

Variant and invariant characteristics of speech movements

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Summary. Upper lip, lower lip, and jaw kinematics during select speech behaviors were studied in an attempt to identify potential invariant characteristics associated with this highly skilled motor behavior. Data indicated that speech motor actions are executed and planned presumably in terms of relatively invariant combined multimovement gestures. In contrast, the individual upper lip, lower lip, and jaw movements and their moment-to-moment coordination were executed in a variable manner, demonstrating substantial motor equivalence. Based on the trial-to-trial variability in the movement amplitudes, absolute positions, and velocities of the upper lip, lower lip, and jaw, it appears that speech motor planning is not formulated in terms of spatial coordinates. Seemingly, object-level planning for speech may be encoded in relation to the acoustic consequences of the movements and ultimately with regard to listener's auditory perceptions. In addition, certain temporal parameters among the three movements (relative times of movement onsets and velocity peaks) were related stereotypically, reflecting invariances characteristic of more automatic motor behaviors such as chewing and locomotion. These data thus appear to provide some additional insights into the hierarchy of multimovement control. At the top of the motor control hierarchy, the overall plan appears to be generated with explicit specification of certain temporal parameters. Subsequently, based upon the plan and within that stereotypic temporal framework, covariable adjustments among the individual movements are implemented. Given the results of previous perturbation studies, it is hypothesized that these covariable velocity and amplitude adjustments reflect the action of sensorimotor mechanisms.

Key words: Speech movements – Motor planning – Motor equivalence – Timing – Coordination

Introduction

Kinematic analysis of complex, natural movements provides perspectives on the organization of the nervous system processes underlying their motor control. In studies of arm reaching movements involving shoulder and elbow actions, it has been shown that terminal hand paths are straight or slightly curved with single-peaked tangential velocities (Abend et al. 1982; Atkeson and Hollerbach 1984; Morasso 1981). Such movements are relatively invariant in these trajectory characteristics when the starting and end positions or the amplitude of hand paths are changed (Morasso 1981; Russell 1976; Viviani and Terzuolo 1980). These data have been interpreted to suggest that these reaching or pointing movements are planned at a goal level, i.e., in terms of hand trajectories in space. By contrast, the more variable individual joint and muscle actions appear to be specified subordinately to the movement goal (Abend et al. 1982; Atkeson and Hollerbach 1984; Bizzi et al. 1982; Lacquaniti and Soechting 1982; Morasso 1981). Subordination of individual joint actions implies their coordination occurs at a different and presumably lower level of the motor control hierarchy than the goal-level planning. Work by other investigators has demonstrated invariant relations between specific constituent joints (Kaminski and Gentile 1984; Kots and Syrovegin 1966; Soechting and Lacquaniti 1981, 1983). Moreover, Hollerbach et al. (1985) have recently reported data consistent with both joint and trajectory-level planning.

One means to test the generality of these various observations is to examine comparable kinematic

patterns for other motor behaviors. Movement patterns for speech offer an interesting possibility in this regard. In motor control of speech, even simple one-syllable words (e.g., book, top) require coordinated actions of an estimated 70+ muscles and movements of 8 to 10 separate body parts distributed from the diaphragm to the lips. However, for speech motor actions, there is no single terminal segment analogous to the hand as in arm reaching movements and many of the constituent components do not interact biomechanically. Finally, coordination of these potentially independent movements must be controlled temporally as well as spatially to accomplish desired goals. In this context, the purpose of the present study was to examine the kinematics of the upper lip, lower lip, and jaw for speech to determine if certain movement patterns, interpreted as evidence for hierarchical motor planning, are also observed in this different motor system. In support of previous observations, the combined or overall action of these three oral movements manifested certain invariant features, while by contrast, the individual movements themselves were executed variably, apparently reflecting their subordinate motor specification. These kinematic analyses also suggested that (1) speech motor planning is not formulated in terms of a spatial coordinate system as hypothesized for certain classes of upper limb movements and (2) certain temporal relations among these multiple constituent movements may be specified stereotypically at an intermediate level of the motor control hierarchy.

Material and methods

Subjects

Four young female adult subjects (S1-S4) participated in the study. All subjects were naive with respect to the objectives of the experiment and with procedures in motor control research.

Apparatus

Inferior-superior movements of the upper lip, lower lip, and jaw were transduced using ultra-light weight cantilever beams instrumented with strain gauges attached to a lightweight head-mounted frame (cf. Barlow et al. 1983). Transducers were attached midsagittally at the vermillion border of the upper and lower lips; the jaw transducer was placed under the chin in a location that yielded negligible artifact from skin movement. Each of the movement signals was digitized at 500 sps (12 bit resolution) on a Digital Equipment Corporation (DEC) PDP-11/44 computer and stored for subsequent processing. All movement signals were digitally low-pass filtered (forward and backward) using a four-pole Butterworth filter design with a cutoff of 20 Hz. Instantaneous velocities were obtained digitally using three-point numerical differentiation. The signals from all trials were viewed on a DEC VT-100 Retrographics terminal and specific events were marked

