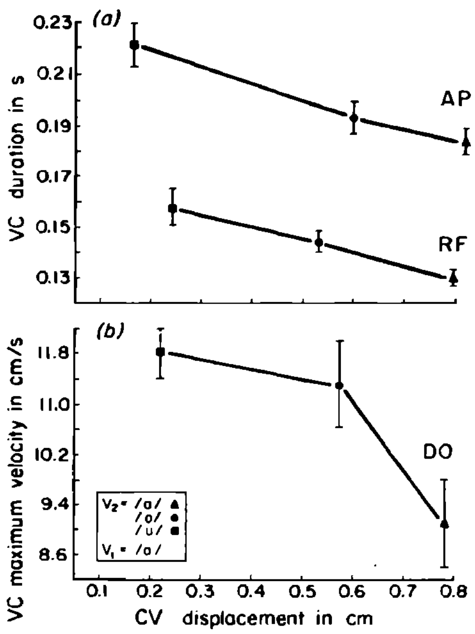

FIG. 6. The mean duration (a) and maximum velocity (b) of the /aC/ transition plotted against the mean displacement of the three CV transitions. The means are pooled across both consonants.

cause the initial movement started from a higher position when the final vowel was low or it reached a somewhat lower position during the consonant closure. This second possibility will be discussed later.

b. Specific vowel-related effects. In order to assess the specific anticipatory effect, the conditions in which the initial vowel was constant and the final vowel varied were analyzed. If different final vowels differentially affected the kinematic parameters of a given VC transition, then the displacement of the final transition should account best for either the displacement, duration, or maximum velocity of the initial transition. Stepwise multiple regression was performed between the kinematic parameters of the initial transition and the displacement of the final transition. The most consistent patterns were found when the initial vowel that was held constant was /a/. The stepwise regression indicated that the displacement of the final transition accounted best for the duration of the VC transition for subjects AP and RF, and the maximum velocity of this transition for subject DO. The pattern of the results is displayed in Fig. 6 with respect to the parameter of the /aC/ transition best accounted for by the CV displacement.

Figure 6(a) shows the VC duration plotted against the CV displacement for subjects AP and RF. Figure 6(b) shows the VC maximum velocity plotted against the CV displacement for subject DO. In both figures the initial vowel is /a/ and the final vowels were /a/, /o/, and /u/. Note that this figure does not show the actual regression lines. Although the parameters of the initial transition best accounted for by the displacement of the final transition were different among the subjects, the trend was similar. The duration and the maximum velocity of the initial transition were inversely related to the displacement of the final transition; in other words, with increases in displacement in the final transition, there were decreases in duration [Fig. 6(a)] and maximum velocity [Fig. 6(b)] in the initial transition. These relationships were similar for both /k/ and /g/.

Based on the analysis of the effects of vocalic context described in the ANOVA above, all three kinematic parameters of the initial transition change as a function of different final vowels. To this extent, the results agree partly with previous reports in which intra-articulator anticipatory effects have been demonstrated as spatial effects. However, the regression analysis indicates that it is the duration (for subjects RF and AP) and the maximum velocity (for subject DO) that changed most significantly and consistently relative to the other parameters of the initial transition. It should be noted that the results for subject DO were less reliable, in comparison to subjects RF and AP, in terms of the standard errors and the proportion of variance accounted for, in both the ANOVA and the regression analysis (these indices will be presented later in Table II). The procedure or data do not provide a sufficient explanation for this difference among the subjects. The different result for subject DO may indicate individual differences in anticipatory strategies.

2. Carryover effects

a. Overall vocalic context effect. To assess the effects of different initial vowels upon the final transition, the kinematic parameters of the CV transition were used as dependent variables in a two-way ANOVA. If different initial vowels affected the kinematic parameters of the CV transitions, then there should have been significant differences between the means of these parameters as a function of the initial vowels. The overall F values were all significant ($p < 0.01$) except in the case of the CV duration of subject RF.

