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The timing of articulatory gestures: Evidence for relational invariants

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In this article, we examine the effects of changing speaking rate and syllable stress on the space–time structure of articulatory gestures. Lip and jaw movements of four subjects were monitored during production of selected bisyllabic utterances in which stress and rate were orthogonally varied. Analysis of the relative timing of articulatory movements revealed that the time of onset of gestures specific to consonant articulation was tightly linked to the timing of gestures specific to the flanking vowels. The observed temporal stability was independent of large variations in displacement, duration, and velocity of individual gestures. The kinematic results are in close agreement with our previously reported EMG findings [B. Tuller *et al.*, J. Exp. Psychol. **8**, 460–472 (1982)] and together provide evidence for relational invariants in articulation.

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INTRODUCTION

A central goal for speech research is to understand the perceptual constancy of a given unit (e.g., feature, phoneme, syllable) in the absence of a unique set of acoustic or articulatory properties. For example, linguistic constraints, such as phonetic context, level of stress, and speaking rate, produce a wide range of articulatory patterns for the same abstract linguistic type. The approach that we adopt here is to ask whether constancies in relational aspects of articulatory patterning can in fact be observed across these speech-relevant transformations. The present work explored the possibility that the relative timing of articulatory gestures spanning several segments is maintained over suprasegmental variations in stress and speaking rate.

The notion of relational invariants (Kelso, 1981) as essential to speech communication is motivated from three disparate sources. First, in nonspeech motor skills such as bimanual coordination, handwriting, typewriting, postural control, and locomotion, the relative timing of kinematic or electromyographic events is maintained across scalar changes in rate and force production (see, for review, Kelso *et al.*, 1983). For example, as a cat walks faster, the duration of the "step cycle" of each limb decreases and the propulsive force produced by limb extension increases (Grillner, 1975; Shik and Orlovskii, 1976). However, the timing of activity in the limb extensor muscles is constant relative to the time between successive flexions (Engberg and Lundberg, 1966).

A second motivation for examining relational invariants is the demonstration that perception of certain linguistic distinctions relies on the relative (not absolute) durations of acoustic constituents. For example, perception of the voiced/voiceless distinction in medial stop consonants is strongly influenced by the duration of silence (closure) preceding release of the consonant. However, Port (1979) found that the duration of silence necessary to specify that the medial stop consonant was voiceless decreased as speaking rate increased (cf. Pickett and Decker, 1960; Summerfield, 1975; Miller and Liberman, 1979; Miller and Grosjean, 1981).

A third motivation for our approach comes from investigations of speech production. These studies, though few in number, suggest that the relative timing of articulatory kinematics at the segmental and syllabic levels is unaffected by suprasegmental variations (e.g., Kozhevnikov and Chistovich, 1965; Kent and Netsell, 1971; Kent and Moll, 1975; Löfqvist and Yoshioka, 1981).

In an earlier paper (Tuller *et al.*, 1982a), we examined whether stable relative timing across suprasegmental variation is also an appropriate characterization of *intersegmental* speech organization. Specifically, we asked whether the muscle activity underlying production of the vowels and medial consonant in utterances such as /pi#pap/ and /pa#pap/ would maintain any systematic temporal patterning across rates and stress levels. Our strategy was to define periods of muscle activity corresponding to the interval between successive vowels and successive consonants. We then examined the timing of various aspects of muscle activity specific to the intervocalic consonant relative to that specific to the vowel interval, and the timing of muscle events for interconsonantal vowels relative to the consonant-specific interval. Comparing the stability of these various timing relations, we found one very consistent result: The average duration of the interval between onsets of muscle activity for successive vowels was systematically related to the average latency (relative to the first vowel) of medial consonant-related muscle activity.[1] Other possible relationships, such as those based on periods of muscle activity related to production of successive consonants, did not show the same degree of stability.

One shortcoming of the electromyographic experiment is that we could only examine the stability of relative articulatory timing on the average of ensembles of tokens. We could not examine whether the same relationship also holds when token-to-token variability is allowed because it is not always possible to define onsets and offsets of muscle activity for individual repetition tokens of an utterance (Baer *et al.*, 1979). Moreover, the eventual goal is to understand the speech signal as structured by movements of the articulators, but the general form of the relationship between electromyographic signals and kinematic variables is by no means transparent. For these reasons, we performed a similar experiment in which articulator movement trajectories were measured and their relative timing examined.