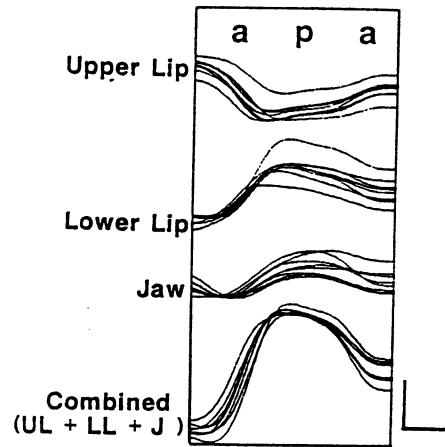


Fig. 1. Eight superimposed upper lip, lower lip, and jaw displacements for the first oral closing movement in 'sapapple'. Traces were aligned at the onset of the lower lip movement for closing. The bottom portion of the figure represents a derived position signal obtained by summing the displacements of the individual articulators over the oral closure period. Data are from one subject. Horizontal and vertical calibrations reflect 50 ms and 5 mm, respectively

Table 1. Coefficients of variation (CV) of the peak closing displacement for each speech structure and the combined signal

	CV	CV	CV	CV
UL	0.092	0.227	0.200	0.152
LL	0.255	0.276	0.297	0.308
J	0.202	0.335	0.233	0.301
C	0.081	0.148	0.152	0.105
Subject	1	2	3	4
	n = 100	n = 176	n = 195	n = 105

for subsequent quantitative analyses. Because the movement signal obtained from the LL transducer reflected the combined action of the LL and the J, this signal was software subtracted from the signal yielding a separate LL movement signal.

Procedure

Subjects repeated the utterance "sapapple" yielding patterns of upper lip, lower lip, and jaw movement coordination. Subjects started each trial at rest with lips lightly touching. There was no syllable rate or specific movement requirements imposed on the subjects; the only instructions were to speak at a moderate vocal intensity level that was understandable 10 to 15 feet away.

Results

Presented in Fig. 1 are multiple UL, LL, and J displacement signals from one subject for the oral

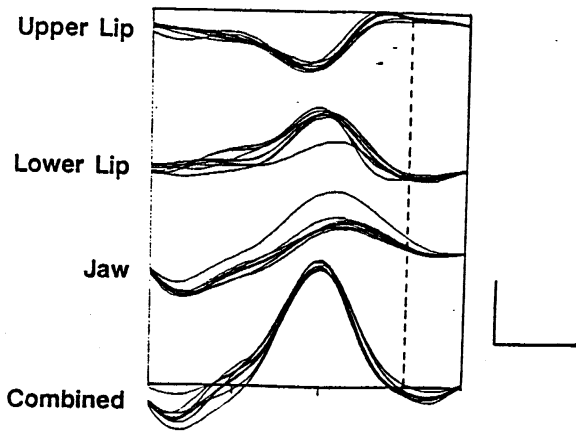


Fig. 2. Eight superimposed upper lip, lower lip, and jaw closing velocity profiles for the first 'p' in 'sapapple'. As in the previous figure, the bottom signal reflects the first derivative of the combined displacement trace previously shown. The dashed line indicates the time of oral closure. Horizontal and vertical calibrations reflect 50 ms and 10 cm/s, respectively

Table 2. Coefficients of variation (CV) of the peak closing velocity for each speech structure and the combined signal

	CV	CV	CV	CV
UL	0.134	0.171	0.148	0.088
LL	0.129	0.238	0.315	0.142
J	0.155	0.281	0.200	0.201
C	0.118	0.151	0.149	0.106
Subject	1	2	3	4
	n = 100	n = 176	n = 195	n = 105

closure associated with the first "p" in "sapapple". To demonstrate qualitatively how these individual movements contribute to oral closure, the instantaneous displacements of the three structures were summed over the closure interval. The onset of the LL movement for closure was used as a reference

with all traces (UL, LL, J, and combined) aligned to the LL onset. The lower trace in Fig. 1 reflects the instantaneous change in the distance between the upper and lower lips (interlip distance). To compare the variability in the peak amplitude of the individual movements with the variability of the combined interlip distance signal, indices of normalized variability (coefficients of variation-CV) were calculated across all trials (within subjects) for the UL, LL, and J peak displacements and the combined interlip signal (Table 1). This measure reflects the ratio of the standard deviation to the mean, allowing a comparison across structures despite different absolute displacements. For the combined signal, the peak displacement was obtained by calculating the relative displacement between the minimum and maximum points of the derived signal. The standard deviation was calculated from the variance of the three structures (UL, LL, and J) using the following formula for correlated variables:

$$S^2_C = S^2_{UL} + S^2_{LL} + S^2_J + 2Cov_{UL LL} + 2Cov_{UL J} + 2Cov_{LL J}$$

where C = combined, Cov = covariance. As seen in Table 1, the CV for the combined signal was always smaller than any of the individual movements. While the differences were small in some cases, it is clear that the variance of the combined signal did not increase proportionally with the larger magnitude of the interlip distance. Inspection of the individual structures indicated that on average the UL was the least variable structure with variability of the LL and the J varying across subjects.

