

Interarticulator Phasing as an Index of Temporal Regularity in Speech

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In this article we examine the effects of suprasegmental variations in speaking rate and syllable stress on temporal organization at the articulator level. Specifically, we wished to determine what articulatory constancies (if any) underlie the preservation of phonetic identity when syllable stress and speaking rate are varied. Electromyographic activity was sampled from five muscles known to be associated with lip, tongue, and jaw movements during selected bisyllabic utterances. Large variations were observed in magnitude and duration of activity in individual muscles. However, analysis of the phase relations among muscles suggested that the timing of consonant-related muscle activity remains fixed relative to activity for the flanking vowels. We argue that this style of coordination, in which the relative timing of activity among muscles is preserved across metrical changes, is not only characteristic of many nonspeech motor activities but may also rationalize certain findings in speech perception.

Two basic types of explanation have been proposed for the changes in acoustic segment duration that occur with variations in speaking rate and syllable stress. One view is that the segmental articulations within quickly spoken or destressed syllables are "overlapped" in time, resulting in shorter acoustic realizations than the same syllables spoken more slowly or with greater syllabic stress (e.g., Kozhevnikov & Chistovich, 1965; Lindblom, 1963; Shaffer, 1976). An alternative view is that the relative timing of segmental articulations remains constant over changes in stress and speaking rate, but the

individual segments themselves change in absolute duration or extent of articulatory movement (e.g., Kent & Moll, 1975; Kent & Netsell, 1971; Löfqvist & Yoshioka, in press). In earlier papers (Kelso, Tuller, & Harris, in press; Tuller, Harris, & Kelso, Note 1), we provided evidence for the latter hypothesis. Compared with the large variations that were observed in the magnitude and duration of electromyographic (EMG) activity in individual muscles, the temporal relation between consonant- and vowel-related activity in a given consonant-vowel (CV) or vowel-consonant (VC) pair remained stable over suprasegmental change. However, no broader conclusions could be drawn concerning the preservation of temporal aspects of articulation because the phonetic structure of the utterances did not allow investigation of relative timing over more than two phonetic segments. It may be that individual articulatory events are temporally constrained relative to some longer period of articulation than examined in previous experiments. The longer period of activity may vary as a function of changes in speaking rate and syllable stress and may possibly be a factor in the perceptual specification of these changes.

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The present work explored the possibility that relative timing of articulatory events is preserved over suprasegmental changes. There are some a priori grounds from two disparate sources that might motivate a relative timing hypothesis. The first comes from the speech perception literature. For example, long and short vowel pairs appear to be distinguished perceptually by vowel duration in relation to perceived rate of speech and not by absolute vowel duration (Rakerd, Verbrugge, & Shankweiler, 1980). The second comes from work on other motor activities that suggests that relative timing (phasing) among muscles and kinematic events is preserved over changes in force or rate (see Kelso, Tuller, & Harris, in press, for review). For example, MacMillan (1975) observed that in a freely locomoting lobster, activity in the individual limb muscles occurs at a constant phase position relative to the step cycle, even when a load was attached to the limb.

As yet, however, no experiment in the speech production literature has been sufficiently expansive to evaluate possible temporal regularities among articulatory events associated with the specification of phonetic segments. This step would seem important because some motoric invariant, perhaps specified as relations among articulators (and the consequent acoustic signals), may allow the perceiver to identify the same phonetic segment in the face of suprasegmental transformations. With this in mind, we obtained electromyographic recordings from lip, tongue, and jaw muscles while subjects produced utterances whose phonetic structure allowed intersegmental timing relations to be examined over more than two phonetic segments. Our results suggest that the preservation of relative timing of muscle activity over suprasegmental change is characteristic of the temporal organization of speech.

Method

Subjects

The subjects were three adult females: two were native speakers of American English, and one was an English-speaking native of New Zealand. Two of the three subjects were naive to the purpose of the experiment. It may be remarked at the outset that neither dialect nor experimental sophistication had any conspicuous effects.

Materials and Procedure

The speech sample consisted of four two-syllable non-sense utterances: /pipip, papap, pipap, papip/. The medial /p/ was presented and spoken as the first element of the second syllable (e.g., "pee-peep"). Each utterance was spoken in two stress patterns, with primary stress on either the first or second syllable. The subjects read quasi-random lists of these utterances at two self-selected speaking rates, "slow" (conversational) and "fast." Each utterance was embedded in the carrier sentence "It's a _____ again," thus minimizing the effects of initial and final lengthening and prosodic variations. Twelve repetitions were produced of each utterance.

Data Recording

Electromyographic activity was recorded from muscles whose activities could be associated unequivocally with either the consonant or the vowels of the utterance set. For example, orbicularis oris is known to participate in bilabial closure for production of /p/ (Fromkin, 1966; Harris, Lysaught, & Schvey, 1965), but is not active for production of /a/ or /i/. Orbicularis oris activity was recorded using paint-on surface electrodes (Allen, Lubker, & Harrison, Note 2) spaced at about .5 cm from the vermilion border of the lips.

Electromyographic activity was also recorded from the anterior portion of genioglossus, anterior belly of the digastric, medial (internal) pterygoid, and the inferior head of lateral (external) pterygoid, using bipolar hooked-wire electrodes (Hirose, 1971). Genioglossus activity is associated with tongue bunching and anterior movement, and is active in production of the vowel /i/ (e.g., Raphael & Bell-Berti, 1975; Smith, Note 3). The anterior belly of digastric and the inferior head of lateral pterygoid are active in association with jaw lowering during speech (e.g., for the production of /a/), whereas the medial pterygoid acts to raise the jaw during speech (e.g., the transition from the low vowel /a/ to /p/ closure). The functional properties of these muscles have been described in detail elsewhere (Tuller, Harris, & Gross, 1981).