I. METHOD

A. Subjects

The subjects were three adult females and one adult male. All were native speakers of English and one subject (BT) was aware of the experiment's purpose.

B. Materials and procedure

The speech sample included utterances of the form b–vowel–consonant–vowel–b with the medial consonant presented and spoken as the first element of the second syllable. Consonants and vowels were chosen to maximize lip and jaw movement. Thus the first vowel (V1) was either /a/ or /æ/, the second vowel (V2) was always /a/, and the medial consonant (C) was either /b/, /p/, /w/, or /v/ (e.g., /ba#wab/, /bæ#pab/, etc.). Each utterance was spoken with two stress patterns, with primary stress placed on either the first or second syllable. The subjects read quasirandom lists of these utterances at two self-selected speaking rates—one conversational and the other somewhat faster. Each utterance was embedded in the carrier phrase "It's a —— again" to reduce the effects of initial and final lengthening and prosodic variations. Three subjects produced 12 repetitions, and one subject ten repetitions, of the 32 utterance types (8 phonetic strings ×2 rates ×2 stress patterns).

C. Data recording

Articulatory movement in the up–down direction was monitored using an optoelectronic device (a modified SELSPOT system). In this system, lightweight, infrared, light-emitting diodes (LEDs) are focused on a photodetector that, with the associated electronics, outputs analog signals corresponding to the x and y position of each LED over time. In this experiment, the LEDs were attached to the subject's upper lip, lower lip, jaw, and nose. A headrest was used to minimize head movements during the experiment. In addition, output of the LED on the nose was continuously displayed on an oscilloscope placed directly in front of the subject, who was told to keep the display on the zero line.

Acoustic recordings were made simultaneously with the movement tracks and both were computer analyzed on subsequent playback from FM tape. Acoustic tokens were first excised from the carrier phrase using the PCM system at Haskins Laboratories, then played in random order to four listeners who judged each token's phonetic makeup and stress pattern. Tokens were omitted from further analysis if more than one listener judged the token as having a different stress pattern from the appropriate one or if any phonetic errors were noted. For only one speaker (JE) was it necessary to omit more than two tokens of any given utterance type.

The movement records were computer sampled at 5-ms intervals. To correct for up-down head movements, output of the nose LED was subtracted (by a computer program) from output of the LEDs attached to the lips and jaw. Similarly, movements of the lower lip were corrected by subtracting movements of the jaw. Velocity records for the jaw, upper lip, lower lip, and lower lip corrected for jaw movement were obtained by software calculation of the first derivative of the position records. For each token, the times at which movements began and ended (indexed by points of zero velocity) were obtained individually for the jaw, the upper lip, and the lower lip corrected for jaw movement.

II. RESULTS

The main thrust of this study was to examine the relative timing of articulatory movements. In keeping with our earlier work and with various studies of nonspeech motor skills, we chose to define articulatory timing in terms of the phase relations among events in the movement trajectories. This requires delimiting some period of articulatory activity and the latency of occurrence of an articulatory event within the defined period. Over linguistic variations, in this case stress and rate, these intervals will change in their absolute durations. The question is whether they change in a systematically related manner.

Our earlier electromyographic study (Tuller *et al.*, 1982a) showed this maximal temporal systematicity when the latency of onset of consonant-associated muscle activity was considered relative to the period between onsets of muscle activity associated with production of successive vowels. We used this result to guide our investigation of articulatory kinematics, although the latencies of gestures associated with successive consonant productions were also examined.

Figure 1 shows the acoustic signal and position-time functions for the jaw, upper lip, and lower lip (independent of jaw movement) for one token of /ba#pab/, spoken with primary stress on the second syllable. The figure illustrates the articulatory intervals discussed in the rest of this article. In all cases, the onsets of articulator movements (A through F in Fig. 1) were determined empirically from zero crossings in the velocity records of individual tokens (not shown in Fig. 1). Points labeled A and B are the onsets of jaw lowering associated with producing the first and second vowels, respectively. The interval from A to B is referred to hereafter as the "gestural cycle associated with production of successive vowels" or, more loosely, the "vocalic cycle." Similarly, the intervals from C to D and from E to F are referred to as "gestural cycles associated with production of successive consonants" or "consonant cycles," indexed by movement onsets of the upper lip and lower lip, respectively. Within the vowel cycle of each individual token, we measured the latency of onset of consonant-related movement in the upper and lower lips (i.e., the intervals A–C and A–E). Within the consonant cycle of each token, we determined the latency of