The velocity of UL, LL, and J movements for oral closure was also examined. Figure 2 shows the instantaneous velocity of the three oral movements and the combined movement. The individual movements and the combined interlip signal display a single-peaked velocity profile. Apparent in Fig. 2 is a fair degree of consistency in the magnitude and duration of the combined closing gesture first deriva-

Table 3. Pearson product-moment correlations (r) among the UL, LL and J peak displacements and peak velocities for the four subjects

		LL	J	LL	J	LL	J	LL	J	
Peak Displacement	UL	0.137	-0.239	-0.035	-0.006	-0.239	0.200	-0.225	0.317	
	LL	—	-0.486	—	-0.156	—	-0.308	—	-0.613	
Subject		1		2		3		4		
	Peak Velocity	UL	0.552	0.430	0.100	-0.048	-0.133	0.542	-0.195	-0.020
		LL	—	0.223	—	0.037	—	-0.119	—	0.295
			n = 100		n = 176		n = 195		n = 105	

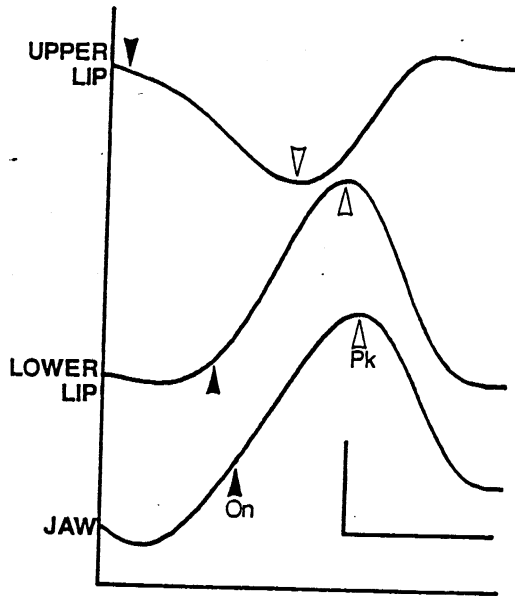


Fig. 3. Upper lip, lower lip, and jaw first derivatives for a single trial from subject 1, illustrating the temporal ordering of the movement onsets (ON) and asynchrony of the times of peak velocity (PK) for the first closing movement in 'sapapple'. Calibrations 5 cm/s and 50 ms

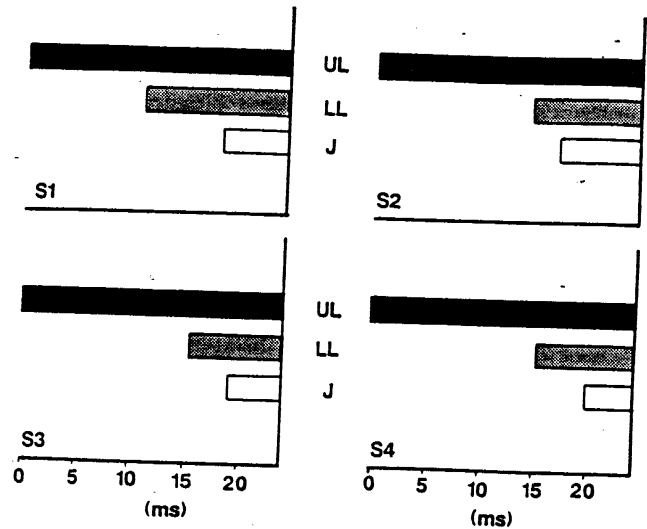


Fig. 4. Bar graphs illustrating the mean absolute timing difference in the occurrence of peak velocity for the LL and J relative to the UL for the four subjects

tive. This consistency may reflect the fact that the temporal acoustic pattern necessary for "p" to be correctly identified by listeners appears to require a certain rate of oral closure (Liberman et al. 1956). Presented in Table 2 are the CVs of the peak movement velocities for the individual structures and the combined signal. Standard deviations were obtained using the formula presented previously. While not as consistent as the displacement, the CV of the combined peak velocity was smaller in 2 of the 4 subjects. As with the displacements, the variability of the derivative of the interlip distance did not increase proportionally with its larger value. Figure 2 also illustrates that the achievement of labial closure is not dependent on the oppositional nature of this task. As shown, labial contact (indicated by the dashed line) occurs only on deceleration of the UL, LL, and J. The contact on deceleration combined with relatively high positive correlations between the amplitude and peak velocity of the individual movements (group average = 0.641, 0.725, 0.901, respectively) indicates that the labial closure goal was not achieved simply by slamming the lips together.