During insertion of the hooked-wire electrodes, the subject was in a slightly reclined position and breathed nitrous oxide to reduce discomfort. Detailed descriptions of electrode placement and insertion techniques may be found in Ahlgren (1966) and Gross and Lipke (1979). Verification of electrode placements used maneuvers for which the role of each muscle is well established (Ahlgren, 1966; Carlso, 1952, 1956; Harris et al., 1965; Møller, 1974; Moyers, 1950; Smith, Note 3).

The EMG potentials from the various muscles were recorded on multichannel FM tape. On subsequent analysis the potentials were rectified and computer sampled, then software integrated with a time constant of 35 msec (a typical smoothing window for data of this type). Repetitions of an utterance were averaged using the Haskins Laboratories EMG system described by Kewley-Port (1974). Acoustic recordings were made simultaneously with the EMG recordings, and both were analyzed on subsequent playback.

Table 1
Adequate Electrode Placements and EMG Recordings for Each Subject

Muscle	Subject		
	PS	BT	JT
Orbicularis oris (bilabial closure for /p/)	X	X	X
Genioglossus (tongue fronting for /i/)	X	X	X
Lateral pterygoid-inferior head (jaw lowering)	X	X	X
Anterior belly of digastric (jaw lowering)	X	X	
Medial pterygoid (jaw raising)	X	X	

Note. EMG = electromyographic.

The EMG tokens were realigned and reaveraged three times, at the onset of the acoustic release burst for the first, second, and third stop consonants, respectively. In this way, average muscle activity could be examined at specific points of interest without the time-smearing effects of averaging tokens that were aligned at a temporally distant point.

Onsets and offsets of activity were determined from data averaged around the acoustic lineup point closest to the activity of interest. The averaging program provided a numerical listing of the mean amplitude of each EMG signal in microvolts during successive 5-msec intervals. Baseline and peak values for each muscle were determined from this numerical listing; the time of onset (and offset) was defined as the time when the relevant muscle activity increased (or decreased) to 10% of its range of activity. Typically, 10% of the range was just slightly higher than the background level of activity in each muscle. Some of the electrodes were displaced during the course of the experiment or recorded EMG activity from a neighboring muscle as well as the muscle of interest; data from these electrodes were not used in the analyses that follow. Table 1 shows for each subject the electrode placements that had stable, uncontaminated EMG activity.

The acoustic recordings were measured for their durational characteristics, using an interactive computer program that displays the acoustic waveform. Measures were made of the interval from the first acoustic evidence of closure for the initial /p/ in the /pV₁pV₂p/ utterances (defined here as the point when the high frequency components of the periodic wave disappear) to the second acoustic evidence of closure (for the medial stop consonant). For ease of communication, this interval will be referred to below as the *acoustic duration of the first syllable*. The measured interval from the second acoustic evidence of closure (for the medial /p/) to the third (for the final /p/) will be referred to as the *acoustic duration of the second syllable*. These measures were averaged for each subject.

Results and Discussion

Acoustic Analysis

The acoustic durations of syllables were examined in a four-way within-subjects analysis of variance, performed on the following variables: syllable (first vs. second), speaking rate (fast vs. slow), syllable stress (stressed vs. unstressed), and vowel (/a/ vs. /i/). Not surprisingly, syllables spoken slowly were significantly longer than the same syllables spoken quickly (283 vs. 200 msec), $F(1, 2) = 23.7, p < .05$. Syllables spoken with primary stress were significantly longer than syllables without primary stress (267 vs. 216 msec), $F(1, 2) = 138.03, p < .01$. Vowel identity also affected syllable duration: Syllables containing /a/ were significantly longer than syllables containing /i/ (258 vs. 226 msec), $F(1, 2) = 46.41, p < .05$ (see Peterson & Lehiste, 1960). Mean acoustic duration of the first syllable was not different from mean acoustic duration of the second syllable (242 vs. 241 msec), $F(1, 2) = 0.13, p > .1$.

The effects of changes in speaking rate and stress on the acoustic durations of syllables are by now well established in the speech production literature. Unstressed syllables and syllables spoken quickly are generally found to be shorter in duration than stressed syllables and syllables spoken slowly (e.g., Fry, 1955, 1958; Kozhevnikov & Chistovich, 1965; Lehiste, 1970; Lindblom, 1963; Tiffany, 1959; Gaitenby, Note 4). Measures of acoustic syllable durations in this experiment support these general findings, suggesting that subjects consistently changed speech rate and stress when instructed to do so.

EMG Analysis: Variations in Individual Muscle Actions

Additional sources of information that indicate whether subjects followed the instructions to change speaking rate and stress are the systematic variations in duration and peak amplitude of activity in individual muscles. The basic results are reported in detail elsewhere (Tuller, 1980; Tuller, Harris, & Kelso, in press). With a shift from stressed

to unstressed syllable production, those muscles directly related to vowel production decreased in both duration and peak amplitude of EMG activity. The effects of a change in speaking rate were less consistent across subjects. These general results agree with other investigations of stress and rate effects on EMG activity (e.g., Gay & Ushijima, 1975; Gay, Ushijima, Hirose, & Cooper, 1974; Harris, 1971, 1973; Sussman & MacNeilage, 1978; Harris, Gay, Sholes, & Lieberman, Note 5), and provide further evidence that subjects changed their rate and stress of speech as instructed.