Figure 7 shows the mean duration, displacement, and maximum velocity of each of the three CV transitions plotted for each of the three initial vowels. Overall, it can be seen that the means of the CV displacement and maximum veloc-

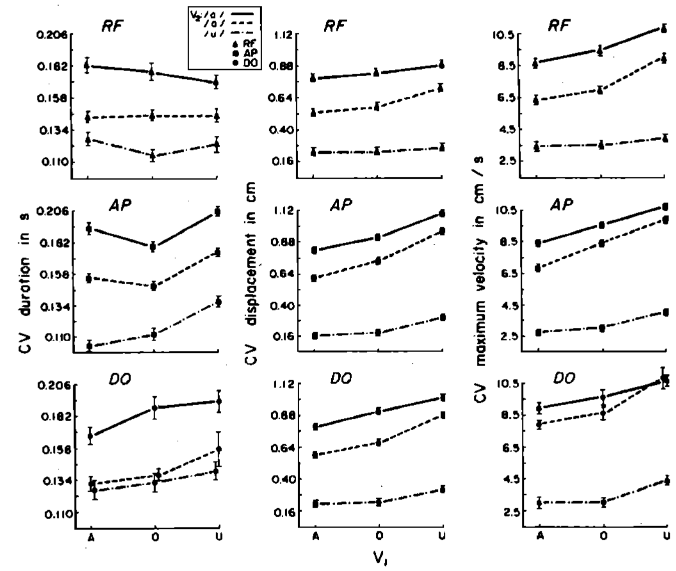

FIG. 7. The mean duration, displacement, and maximum velocity of the three CV transitions shown for each of the three initial vowels. The means are pooled across both consonants.

ity increased as the initial vowel shifted from low to high. This trend is less consistent in the case of the CV duration. In other words, different initial vowels had a highly significant effect upon the displacement and maximum velocity of the final transition. Different initial vowels had a relatively small and inconsistent effect upon the duration of the final transition, and in the case of subject RF the effect was nonsignificant. This is consistent with the overall pattern that variations in displacement were accompanied by corresponding variations in maximum velocity but not by systematic differences in duration.

b. Specific vowel-related effect. In order to assess the specific carryover effect, the conditions in which the final

TABLE II. Partial correlation coefficient (r), proportion of variance accounted for (r^2), and standard error of estimate (SEE) for the relationships indicating anticipatory and carryover effects. The dependent variables are duration (T), displacement (D), and maximum velocity (MV).

Subject	Consonant	Variable	r	r^2	SEE
		Anticipatory effects			
RF	/k/	T	− 0.38	0.15[a]	0.21
	/g/	T	− 0.62	0.38[a]	0.20
AP	/k/	T	− 0.41	0.17[a]	0.25
	/g/	T	− 0.38	0.15[a]	0.28
DO	/k/	...	...	...	...
	/g/	MV	− 0.31	0.09[b]	0.24
		Carryover effects			
RF	/k/	MV	− 0.62	0.39[a]	0.15
	/g/	MV	− 0.53	0.28[a]	0.18
AP	/k/	D	− 0.53	0.28[a]	0.22
	/g/	D	− 0.56	0.30[a]	0.22
DO	/k/	MV	− 0.62	0.38[a]	0.15
	/g/	...	...	...	...

[a] $p < 0.01$.
[b] $p < 0.05$.

vowel was constant and the initial vowel varied were analyzed. If various initial vowels differentially affected the kinematic parameters of a given CV transition, then the displacement of the initial transition should account best for either the displacement, duration, or maximum velocity of the final transition. Stepwise multiple regression was performed between the kinematic parameters of the final transition and the displacement of the initial transition. The most consistent patterns for all subjects were obtained when the final vowel that was held constant was /a/. The stepwise procedure indicated that the displacement of the initial transition accounted best for the displacement, for subject AP, and the maximum velocity, for subjects RF and DO, of the final transition. These results can be viewed as similar for the three subjects, since displacement and maximum velocity were strongly related. The pattern of the results is displayed in Fig. 8 with respect to the parameter of the /Ca/ transition best accounted for by the VC displacement.