The relations among the constituent UL, LL, and J movements were also examined. Table 3 presents the across-trial correlations among the peak displacements and velocities for each of the subjects. As shown, these correlations (i.e., UL vs LL, UL vs J, LL vs J) are not particularly high. Although many of

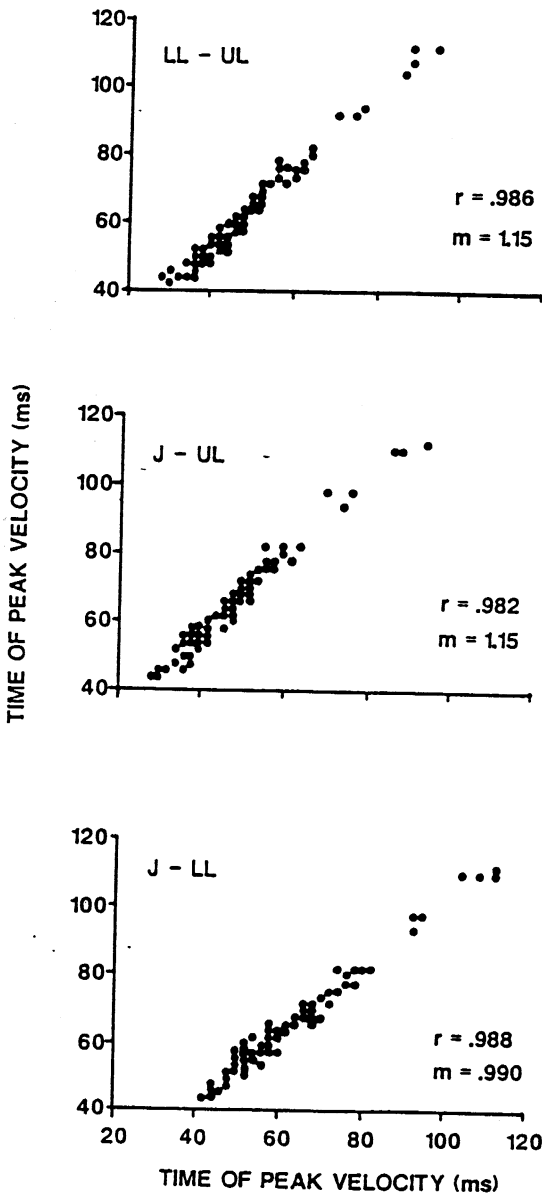
the correlations reached statistical significance due to the large number of degrees of freedom, the amount of variability explained by any pair is low. It appears that the relationship between any two movements is variable across trials.

In contrast to the variable relations within and among the peak velocities and amplitudes of the individual movements, certain temporal parameters were found to be highly consistent within and across subjects. Movement onsets were found to be consistently ordered and asynchronous; the UL movement onset always preceded the LL movement onset which, in turn, always preceded the J movement onset (see Fig. 1). Movement onset, identified in the velocity profiles in Fig. 3, was defined as the time at which the positive-going velocity for the first closing movement exceeded 10% of the peak velocity. Movement onset times among the UL, LL, and J were consistent in their sequencing and significantly different from one another for all subjects ($p < 0.01$; t-test for paired data). Averaged across subjects, the time between UL movement onset and LL movement onset was 23 ms, while the time between LL movement onset and J movement onset was 12 ms. While 10% of the peak velocity may be a rather high criterion, subsequent analyses using the velocity zero-crossing, 1%, and 5% of the peak velocity yielded relatively similar results. That is, regardless of the movement onset criterion, the UL movement onset always preceded the LL movement onset which always preceded the J movement onset.

More striking was the consistent temporal sequencing and the timing of the UL, LL, and J

Table 4. Correlations of the time at which peak velocities occurred for individual UL-LL, UL-J, and LL-J movements for the four subjects

		LL	J	LL	J	LL	J	LL	J
Time of peak velocity	UL	0.945	0.923	0.926	0.977	0.771	0.987	0.986	0.982
	LL	—	0.976	—	0.920	—	0.765	—	0.988
Subject		1		2		3		4	
		n = 100		n = 176		n = 195		n = 105	



velocity peaks. As shown in Fig. 3, the velocity peaks of UL, LL, and J occurred in the same sequence as the movement onsets: UL peak velocity preceded LL peak velocity which, in turn, preceded J peak velocity. A summary of the differences in the timing of the UL, LL, and J peak velocities is presented in Figure 4. As shown, the temporal ordering of the velocity peaks was consistent across subjects. The differences in peak velocities were all statistically significant ($p < 0.005$, t-test for paired data).

In addition to the consistent sequencing, the timing among the individual velocity peaks was highly correlated for all subjects, with coefficients ranging from 0.765 to 0.988 (Table 4). Figure 5 illustrates these peak velocity relationships in detail with data from one subject. The x and y axes reflect the times of peak velocity relative to the onset of UL movement. Apparently, with variations in the duration of the closing gesture, the timing of the velocity peaks changed in a coupled and proportional manner, as evidenced by the correlations and the slopes of the individual regression lines, respectively. In this subject, for example, the movement durations varied widely across repetitions; 60–124 ms (UL), 38–78 ms (LL), and 32–150 ms (J).