EMG Analysis: Intersegmental Timing

The main thrust of the present study was to examine intersegmental timing among articulatory muscles across metrical variations in rate and stress. However, it is not clear how best to define temporal events over stretches of speech that go beyond single syllables. In keeping with current investigations of nonspeech motor skills, we chose to define the timing of articulatory activity in terms of the phase relations among muscle actions. This analysis requires demarcation of some "period" of articulatory activity and the latency of occurrence of activity for an articulatory event within the defined period (cf. von Holst, 1973; Stein, 1971, 1976, among others). To this end, several periods of articulatory activity were demarcated, defined as the time between two successive occurrences of the same type of EMG event in two muscles related to production of one segment type. The three EMG events were onset, peak amplitude, and offset of muscle activity; the two segment types were consonants and vowels. Within each defined period, the latency of the same sort of EMG event was determined for a muscle related only to the other segment type. Consider, for example, the first CVC of the utterance /pipap/. A period can be defined as the time between the onset of orbicularis oris activity for the initial /p/ to the onset of medial pterygoid activity for the medial /p/; the latency of an event within this period can be defined as the time from the onset of activity in orbicularis oris for the initial /p/ to the onset

of activity in genioglossus for production of the vowel /i/.¹

Nine "periods" and corresponding events (or "latencies") within each period were defined in this way and are indicated schematically in Figures 1, 2, and 3. Within each utterance type, pairs of periods and latencies were obtained for each subject, and for each possible combination of muscles. For the example used above, periods and latencies were determined for the utterance /pipap/, spoken under the four different speaking conditions (i.e., slow rate with the first syllable stressed, slow rate with the second syllable stressed, fast rate with the first syllable stressed, and fast rate with the second syllable stressed). This resulted in a set of four coordinate pairs for which a Pearson's product-moment correlation was calculated. High linear correlations would signify that the measured latency and period maintained their relative timing over variations in speaking rate and syllable stress.

Figures 1, 2, and 3 show the distributions of correlations for the different measures. Each correlation is a single entry in the frequency distributions. The same muscle set is represented in each figure, within the restrictions imposed by the defined period and latency. One measure showed a higher correlation and less variability than all other measures. Specifically, a high linear correlation (ranging from .87 to .99) was obtained between the period from the onset of muscle activity for V_1 to the onset of muscle activity for V_2 , and the latency of the onset of activity for p_2 relative to the onset of activity for V_1 (Figure 2a). All other definitions of period and latency produced wider distributions, although some correlations of .8 and above were also evident. However, in the latter cases there was nothing systematic about the high correlations; they did not reflect the same subject(s), utterance(s), or muscle combination(s). Moreover, the shape of each distribution differed significantly from the curve in Figure 2a, for correlations greater

¹ Recall that EMG onsets, offsets, and peaks were determined from data averaged around the closest acoustic lineup.