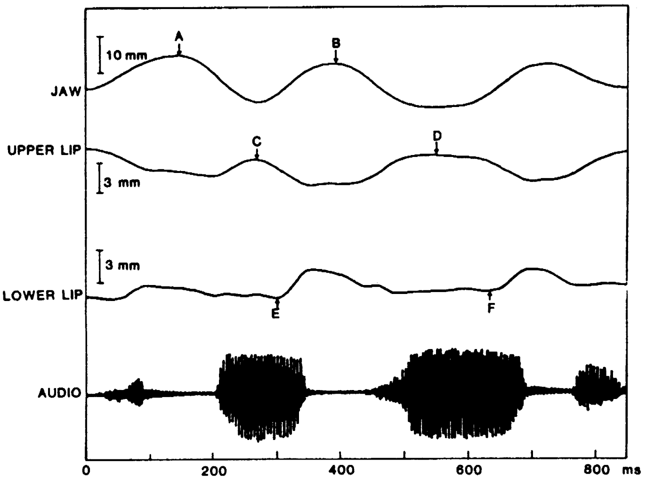

FIG. 1. Movements of the jaw, upper lip, and lower lip corrected for jaw movement, and the acoustic signal for one token of /ba#'pab/. Articulator position (the y axis) is shown as a function of time. Onsets of jaw and lip movements (empirically determined from zero crossings in the velocity records) are indicated (see text for details).

onset of jaw lowering associated with vowel articulation (C–B and E–B).

One kinematic measure that is intuitively commensurate with the temporally stable EMG measure is the latency of onset of lower lip raising for producing the medial labial consonant (A–E) relative to the period from the onset of jaw lowering for the first vowel to the onset of jaw lowering for the second vowel (A–B). These measures are illustrated quantitatively in Fig. 2 which shows one subject's (JE) productions of the utterances /ba#bab/, /ba#pab/, /ba#vab/, and /ba#wab/. Each point on a graph is one token of an utterance type, and the four stress-rate conditions are plotted on a single graph.

A Pearson product-moment correlation was calculated for each distribution. Obviously, the calculated correlations are very high: 0.93, 0.92, 0.94, and 0.92. However, the changes that occur are not ratiomorphic; the calculated regression lines (not shown in the figures) do not intercept the y axis at the origin. Utterances with /æ/ as the first vowel showed essentially identical results, with correlations for this speaker of $r = 0.9$ and above. Again, the changes were systematic but not ratiomorphic.

Figure 3 again shows the timing of medial consonant articulation relative to the timing of the flanking vowels for the same subject as in Fig. 2. In this case, however, we have defined the onset of consonant articulation as the onset of the lowering gesture in the upper lip (interval A–C in Fig. 1) Utterances with medial /v/ are not included because no systematic upper lip movement was noted. Again, the changes in duration of the two measured intervals are highly correlated for utterances with /a/ as the first vowel (shown in Fig. 3) as well as in utterances whose first vowel was /æ/. It can be seen from the figures, however, that correlations within each stress-rate condition tend to be lower than the correlations across conditions, particularly in those conditions whose range is small along one axis.