Figure 8(a) shows the displacement of the CV transition plotted against the VC displacement, for subject AP. Figure 8(b) shows the maximum velocity of the CV transition plotted against the VC displacement, for subjects RF and DO. In both figures, the final vowel was /a/ and the initial vowels were /a/, /o/, and /u/. As in Fig. 6, this figure does not show the actual regression lines. The displacement and maximum velocity of the final transition were inversely related to the displacement of the initial transition. In other words, greater displacement from the initial vowel to the consonant was accompanied by less displacement [Fig. 8(a)] and maximum velocity [Fig. 8(b)] for the final transition, and vice versa. These patterns were similar for both intervocalic consonants.

These carryover effects are consistent with typical in-

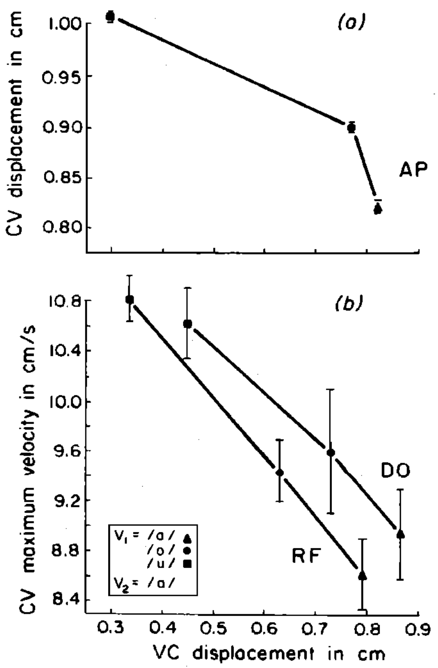

FIG. 8. The mean displacement (a) and maximum velocity (b) of the /Ca/ transition plotted against the mean displacement of the three VC transitions. The means are pooled across both consonants.

tra-articulator observations reported previously. That is, the carryover effects were reflected in displacement or target-position variations. The trend of inverse relationships between the initial and final transitions has also been observed previously (Kent and Moll, 1972b; Sussman *et al.*, 1973; Gay, 1974).

An elliptical trajectory which is not reflected in a single axis measurement could be offered as an explanation for the inverse relationship observed here. However, there are reasons to assume that these results are not the product of elliptical tongue dorsum trajectories. X-ray tracings of tongue dorsum trajectories for /a/ and /u/ indicate that the extent of anterior–posterior gestures for these vowels is similar (e.g., Kent and Moll, 1972a). In addition, acoustical analysis indicated that the carryover effects of /a/ and /u/ upon the $F2$ values for a subsequent vowel were similar (Bell-Berti and Harris, 1976; Fowler, 1981b). These observations suggest that there are comparable trajectories for /a/ and /u/ and these should presumably have similar anterior–posterior effects on a single axis measurement. Thus an elliptical trajectory alone would not account for the differential effects of various initial vowels upon the displacement of the final transition observed here. An explanation based on different tongue heights as a function of the preceding vowel will be discussed later.

3. Comparison between anticipatory and carryover effects

Since the anticipatory effects were primarily temporal and the carryover effects primarily spatial as shown by the stepwise regression, a direct comparison of the magnitude of the effects was not possible. However, the effects could be compared in terms of the strengths of the relationships between the initial and final transitions which indicated these effects. Several indices were computed for the kinematic parameters of a given transition, which the regression analysis indicated as being best accounted for by the displacement of the opposite transition (see previous section). These indices are presented in Table II.