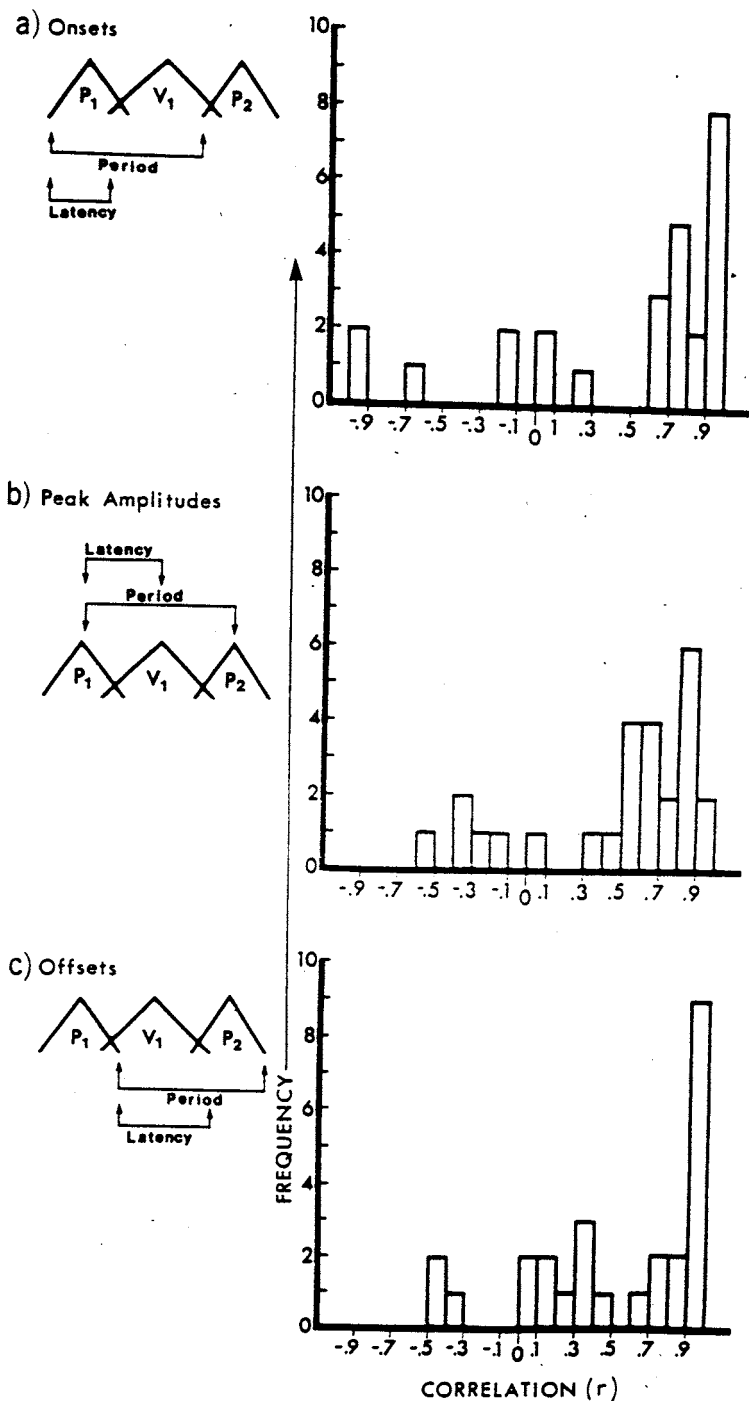


Figure 1. Distribution of correlations for periods and latencies as indicated, for measures of initial /p/-vowel-medial /p/ (p_1 , V_1 , p_2).

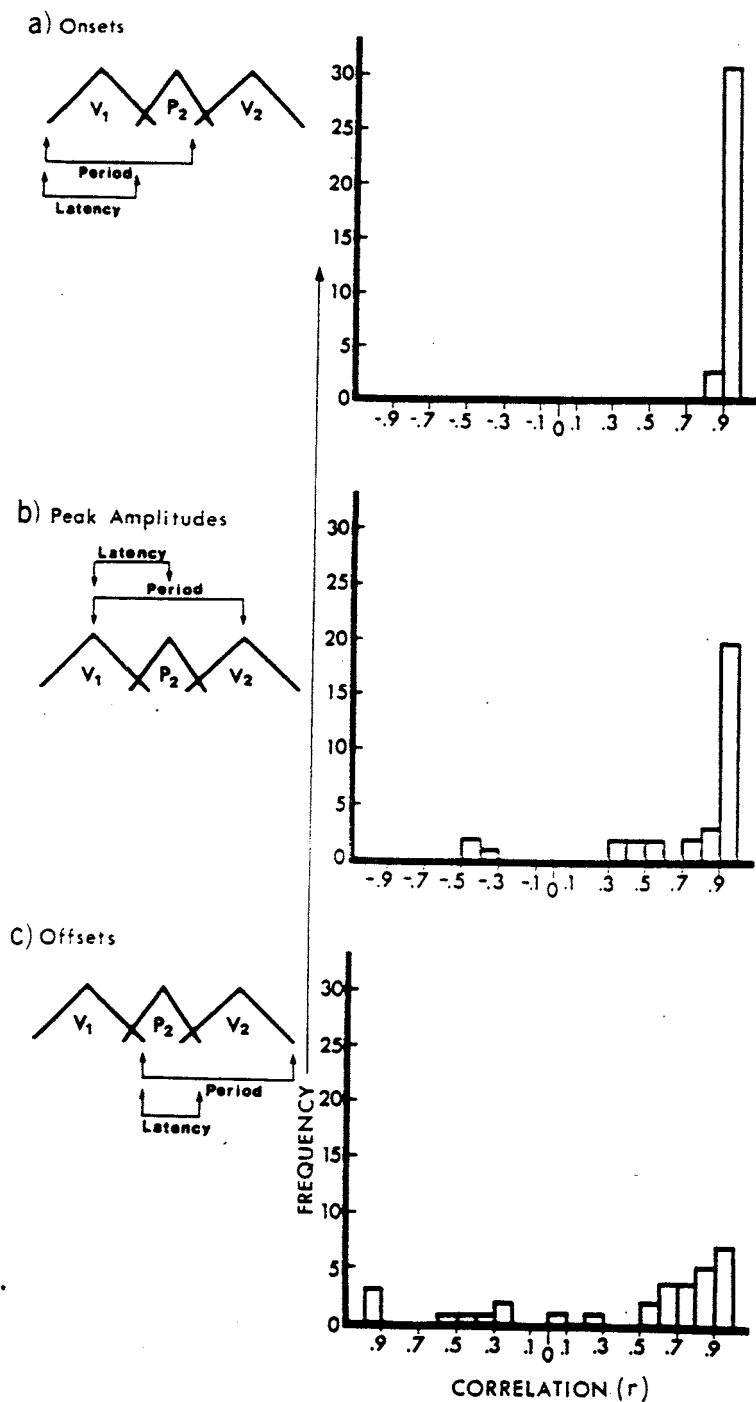


Figure 2. Distribution of correlations for periods and latencies as indicated, for measures of first vowel-medial /p/-second vowel ($V_1P_2V_2$).