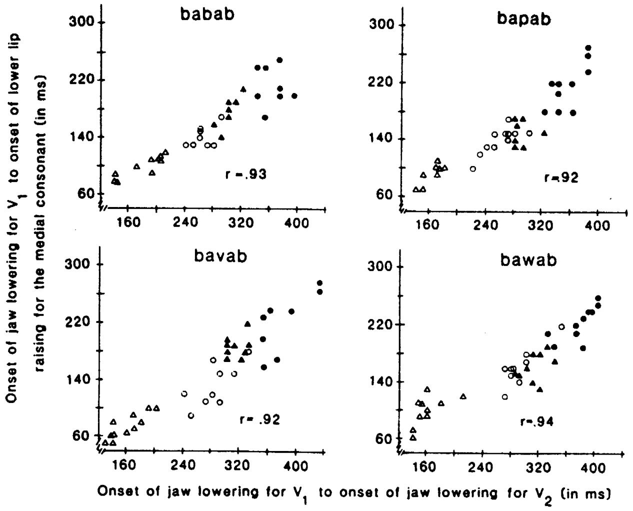

FIG. 2. Timing of lower lip raising associated with medial consonant articulation as a function of the period between successive vowel-related gestures for one subject's (JE) productions of ba–consonant–ab utterances. Filled circles are from tokens spoken at a conversational rate with primary stress on the first syllable; open circles are tokens spoken at a conversational rate with stress on the second syllable; filled triangles are spoken faster with primary stress on the first syllable; open triangles are fast, stress on the second syllable.

Although Figs. 2 and 3 illustrate the data from only a single subject (JE),[2] the three other subjects showed essentially the same pattern. The left half of Table I shows the values for all four subjects obtained by correlating the period between the onsets of successive vowel articulations with the latency of onset of consonant articulation. Correlations obtained when consonant articulation is defined by the raising gesture of the lower lip are shown separately from correlations in which consonant articulation is defined by the low-

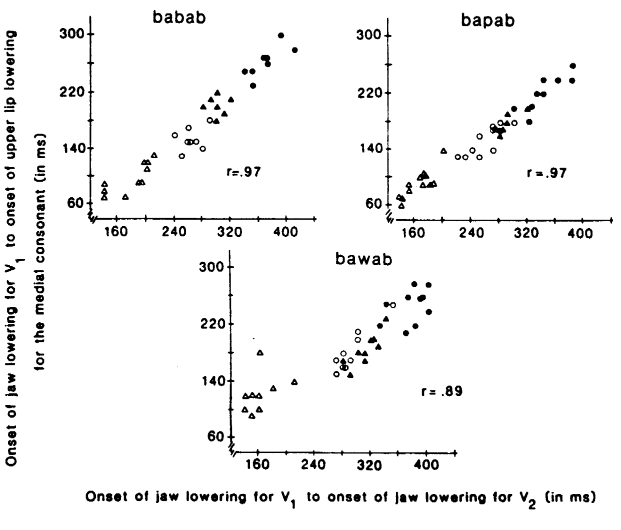

FIG. 3. Timing of upper lip lowering associated with medial consonant articulation as a function of the period between successive vowel-associated gestures for one subject's (JE) productions of ba–consonant–ab utterances. Symbols as in Fig. 1.

TABLE I. Pearson product-moment correlations for all four subjects, describing relationships between various periods and latencies, as indicated.

	Vowel cycle				Consonant cycle			
	aba[a]	æba[a]	aba[b]	æba[b]	aba[c]	æba[c]	aba[d]	æba[d]
CH	0.93	0.91	0.98	0.97	0.41	0.02	0.49	0.13
NM	0.84	0.89	0.92	0.94	0.64	0.46	0.28	0.62
JE	0.93	0.90	0.97	0.90	0.63	0.55	0.31	0.22
BT	0.95	0.95	0.96	0.93	0.52	0.61	0.47	0.41
	apa[a]	æpa[a]	apa[b]	æpa[b]	apa[c]	æpa[c]	apa[d]	æpa[d]
CH	0.96	0.87	0.95	0.97	− 0.02	0.35	0.22	0.26
NM	0.93	0.94	0.91	0.92	0.49	0.22	0.61	− 0.02
JE	0.92	0.94	0.97	0.89	0.39	0.29	0.36	0.64
BT	0.97	0.96	0.96	0.93	0.71	0.31	0.46	0.21
	awa[a]	æwa[a]	awa[b]	æwa[b]	awa[c]	æwa[c]	awa[d]	æwa[d]
CH	0.91	0.95	0.91	0.90	0.71	0.31	0.61	0.08
NM	0.93	0.91	0.95	0.94	0.51	0.51	0.43	0.69
JE	0.94	0.92	0.89	0.84	0.24	0.72	0.37	0.05
BT	0.97	0.93	0.91	0.94	0.33	0.38	0.51	0.24
	ava[a]	æva[a]			ava[c]	æva[c]		
CH	0.94	0.93			0.69	0.21		
NM	0.86	0.89			0.51	0.63		
JE	0.92	0.95			0.46	0.52		
BT	0.96	0.90			0.56	0.33		