Despite the regular temporal sequencing of the peak velocities, plots of the instantaneous velocities from movement onset to peak displacement indicated that these movements were not coupled on a moment-to-moment basis. Figure 6a and 6c are representative instantaneous velocity-velocity plots for UL/LL, UL/J, and LL/J for two of the four subjects; the absence of stereotypic relations among the individual movements during the oral closure is obvious. Interestingly, when the peak velocities for each structure are normalized, the interrelations among these movements are somewhat more regular, particularly in the deceleratory phase of the movements (Fig. 6b, d); however, considerable variability remains. Further, position-position plots presented in Fig. 7 demonstrate a number of notable points. Qualitatively, the slopes of the lines relating any two structures are not entirely parallel, although some

Fig. 5. Scatter plots of the time of peak velocity re: the onset of upper lip movement for subject 4. The correlation coefficients (r) and slope of the regression line (m) are presented for each articulator pair

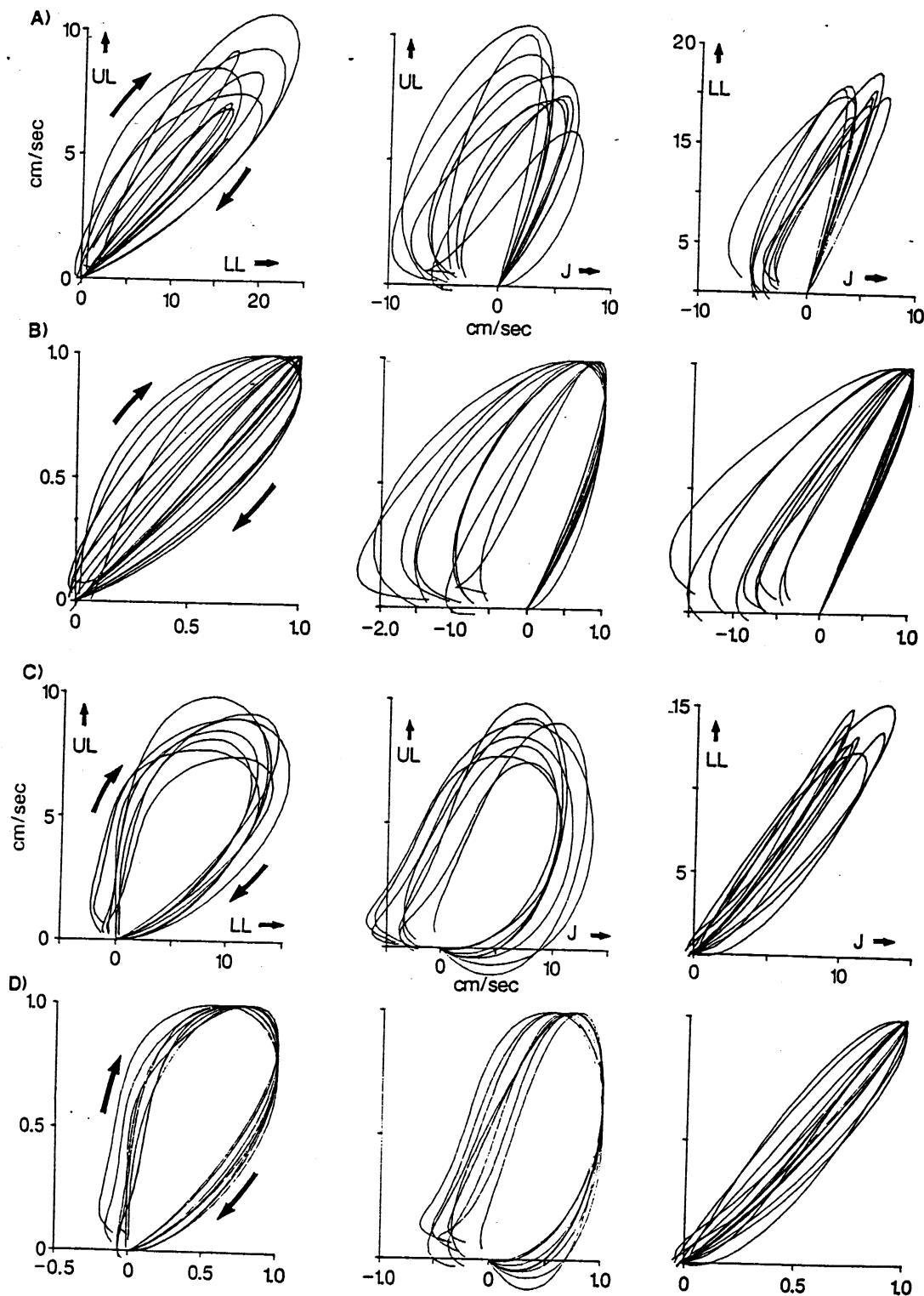


Fig. 6. A, C the relations between the instantaneous velocities of the UL-LL, UL-J, and LL-J during oral closure for two subjects ($n = 10$ for A; $n = 8$ for C). In B, D, the velocities have been normalized with respect to the maximum velocity of each corresponding articulator. Short arrows indicate the labelled articulator axis; longer arrows indicate the progression of motion, which is the same for all plots