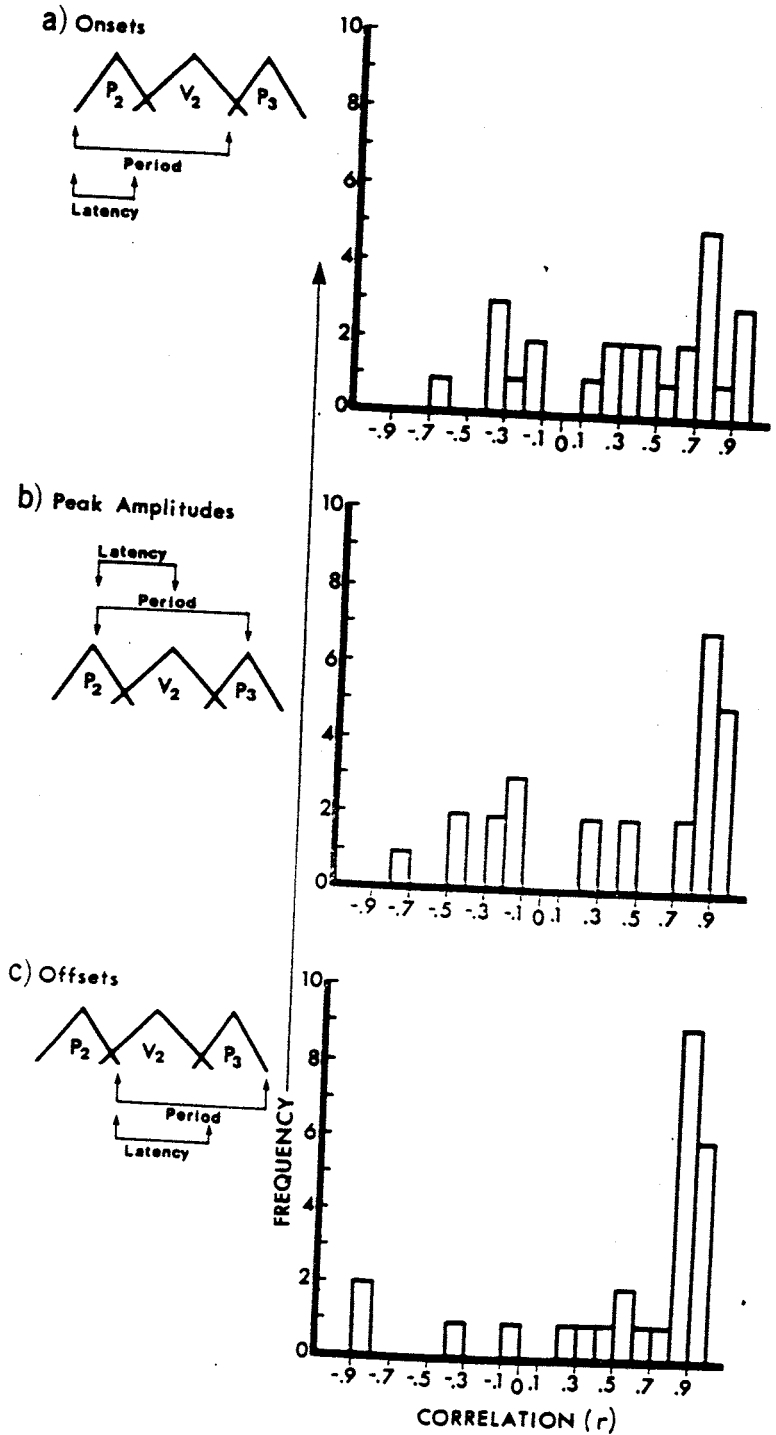


Figure 3. Distribution of correlations for periods and latencies as indicated, for measures of medial /p/-second vowel-final /p/ ($p_2V_2p_3$).

than .8 (Kolmogorov-Smirnov test, $ps < .01$, one-tailed).

A subset of the individual correlations that comprise the distribution of Figure 2a is shown in Figure 4. The period from V_1 onset to V_2 onset is plotted along the x-axis; the y-axis shows the latency of p_2 onset relative to V_1 onset. Parts A and B represent two different muscle combinations. The utterances examined are indicated at the top of

each column, and subjects are indicated for each row. Also shown are the individual Pearson's product-moment correlations of the four stress-rate conditions (slow with the first syllable stressed, slow with the second syllable stressed, fast with the first syllable stressed, and fast with the second syllable stressed). Examination of the plots of latency by period, and the resulting correlations, reveals that the high correlations de-