The partial correlation coefficients for the relationship between the variables are presented in Table II. The partial correlations for the carryover effects were higher in most cases than those for the anticipatory effects, and as reported above, were negative in all cases. In addition, it can be seen that the proportion of variance accounted for (r^2) was less for the anticipatory than for the carryover effects. The standard errors of estimate (SEE) for the carryover effects were less than those for the anticipatory effects. These indices show that the relationships between the initial and final transitions which indicate the carryover effects, for all three subjects, were stronger relative to the relationships indicating the anticipatory effects. This asymmetry in the relative strength of coarticulatory effects agrees with previous reports which were based on a more direct comparison of the magnitude of the effects (Bell-Berti and Harris, 1976; Fowler, 1981a, b).

To summarize: The most consistent anticipatory effect, for two subjects, can be described as a temporal shortening of the VC transition as a function of the final vowel. The duration of the initial transition is progressively shortened as the final vowel goes from high to low. The anticipatory effect for the third subject, which was less reliable, can be described as decreases in the maximum velocity of the initial transition with increases in the displacement of the final transition. The most consistent carryover effect, for all subjects can be described as the spatial shortening of the CV transition as a function of the initial vowel. The vertical displacement of the final transition is progressively reduced as the initial vowel goes from high to low. The carryover effects were found to be stronger than the anticipatory ones. In addition, all the effects were similar for both intervocalic consonants.

III. GENERAL DISCUSSION

The anticipatory and carryover effects between the raising and lowering gestures of the tongue dorsum, for VCV sequences with back vowels and velar consonants, are characterized by two main features. The first is the different kinematic nature of the anticipatory and the carryover effects. The anticipatory effect, for two subjects, was primarily temporal, while the carryover effect, for all three subjects, was primarily spatial. The second feature is the pattern of both effects. Regardless of the nature of the effect, spatial or temporal, the corresponding kinematic parameter decreased with greater displacement for the preceding (carryover) or following (anticipatory) transition. We would like to suggest that both features may result from factors related to vowel-specific onset times of the lingual movements toward the final vowel.

There are several indications that during the contact period for a velar stop, the tongue dorsum will start moving sooner for a following open vowel, as compared to a closed vowel. In an electropalatographic examination of VCV sequences, Butcher and Weiher (1976) assessed linguo–palatal contact durations for different vowels. Their results show shorter closure durations when the second vowel was /a/, as compared to /u/, irrespective of the identity of the first vowel (Butcher and Weiher, 1976, p. 64, Table I). This would seem to indicate earlier movement onset of the tongue toward an open vowel relative to the beginning of the closure. In a separate analysis of the data reported here (Parush and Munhall, 1982), the period between the acoustic offset of the first vowel and the movement onset for the second vowel (during the consonant closure), was related to the total displacement for the second vowel. Highly significant negative correlations indicated an earlier movement onset toward an open vowel as compared to a closed vowel. In a cinefluorographic investigation of VCV sequences, Gay (1977) too found that movements of the tongue body toward the final vowel were under way before the consonant release. He reported a tendency for an earlier opening gesture to occur for a following open vowel. Overall, these findings indicate that the tongue dorsum tends to move earlier, during the consonant closure, toward a lower vowel.

In intra-articulator anticipatory effects, the identity of the final vowel does not greatly affect the vertical displacement from the initial vowel to the consonant, however, it affects the duration of this transition. Changes in tongue dorsum height which are due to the final vowel have been shown to start only toward the consonant release (Gay, 1977). Alfonso and Baer (1982) suggested that anticipatory movements for the vowel, in /epVp/ sequences, occur primarily in the horizontal direction and very little in the vertical direction. In other words, the vertical vowel-related movements of the tongue start while the horizontal gestures are already under way. All these findings suggest a small effect of the final vowel upon the vertical displacement from the initial vowel. However, the tongue starts to move earlier toward a final open vowel (Butcher and Weiher, 1976; Gay, 1977). This early movement onset shortens the duration of the transition from the initial vowel to the consonant (which is measured as the period between movement onset toward closure and movement onset toward the final vowel). When the final vowel is high, the movement towards it starts later, resulting in a longer duration for the VC transition.