[a] Latency = V_1 (jaw) to medial C (lower lip); period = V_1 to V_2 (jaw).
[b] Latency = V_1 (jaw) to medial C (upper lip); period = V_1 to V_2 (*jaw*).
[c] Latency = C_2 (lower lip) to V_2 (jaw); period = C_2 to C_3 (lower lip).
[d] Latency = C_2 (upper lip) to V_2 (jaw); period = C_2 to C_3 (upper lip).

ering gesture of the upper lip. The lowest correlation obtained for any utterance was 0.84 (accounting for 71% of the variance). Let us underscore that these high correlations occur even though other aspects of the movements, such as their displacement, velocity, and duration, change substantially (Tuller *et al.*, 1982). The right half of Table I shows the correlations obtained between the period duration of the within syllable gestural cycle for consonants and the latency of production of the intervening vowel. In Fig. 1, these measures corespond to the intervals C–D and C–B for the upper lip and jaw, and E–F and E–B for the lower lip and jaw. The resulting correlations span a wide range of values (from − 0.02 to 0.72), clustering in the 0.2 to 0.65 range.

One question that arose from this analysis was whether the high correlations obtained between the duration of the vocalic period and the timing of the medial consonant could be a statistical artifact. Most of the durational stretching and shrinking across rate and stress changes occurs in the vowel-related articulator movements. This alone might account for the fact that the correlations between two intervals that both contain the vowel-related movements are higher than the correlations between intervals, only one of which contains vocalic movements (cf. Barry, 1983; Tuller *et al.*, 1983). In the former situation, the range of both variables is quite large, whereas in the latter, the range of one variable is relatively small.

To explore this possibility, we determined the correlation coefficients that would occur if consonant gesture latencies occurred at random with respect to gestural periods for successive vowels. To this end, we subtracted the latency (A–C or A–E in Fig. 1) from the period (A–B) for all individual tokens of an utterance type. The resulting values (C–B or E–B) were then randomly paired with the latency values. Adding the members of a pair results in a new period duration and period/latency for each token. These new pairs of values have the same property of our original measure, that variability in vowel duration contributes both to period and to latency. We then calculated the correlations between the new period and latency pairs. Using Fisher's *r*-to-*z* transform and *t* tests, we compared the new correlations with the original correlations obtained from the period and latency pairs as measured from the data. Figure 4 shows the difference between the *z* score for the actual correlation and the *z* score for the correlation obtained with random pairing of periods and latencies for the 56 comparisons.[3] In all cases, the correlation obtained from the randomly paired periods and latencies was significantly lower (at least at the 0.05 level) than the correlation of periods and latencies that actually occurred.

A related question is whether our results are due to an overall tempo effect (MacNeilage, in press) and thus do not specifically implicate the gestural cycle for vowels as an important variable in speech motor control. We tested this possibility by examining the interval from the onset of jaw low-

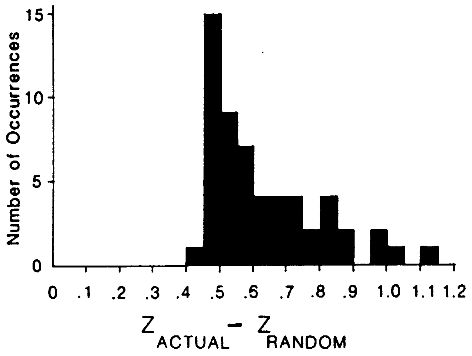

FIG. 4. Differences between z scores for the "actual" correlations and z scores for the correlations obtained by random pairing of periods and latencies.

ering for the second vowel to the onset of upper lip lowering for the final consonant (interval B–D in Fig. 1) relative to the interval between jaw lowering for successive vowels (interval A–B). Notice that in this analysis, the defined cycle does not include the relevant consonant-related articulation. Nevertheless, these variables should still be strongly correlated if an overall tempo effect is involved. The resulting linear correlations, however, were extremely weak, ranging from -0.6 to 0.2 across the four speakers, and clustering (83%) in the -0.1 to -0.4 range. The correlations were generally negative because stressed and unstressed syllables alternate in our data set. Thus long vowel intervals (utterances with the first syllable stressed) are followed by short lip closing gestures (unstressed, syllable-initial consonants). Taken together with the results of randomly pairing periods and latencies, these results indicate that neither variations in vowel duration nor overall speech tempo can account for the systematic relationship between the timing of intervocalic consonant articulation and the period between its flanking vowels.