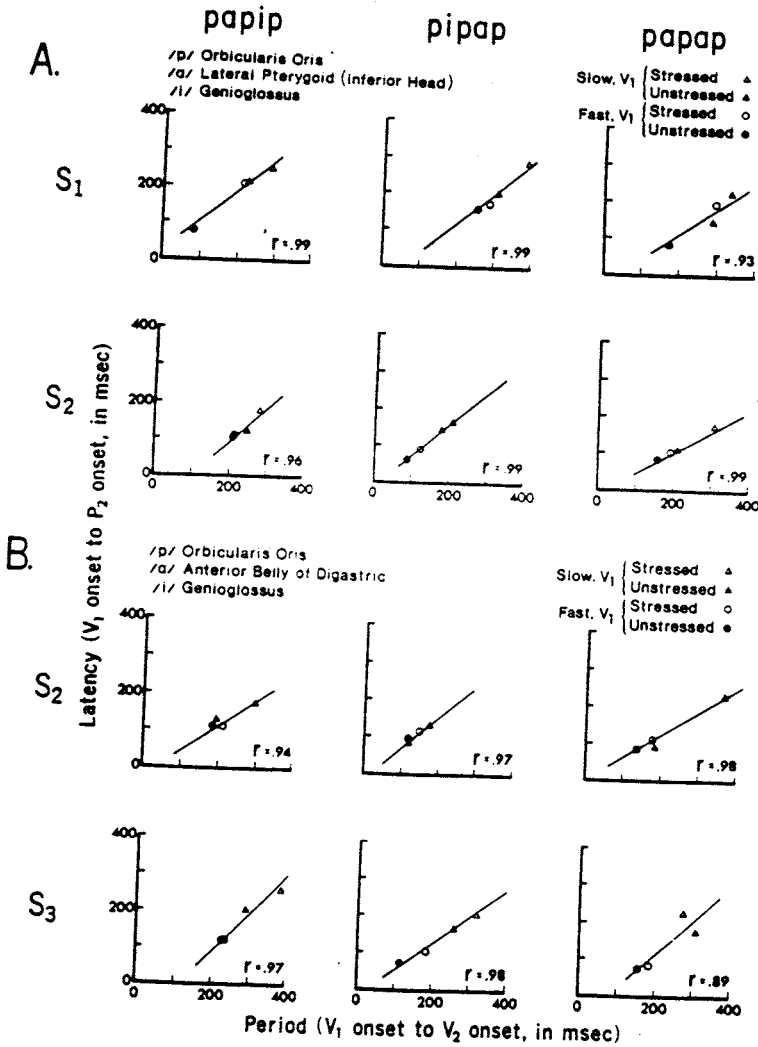


Figure 4. Plots of period by latency for individual subject's productions of three utterance types. (Each point represents the mean of 12 repetitions of the indicated utterance and is labeled as to its stress and rate characteristics. Also indicated are the muscles examined and the Pearson's product-moment correlations.)

scribe points that are tightly distributed around the regression line.

Figure 4 also reveals that although the high correlation was obtained over the various possible muscle combinations and utterances, the slope of the regression line did not remain constant regardless of the specific muscles or utterances involved. The same combination of muscles specific to production of two different utterances usually showed two different relationships of latency to period. Similarly, two different combinations of muscles often showed different relationships of latency to period for production of the same utterance type.

The preservation of relative timing in the muscle activity patterns is illustrated in Figure 5. Each muscle trace represents the average of 12 tokens of the utterance /papip/ produced by one subject. Arrows indicate the

onsets of activity for /a/ (anterior belly of digastric), /p/ (orbicularis oris), and /i/ (genioglossus). The period from the onset of activity in anterior belly of digastric (for V_1) to the onset of activity in genioglossus (for V_2) was calculated for each of the four stress-rate conditions (shown in each quadrant of the figure), as was the latency of orbicularis oris onset (for C_2) relative to the onset of activity in anterior belly of digastric (for V_1). In this case, the ratio of latency to period was unaffected by suprasegmental changes although variations in duration and peak amplitude of activity in individual muscles were evident. In all cases, the relationship maintained was linear, though not necessarily ratiomorphic.

To summarize, in a pVpVp utterance embedded in a carrier phrase, the timing of onsets of activity for successive vowel and

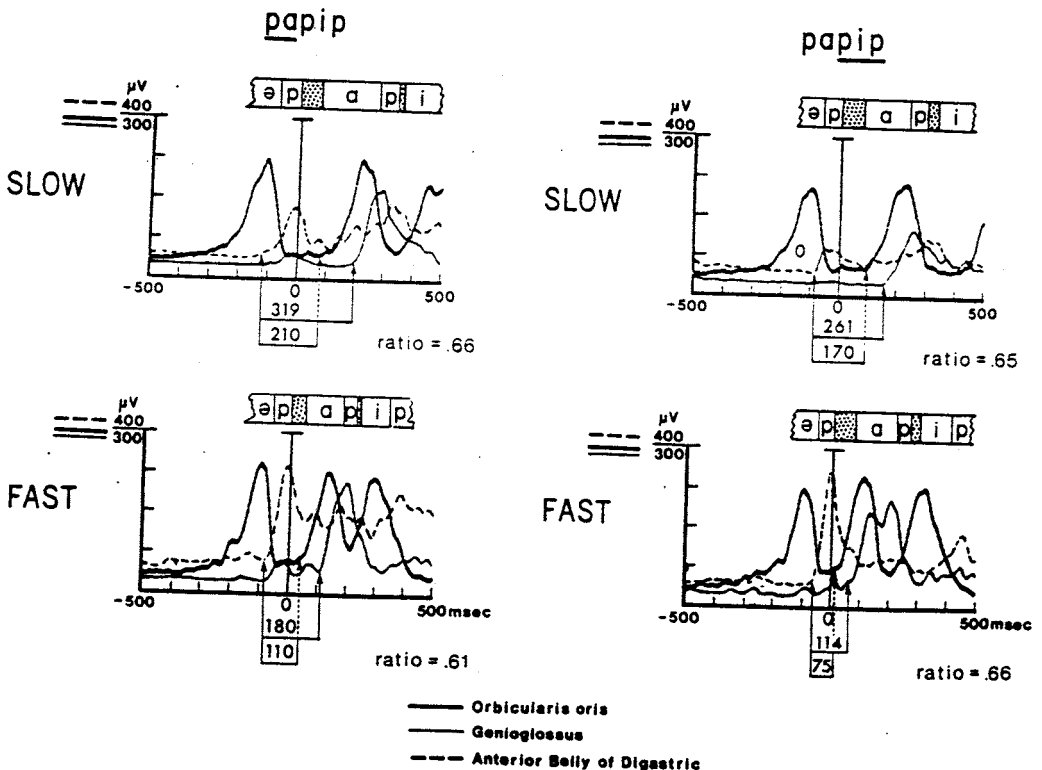


Figure 5. The utterance /papip/ spoken by one subject at two rates and with two stress patterns. (Each muscle trace represents the average of 12 repetitions of the utterance. Arrows indicate onsets of activity for anterior belly of digastric [jaw lowering for /a/; the dotted line], orbicularis oris [lip movement for /p/; the thick line], and genioglossus [tongue fronting for /i/; the thin line]. The ratio of the latency of consonant-related activity relative to the vowel-to-vowel period is indicated for each stress and rate condition.)