In intra-articulator carryover effects, the identity of the initial vowel does not greatly influence the duration of the transition from the consonant to the final vowel, however, it affects the vertical displacement of this transition. The findings here show that the duration of the CV transition was not systematically affected by the identity of the initial vowel. Previous findings indicate that durations of lingual CV transitions are affected only slightly by the vocalic context of this syllable (Kent and Moll, 1969; Kuehn and Moll, 1976). These findings suggest then that the duration of CV transitions is relatively independent of the preceding vocalic context. However, the position of the tongue dorsum, in the vertical dimension, during a consonant closure has been shown to be affected by the preceding vowel. Kent and Moll (1969) found that the tongue height is lower, during closure, in /a/ context as compared to /i/. Similarly, Gay (1977) showed that at the initial part of the consonant closure, the tongue dorsum is higher for a preceding /u/ as compared to a preceding /a/. Butcher and Weiher (1976) found that the carryover effect of the initial vowel, either /a/ or /u/, extends up to 40% of the closure time. All these findings suggest that the height of the tongue dorsum for the preceding vowel affects its height during the initial part of a velar consonant closure. The earlier movement onset of the tongue dorsum, during closure, toward a lower final vowel (e.g., /a/), could occur while the tongue height is still affected by the preceding vowel. If the preceding vowel is /u/, the tongue dorsum can start moving toward the final vowel at a higher position than if the preceding vowel is /a/. This will result in a greater vertical displacement toward the final vowel, following an initial high vowel, and less displacement following an initial low vowel. This explanation can also account for the fact that the most systematic effects of the initial vowel on the final transition were found when the final vowel was /a/. If the final vowel is /u/, it is less likely that movement towards it will start when tongue height is still affected by the preceding vowel. This will result in less systematic effects as a function of the preceding vowel.

The notion of vowel-specific onset time is similar to the notion of an articulator-specific onset time in a temporal model proposed by Bell-Berti and Harris (1981). The vowel-specific onset times of the lingual gestures toward the vowel can be achieved in the following way. Different muscles, which can be viewed as antagonistic, are activated for the raising and lowering gestures of the tongue. The raising gestures toward a velar stop are achieved by the palatoglossus (Bell-Berti and Hirose, 1973). The lowering gestures are achieved by contraction of the styloglossus and the posterior genioglossus for the high back /u/ (Perkell, 1969; Hirose *et al.*, 1979; Alfonso and Baer, 1982; Alfonso *et al.*, 1982), and the hyoglossus and the middle pharyngeal constrictor for the low back /a/ (Alfonso *et al.*, 1982; Wood, 1979). It is possible that the different lowering muscles have different activity onset times relative to the raising gesture of the tongue, resulting in different movement onset times for the various vowels.

The vowel-specific onset times of lingual movements may reflect the constraints upon the tongue dorsum in producing different acoustical results for the CV component of the VCV sequence in different contexts. Such acoustical results can be different VOT values in the temporal domain, or different $F1$ values in the spectral domain, for the different vowels, and could be partially due to different onset times of the tongue dorsum from the consonant to the different vowels. It should be noted that the acoustical consequences are not produced by the tongue alone. Lip rounding is critical for the acoustical characteristics of /u/, which jaw lowering contributes to the acoustics of /a/ (e.g., Lindblom and Sundberg, 1971). The late onset of the lingual movement toward /u/ may be accompanied by an early lip rounding. In contrast, an early movement onset toward /a/ may offset a delay in jaw lowering for this vowel. Other examples of compensatory articulation have been demonstrated in studies in which normal movements of speech articulators were perturbed (e.g., Folkins and Abbs, 1975; Abbs, 1979; Gay and Turvey, 1979).

The characterization proposed here cannot be generalized without further intra-articulator research to find whether the specific nature of the coarticulatory effect is similar across articulators. It is also not clear whether the vowel-specific onset time is present in the kinematic patterns of other articulators. However, the overall features of a kinematic characterization such as the one observed here can be tested in different articulators and provide more information about the spatio–temporal aspects of intra-articulator coarticulation and their relation to inter-articulator coordination.

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