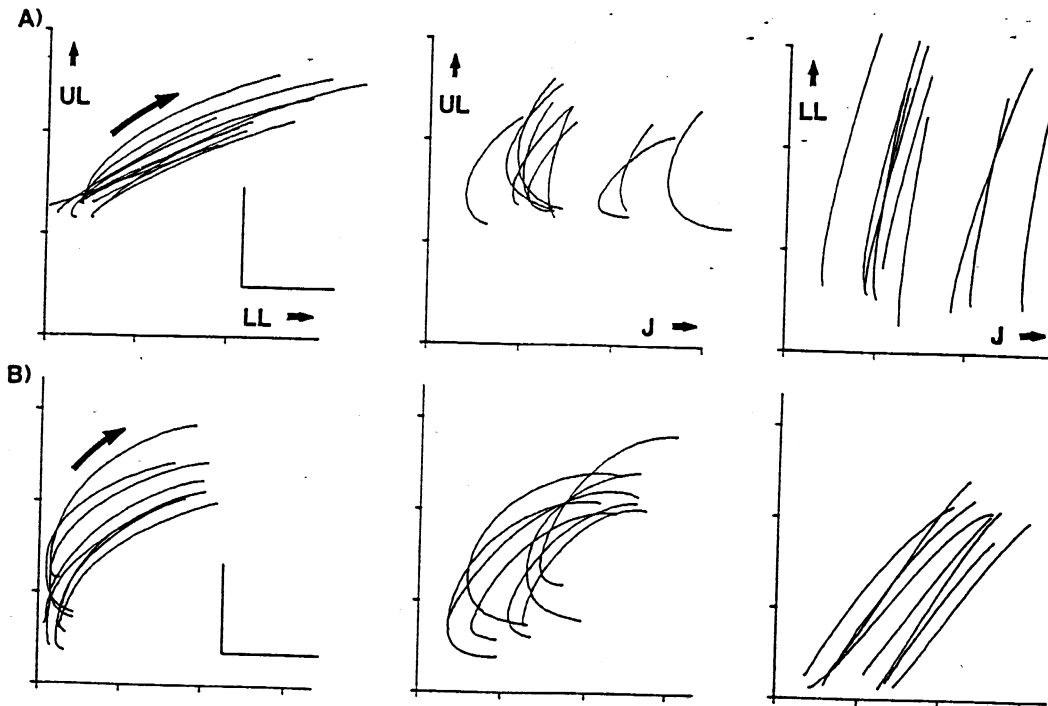


Fig. 7. Position-position plots of the trials previously presented in Fig. 6. Short arrows indicate the articulator axis; longer arrows indicate the direction of movement. Horizontal and vertical calibrations are 5 mm

consistency can be seen in the UL/LL and LL/J relationships. Figure 7 also illustrates an absence of any spatial regularity in the relations among these individual movements; there is substantial variability in both the starting and ending positions of these movements. Finally, the curvilinear trajectories most notable in the UL/J plots result from the temporal asynchrony of the movement onsets similar to that observed in the upper limbs for certain two-joint movements (Wadman et al. 1980).

Discussion

Consistent with previous investigations of multiarticulate tasks such as pointing and reaching (Morasso 1981; Abend et al. 1982), the combined UL, LL, and J oral closure movement manifests a single-peaked velocity profile. This single-peaked velocity profile was achieved despite considerable variability in the moment-to-moment instantaneous velocity and displacement relations among the individual movements. In parallel, the combined UL, LL, and J action was shown to be significantly less variable in its peak displacements and peak velocities than the displacements and velocities of the constituent parts. Similar to the object-level planning suggested for upper limb movements (Hollerbach 1982), these

observations indicate that overall labial closure action is planned or specified at a higher level in the motor control process than the velocity and displacement details of the individual movements.

The nature of motor planning for speech

In contrast to upper limb reaching movements, motor planning for speech oral closure is obviously not in terms of the trajectory of a single terminal segment such as the hand; rather the goal is the combined oppositional actions of the three speech structures in achieving labial contact. Importantly, the point of labial contact was not consistent with regard to either an internal or external spatial reference (see also Saltzman, in press for related discussion). That is, the point in space at which the lips made contact varied with the relative displacements of the UL, LL, and J, all of which varied substantially. These considerations suggest that, unlike arm reaching movements, the motor plan underlying this speech objective was not formulated with regard to spatial coordinates (cf. Bernstein 1967; Lashley 1930; Morasso 1981). The absence of spatially-based speech motor planning is not surprising given the ultimate acoustic objectives for speech tasks. It has been shown analytically, with mathemat-

ical models of the vocal tract for generating speech (Rothenberg 1968; Stevens and House 1955, 1961), that the attainment of specific spatial targets for individual oral movements is not critical (see however, Perkell and Nelson 1982). In the present experiment, the multiple trials of "sapapple", for which no consistent spatial goals were manifest, yielded acoustic patterns that were acceptable in the auditory-perceptual domain of human listeners. The single consistent kinematic factor observed in this study was oral closure which has significant consequences for the generated acoustic signal and resultant auditory perception. In this respect, it seems reasonable to suggest that object level planning for speech actions may be encoded in the acoustic consequences of the movements and ultimately with regard to auditory perception. Several earlier speech investigators, based upon observations of variable speech movements and variable vocal tract shapes yielding acceptable acoustic signals, have made similar suggestions (cf. Ladefoged et al. 1972). In a recent kinematic study of finger-thumb pinch, Cole and Abbs (in press) provided related evidence suggesting that higher level motor planning may not be formulated with regard to spatial coordinates, but rather in relation to the sensory consequences of successful task performance.