Another prediction of the stable relative timing of consonant and vowel articulations is that the small changes in duration of consonantal gestures should be correlated with the relatively larger changes in duration of vowel-related gestures. To explore this further, we determined the duration of "vowel-specific movement," defined as the interval from the onset of jaw lowering for the first vowel to the onset of lip movement for the medial consonant (A–C and A–E in Fig. 1), and the duration of "consonant-specific movement," defined as the interval from the onset of lip movement for the medial consonant to the onset of jaw lowering for the second vowel (C–B and E–B in Fig. 1). We then correlated these measures across stress and rate conditions for each utterance type and, using t tests, determined whether the resulting correlations were significantly greater than zero. In all 56 cases, the durations of consonant and vowel movements (as defined above) were positively correlated (rs ranged from 0.52 to 0.87; ts ranged from 3.55 to 10.29; ps < 0.01).

Although the above analyses examine the commonalities in organization across disyllables with different intervocalic consonants, we expected to observe consonant-related differences predictable from the acoustic-phonetic literature. For example, the period of voicing for a vowel prior to supraglottal occlusion for a voiced stop consonant such as /b/ tends to be longer than voicing for the same vowel before closure for the voiceless stop consonant /p/ (e.g., House, 1961; House and Fairbanks, 1953; Peterson and Lehiste, 1960). For the four speakers in this study, the acoustic duration of the voiced portion of each vowel was measured and ANOVAs computed to test the effect of consonant (/p/ vs /b/), stress, and speaking rate on vowel-related voicing duration. The acoustic measures were from the first full pitch period after initial consonant release to the first acoustic indication of closure for the medial stop consonant. ANOVA revealed that all four speakers produced significantly longer voicing for vowels before /b/ than before /p/ [Fs (1,59) ranged from 39.02 to 78.61, ps < 0.001], although for one speaker (CH), this effect was rather small (22-ms mean difference).

In light of these results, one might predict that the latency of consonant articulation relative to the preceding vowel (as indexed, for example, by the onset of lower lip raising) occurs later in /b/ than in /p/. Examination of Figs. 2 and 3 reveals, perhaps surprisingly, that the range of latencies for the onset of lower lip movement is fairly stable across intervocalic consonants. Although the mean latency values within each stress-rate condition tend to be later for /b/ than for /p/, this small difference does not account for the total measured acoustic difference. The onset of upward jaw movement, however, does migrate with context, being 20 to 40 ms earlier in vowel-/p/ than vowel-/b/ utterances.

Another hypothesis is that the period-latency functions might reflect the manner of consonant production. In fact, the calculated regression lines (not shown in the figures) for /v/ and /w/ did tend to have flatter slopes, reflecting earlier articulatory onsets, than the regression lines for /p/ and /b/. However, the ordering of slopes is not identical across subjects. We also evaluated consonant effects on the duration and peak instantaneous velocity of upward movements of the composite lower lip–jaw system. A significant consonant effect was found for both the duration and velocity of lower lip movements for all speakers [Fs(3,240) ranged from 6.86 to 351.8; ps < 0.001]. Scheffé *post hoc* comparisons showed that for three of the four speakers, the duration of the upward lower lip gesture was longer for vowel-/v/ and vowel-/w/ transitions than for vowel-/p/ and vowel-/b/ transitions (ps < 0.05). In addition, the peak instantaneous velocity of the composite lower lip–jaw system for all speakers was higher for vowel-/p/, vowel-/b/, and vowel-/v/ gestures than for vowel -/w/ gestures (ps < 0.05). Although the difference in peak instantaneous velocity for vowel -/p/ and vowel-/b/ gestures was just short of significance at the 0.05 level, all four speakers showed a tendency for vowel-/p/ gestures to have higher velocities than vowel-/b/ gestures (see also Kuehn, 1973).