consonant segments appears to be temporally constrained in relation to a longer period of articulation than previously examined, namely, the period between onsets of activity for successive vowels. The onset of activity for consonant articulation was strongly linked to the timing of activity for the flanking vowels.² This preservation of relative timing of muscle activity was observed for all utterances and muscle combinations sampled, and was independent of the large variations in duration and peak amplitude of activity in the individual muscles that occur with suprasegmental changes.

General Discussion

The results of the present experiment suggest that an appropriate description of temporal aspects of articulation is relative to a longer articulatory period than previously examined in the speech production literature. For eight of the nine experimentally defined articulatory periods and latencies, linear correlations of period and latency produced a wide distribution of correlations. In contrast, for pV_1pV_2p utterances, when the articulatory period was defined as the interval from V_1 onset to V_2 onset, and the latency defined as the interval from V_1 onset to onset of the medial consonant, the correlations of latency and period produced a distribution that was not only narrow but restricted to high values. In other words, the timing of consonant articulation remained fixed relative to the surrounding vowel articulations.

Let us consider the implications of this result in some detail. Specifically, why might the interval between successive vowels appear to constitute a significant articulatory period for the utterances examined? One of the main findings in the literature on speech acoustics is that vowels are much more "elastic" than consonants when speaking rate and stress vary (e.g., Kozhevnikov & Chistovich, 1965; Lehiste, 1970; Gaitenby, Note 4). Thus, were the period of articulatory activity defined between two consonants, the bulk of the durational change would affect only the measured period, so that the relative timing of latency and period would not be maintained. However, when the period of activity is defined as the inter-

val between the onsets of two vowels (Figure 2a), the major durational changes that occur as stress and speaking rate vary will affect both latency and period, leaving open the possibility that they could change in a related manner.

If the internal timing relations of an utterance were maintained over suprasegmental modulations, changes in other variables might not disrupt the perceiver's ability to identify the utterance's phonetic composition. This hypothesis is supported by recent reports of rate effects on phonetic perception. These data suggest that the timing of some event contributing to a phonetic distinction is not constrained within absolute temporal boundaries but is perceived in relation to some longer period specifying speech rate. For example, Port (1979) examined the influence of speech rate on the perception of the voiced/voiceless distinction in medial stop consonants, cued in part by the duration of silence preceding the consonant release. The duration of silence necessary to specify that the medial stop consonant was voiceless, and not voiced, decreased as speaking rate increased. This example suggests that category distinctions that have a temporal basis may be perceived relative to total speech time, interpreted as speaking rate (cf. Miller & Grosjean, 1981; Miller & Liberman, 1979; Pickett & Decker, 1960; Summerfield, 1975, Note 6).

Just as relative timing has significance for speech perception, so it appears to be important in the control and coordination of nonspeech motor skills. For example, it is well known that the duration of the "step cycle" in the limb of a freely locomoting cat decreases as speed of locomotion increases. However, the timing of periods of extensor activity remains fixed relative to the step cycle (Engberg & Lundberg, 1969;

² It should be emphasized that this result does not necessarily entail the notion that speech production is organized as continuous vowel-to-vowel production with consonants superimposed on this basic organization (see Fowler, 1977; Öhman, 1966; Perkell, 1969). In locomotion, the timing of extensor activity may remain fixed relative to the time between successive flexions (see Engberg & Lundberg, 1969), yet the organization of locomotion is not described as continuous flexion-to-flexion with extension superimposed on this basic cycle.

MacMillan, 1975; cf. Grillner, 1975 and Shik & Orlovskii, 1976). Other activities in which the timing of component events change in a predictable (linear, but not ratio-morphic) fashion include mammalian respiration and mastication (Grillner, 1977). It may be argued that these activities and speech differ on a number of dimensions that preclude valid comparison. The first set of activities can be considered stereotypic and more likely to reveal strictly rhythmical properties. Speech is less obviously stereotypic and less likely to exhibit a highly stable space-time organization. Although these are common criticisms of parallels between speech and other activities, it is worth noting that a style of coordination—observed here—in which temporal relations are preserved over changes in individual components also holds for nonspeech activities that are not obviously rhythmic and whose fundamental pattern is not immediately apparent.

When individuals are asked to vary their handwriting speed without varying movement amplitude (Viviani & Terzuolo, 1980), the relative timing of certain movements does not change with speed. Specifically, the tangential velocity records resulting from different writing speeds reveal that overall duration changes markedly across speeds. But when the individual velocity records are normalized for differences in overall duration, the resulting pattern is highly invariant. The same timing relations are preserved over changes in magnitude of movements, over different muscle groups, and over different environmental (e.g., frictional) conditions (cf. Denier van der Gon & Thuring, 1965; Hollerbach, 1980; Wing, 1978).