At some level, the motor plan for this task must involve a representation of the combined upper lip, lower lip, and jaw movement. The simplest possibility is that the plan involves specification of the necessary oral closure with certain parameters indicated for the rate of that closure. Motor planning of this kind must, however, be task specific, varying entirely in form for different classes of speech movements. Many multiarticulate movements for speech do not involve occlusion of the airway or contact between oral structures. One possibility is that all classes of speech movements may be coded in terms of relational interactions in which the movement goal is specified in terms of the combined movement actions to yield a relatively invariant goal. For speech movements, task-specific consequences would be based on well-developed kinematic-acoustic transformations to yield consistent acoustic goals.

One potential limitation of the present study is that only a single speech task was used. It is not clear, based on these data, that speech motor planning always involves relational interactions yielding relatively invariant movement goals. In order to generalize from the above results to differing initial conditions and different combined lip/jaw actions, kinematic analyses need to be conducted for other speech utterances. Preliminary results from a forthcoming study have indicated that the temporal

sequencing and order of movement onsets and peak velocities maintain patterns consistent with those shown in the present study.

Motor equivalence in speech motor control

The results from the present experiment permit one to consider some of the requisite characteristics of transforming a planned goal (presumably acoustically-significant oral closing) into the necessary muscle actions and forces for the observed lip and jaw movements. These data suggest that these three oral movements are generated interdependently; their trial-to-trial peak displacements are covariable. This covariability suggests that the coordination among these three movements is controlled in relation to a higher-level oral closure goal. Further, this interdependency reflects the phenomenon of motor equivalence; namely, consistent upper lip-lower lip contact achieved in a controlled manner with variable displacements and velocities of the individual movements (see also Hughes and Abbs 1976). Motor equivalence reflects complementary adjustments in a system's multiple degrees of freedom in accomplishing a particular motor goal. For the movements of the speech articulators, the number of degrees of freedom reflect an overspecified (Hogan 1985) or overcomplete (Pellionisz 1985) system. Systems with such redundant degrees of freedom have been considered potentially detrimental to the control process (Bernstein 1967; Turvey et al. 1978). More recently, it has been suggested that redundant degree-of-freedom systems may permit invariant object-level goals to be executed variably, thereby facilitating the control process (Abbs et al. 1984; Arbib 1981; Cole and Abbs 1986; Hinton 1984; Hogan 1985; Saltzman 1979). The variable manner in which the control process operates provides the flexibility to adjust to changes in internal or external conditions prior to or during the evolving movement. As such, motor equivalence adjustments appear to accommodate the dynamic and naturally occurring movement variability accompanying speech. To this point, it has been reported that the degree of covariable patterning (motor equivalence) among the movements of the UL, LL, and J is increased for higher speech rates (Hughes and Abbs 1976).

The observation of motor equivalence among upper lip, lower lip, and jaw movements in the present experiment allows for some additional considerations regarding the underlying control process. The variability in the initial and final positions of the speech articulators and the lack of velocity coupling among them suggest that control schemes reflecting

highly invariant relations may not apply to the control and coordination of speech movements, except at an abstract goal level. A similar suggestion has been made by Saltzman (in press) in the modeling of bilabial closure. While there is some degree of coupling among the articulators (noted in Fig. 6 and 7), there is also a notable degree of variability. Any theoretical explanation must account for such variability. During speech, the shape of the vocal tract is changing constantly. In order to produce the acoustical patterns necessary for auditory perception, there must be a mechanism for monitoring the changing states of the individual structures as well as coordinating the multiple degrees of freedom to achieve upcoming movement goals. Previous results from speech perturbation studies coupled with the observations in the present study appear to suggest that such adjustments result from sensorimotor mechanisms operating within and among these oral movements to accomplish the planned multiarticulate goals (Abbs and Gracco 1984; Folkins and Abbs 1975; Gracco and Abbs 1985; Kelso et al. 1984).

A central pattern generator in the speech motor hierarchy

An additional finding of the present study that addresses the hierarchy underlying multiarticulate movement control is the notable temporal regularity in certain parameters of the individual oral movements as contrasted to the much more variable patterns of their moment-to-moment velocity and displacement. These patterns, perhaps unique to motor tasks having both temporal and spatial requirements (such as speech), may indicate an additional stratification in the hierarchy for motor control of multiarticulate movements. Specifically, given the high degree of temporal regularity on the one hand and almost total absence of regularity in displacement and velocity on the other, it would seem unlikely that these two sets of variables are specified conjointly. The level for specification of the stereotypic timing is most probably intermediate between the object level planning and the covariable specification of moment-to-moment velocity and displacement. In the limbs, it has been suggested that consistent sequencing among constituent movements, as seen in the present study, is characteristic of motor tasks which have specific temporal requirements; temporal coordination is argued to be invariant, allowing other aspects of the control process to vary (Lacquaniti and Soechting 1982). An additional consideration is that multiarticulate speech movements, which must be well coordinated

temporally, also require the flexibility to rapidly adjust to the changing peripheral conditions occurring during speech. The stereotypic timing relations observed would make the moment-to-moment velocity and displacement adjustments easier to implement. Additionally, the temporal asynchrony may provide the nervous system with more available time to make the nonautogenic adjustments characteristic of speech movement control (cf. Abbs et al. 1984).