III. DISCUSSION

To summarize, in this experiment the timing of movement onset for gestures appropriate to consonants was tightly linked to the timing of movement onsets for vowel-related gestures.[4] This stability of relative articulatory timing was independent of often large variations in duration, displacement, and velocity of individual articulators. Moreover, performance of the one speaker who was aware of the experiment's aim was in all ways similar to the performance of the three naive speakers. These kinematic results are compatible with the earlier EMG findings (Tuller *et al.*, 1982a) and together, we feel, provide evidence for relational invariants in articulation. Nevertheless, a few caveats are in order.

First, the measure of movement onset is not meant to be isomorphic with the measure of EMG onset in the earlier experiment. The relationshp between parameters of muscle activity and the resulting kinematics has yet to be elucidated in systems far less complex than the vocal apparatus (e.g., Bigland and Lippold, 1954; Cooke, 1980; Wallace and Wright, 1982).

Second, we have chosen to examine the relative timing of onsets of movement trajectories but do not mean to imply that movement onset enjoys privileged status as a directly controlled variable. A good deal of debate in the motor control literature surrounds the question of what variables the nervous system regulates (cf. Stein, 1982 and commentaries). Nevertheless, we feel confident that the timing of onset of articulator movement is highly correlated with whatever kinematic or dynamic aspects of movement are apposite to the nervous system.

A third reason for caution when generalizing these results is that we did not examine the behavior of the most important articulator, namely, the tongue. Although we expressly restricted our corpus to consonants having minimal tongue involvement (so far as we know), any adequate account of speech motor control must include a description of lingual articulation. These data are buttressed, however, by results of a recent, but more limited, parallel experiment that monitored tongue movements of one speaker (Harris *et al.*, in press; see also Ostry *et al.*, 1983; Parush *et al.*, 1983).

Fourth, we have only examined phonetically very simple material—the behavior of single consonants between two fairly unreduced vowels, with the intervocalic consonant in syllable-initial position. The description is incomplete in that it does not address the syllable affiliation of the consonant, the number of intervocalic consonants, the role of extremely reduced vowels or schwa, or cases where extensive anticipatory coarticulation is possible.

Despite these limitations, the view that the period between successive vowel gestures is a significant articulatory event and that consonant gestures are timed relative to such periods is supported by the literature on compensatory shortening and coarticulation. For example, it is well known that intervocalic consonants shorten the measured acoustic duration of the surrounding vowels (e.g., Lindblom and Rapp, 1973). This may mean that all aspects of the articulation of vowels are shortened when consonants follow or precede them. Alternatively, it may mean that the consonants and vowels are produced in concert, with the trailing edges of the vowels progressively "overlaid," as it were, by the consonants (Fowler, 1981). In this view, vowel articulations occur continuously throughout the production of consonants and consonant clusters. An articulatory organization of this sort was first proposed by Öhman (1966), to explain the changes in formant transitions of intervocalic consonants as a function of the flanking vowels. Fowler (1977) has elaborated this view by suggesting that the vocalic cycle plays an important organizing role in speech production and perception. More recent articulatory evidence that the influence of both preceding and following vowels is apparent throughout the intervocalic consonant might also be interpreted as indicating a significant vowel-to-vowel articulatory period (Sussman *et al.*, 1973; Barry and Kuenzel, 1975; Butcher and Weiher, 1976; Gay, 1977; Harris and Bell-Berti, 1984).

In conclusion, we believe that these data indicate an organizational scheme that speech production shares with many other forms of coordinated activity (see Boylls, 1975; Fowler *et al.*, 1980; Grillner, 1982; Kelso *et al.*, 1983; Kelso and Tuller, 1984; Turvey *et al.*, 1978, for reviews), characterized by the temporal stability of movements relative to a cycle and the independence of the relative timing of movement from modulations in displacement or force. In fact, this appears to be one of the main signatures of muscle-joint ensembles when they cooperate to accomplish particular tasks.

ACKNOWLEDGMENTS

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[1] This result has since been replicated for speakers of French, using a somewhat more extended phonetic inventory and muscle set (Gentil *et al.*, 1984).

[2] Data from a different speaker (CH) are plotted in Tuller *et al.* (1982b), and a subset of data from a third speaker (BT) is plotted in Tuller *et al.* (1983).

[3] Four subjects × six utterance types × two measures of consonant articulation, plus four subjects × two utterance types with one measure of consonant articulation.

[4] Recent work by Lubker (1983) suggests that for speakers of Swedish, the timing of vowel and consonant movements is constrained as for the English speakers.

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