The consistent sequencing and inter-movement timing among the UL, LL, and J for oral closure suggest the operation of a pattern generator comparable to that associated with motor behaviors such as swallowing, chewing, or locomotion. The finding that the timing among these oral movements was adjusted proportionally also suggests that this pattern generation process is sensitive to changes in the overall kinematic pattern, such as oral closure duration. For less voluntary motor behaviors, like chewing and locomotion, the temporal aspects of muscle contraction and movement are often stereotypically controlled in this manner with the magnitude of contraction and resulting movement amplitudes modulated in accordance with external conditions under the influence of continuous sensory input (cf. Andersson and Grillner 1983; Duysens and Pearson 1980; Grillner 1974; Grillner and Rossignol 1978; Herman et al. 1976; Lund and Olsson 1983). Similarly, it has been observed that perturbations to the jaw or lips during oral closure lead to modifications in movement amplitudes and velocities and in the magnitudes of associated muscle activity (Abbs and Gracco 1984; Folkins and Abbs 1975; Gracco and Abbs 1985; Kelso et al. 1984). Unfortunately, none of these previous speech studies have included analyses to determine whether such magnitude adjustments are accomplished without changes in the relative timing among movement onsets or peak velocities. Preliminary analyses of these patterns (Gracco, unpublished observations) indicate that while there are statistically significant changes in upper lip, lower lip, and jaw displacements, velocities, and movement durations in response to lower lip perturbations during oral closure, the relative timing among the peak velocities of these movements is unchanged.

An important consideration in interpreting the consistent temporal sequencing of the UL, LL, and J is that these structures have different biomechanical properties. Because the lips and jaw differ in their inertial characteristics (cf. Müller et al. 1977; Müller and MacLeod 1984), it could be argued that with muscle forces applied simultaneously to all three structures, the movement onsets would occur in the same order observed. However, the agonist muscles underlying oral closing in these three structures do

not appear to be activated simultaneously or in the same sequence as their movement onsets or velocity peaks (cf. Folkins 1981; Gracco, unpublished observations; Sussman et al. 1973). On this basis, it appears that the lip and jaw muscles are temporally activated in such a manner to produce the relatively invariant timing patterns observed. Moreover, preliminary analyses of the oral opening following the first "p" in "sapapple" indicate that the sequence of movement onsets and velocity peaks was consistently different from that of the oral closing pattern; these data further argue against a strict biomechanical explanation of the sequence observed for closing. The change in movement sequencing from oral closing to opening also implies that these temporal patterns are modified as the plan is changed (i.e., from closing to opening). Ideally, to substantiate the stereotypic timing observed here, one would like to have parallel data on the timing of EMG among UL, LL, and J muscles. However, such EMG data are difficult to obtain. At least nine different facial and masticatory muscles contribute to the oral closing movements observed.

At the outset of this paper, it was noted that kinematic analyses yield information regarding the requisite nervous system processes underlying control of multiarticulate movement. Given the database available on the influences of brain damage upon speech, the present observations may offer some directions regarding these neurobiological correlates. In general, it is thought that the goal-level planning for speech is a function of the posterior neocortical areas; lesions to certain of these regions generally lead to problems in which overall speech goals (linguistic or phonological elements) are incorrectly selected without loss of the smooth flow of the speech pattern (Blumstein 1973; Blumstein et al. 1980; Goodglass and Kaplan 1972). By contrast, lesions to anterior speech areas lead to patterns referred to as nonfluent aphasia in which oral movements are fragmented and manifest considerable discoordination (Mohr 1976; Schiff et al. 1983; Tonkonogy and Goodglass 1981). As hypothesized by the present authors (Abbs 1986; Gracco and Abbs 1986), these anterior areas also appear to be sites that receive substantial somatic sensory input from the orofacial region and may be the basis for mediating sensorimotor adjustments to unanticipated perturbations. As such, the higher level planning and lowest level covariable adjustments may be associated with functions of posterior and anterior speech areas of the cerebral cortex, respectively. More detailed hypotheses regarding the neurobiological stratification of the speech motor control process can be obtained from the clinical literature. However, this

latter work is limited by the absence of information on the exact location and extent of the associated lesions, the substantial difficulty of inferring normal function from damaged systems, and the paucity of quantitative data on specific speech movement impairments. New brain imaging techniques, combined with the kinematic measures utilized in the present investigation, may permit more rigorous development of brain-behavior models for speech motor control.

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