Thus in handwriting, the relative timing of individual strokes remains fixed, although their duration and magnitude may vary markedly. This illustrates a general feature of coordinated activity, namely, that the timing relations among elements are independent of modulations in power or force (see Kelso et al., in press, for review). The experiment described here suggests that speech production shares a qualitatively similar style of organization, at least at the EMG level. A temporal patterning of components, in this case muscle activities, was preserved

independent of changes in the duration and absolute magnitude of activity in the individual muscles. Although the work described here was restricted to the special case of mutually independent consonant and vowel activities (in theory allowing maximal coarticulation) and examined a rather limited phonetic set, the congruence of its findings with the literature on speech perception and the commonalities shared with other motor activities suggests that the study of relational invariances may be a powerful approach toward an understanding of speech production.

Reference Notes

1. Tuller, B., Harris, K. S., & Kelso, J. A. S. *Articulatory motor events as a function of speaking rate and stress* (Status Report on Speech Research SR-65). New Haven, Conn.: Haskins Laboratories, 1981.
2. Allen, G. D., Lubker, J. F., & Harrison, E., Jr. *New paint-on electrodes for surface electromyography*. Paper presented at the 83rd meeting of the Acoustical Society of America, Buffalo, New York, April 1972.
3. Smith, T. S. *A phonetic study of the extrinsic tongue muscles* (UCLA Working Papers in Phonetics, No. 18). Los Angeles, Calif.: University of California, Los Angeles, 1971.
4. Gaitenby, J. H. *The elastic word* (Status Report on Speech Research SR-2). New Haven, Conn.: Haskins Laboratories, 1965.
5. Harris, K. S., Gay, T., Sholes, G. N., & Lieberman, P. *Some stress effects on electromyographic measures of consonant articulations* (Status Report on Speech Research SR-13/14). New Haven, Conn.: Haskins Laboratories, 1968.
6. Summerfield, A. Q. *Cues, contexts and complications in the perception of voicing contrasts*. (Speech Perception No. 4). Belfast: Queen's University, Department of Psychology, 1975.

References

- Ahlgren, J. Mechanism of mastication. A quantitative cinematographic and electromyographic study of masticatory movements in children, with special reference to occlusion of the teeth. *Acta Odontologica Scandinavica*, 1966, 24, Suppl. 44, 1-109.
- Carlsson, S. Nervous coordination and mechanical function of the mandibular elevators. *Acta Odontologica Scandinavica*, 1952, 10, Suppl. 11, 1-132.
- Carlsson, S. An electromyographic study of the activity and an anatomical analysis of the mechanism of the lateral pterygoid muscle. *Acta Anatomica*, 1956, 26, 339-351.
- Denier van der Gon, J. J., & Thuring, J. P. The guiding

- of human writing movements. *Kybernetik*, 1965, 4, 145-147.
- Engberg, I., & Lundberg, A. An electromyographic analysis of muscular activity in the hindlimb of the cat during unrestrained locomotion. *Acta Physiologica Scandinavica*, 1969, 75, 614-630.
- Fowler, C. *Timing control in speech production*. Bloomington: Indiana University Linguistics Club, 1977.
- Fromkin, V. A. Neuromuscular specifications of linguistic units. *Language and Speech*, 1966, 9, 170-199.
- Fry, D. B. Duration and intensity as physical correlates of linguistic stress. *Journal of the Acoustical Society of America*, 1955, 27, 765-768.
- Fry, D. B. Experiments in the perception of stress. *Language and Speech*, 1958, 1, 126-152.
- Gay, T., & Ushijima, T. Effect of speaking rate on stop consonant-vowel articulation. *Proceedings of the Speech Communication Seminar, Stockholm*, 1974. Uppsala: Almqvist and Wiksell, 1975.
- Gay, T., Ushijima, T., Hirose, H., & Cooper, F. S. Effect of speaking rate on labial consonant-vowel articulation. *Journal of Phonetics*, 1974, 2, 47-63.
- Grillner, S. Locomotion in vertebrates. *Physiological Reviews*, 1975, 55, 247-304.
- Grillner, S. On the neural control of movement—A comparison of different basic rhythmic behaviors. In G. S. Stent (Ed.), *Function and formation of neural systems* (Life Sciences Research Reports, Vol. 6). Berlin, West Germany: Dahlem, 1977.
- Gross, R. D., & Lipke, D. A technique for percutaneous lateral pterygoid electromyography. *Electromyography Clinical Neurophysiology*, 1979, 19, 47-55.
- Harris, K. S. Vowel stress and articulatory reorganization. In *Status Report on Speech Research SR-28*. New Haven, Conn.: Haskins Laboratories, 1971. (ERIC Document Reproduction Service No. ED 061 837)
- Harris, K. S. Stress and syllable duration change. In *Status Report on Speech Research SR-35/36*. New Haven, Conn.: Haskins Laboratories, 1973. (ERIC Document Reproduction Service No. ED 094 444)
- Harris, K. S., Lysaught, G. F., & Schvey, M. M. Some aspects of the production of oral and nasal labial stops. *Language and Speech*, 1965, 8, 135-147.
- Hirose, H. Electromyography of the articulatory muscles: Current instrumentation and techniques. In *Status Report on Speech Research SR-25/26*. New Haven, Conn.: Haskins Laboratories, 1971. (ERIC Document Reproduction Service No. ED 056 560)
- Hollerbach, J. M. *An oscillation theory of handwriting*. Cambridge, Mass.: MIT Artificial Intelligence Laboratory, 1980.
- Holst, E. von. *The behavioral physiology of animal and man: The collected papers of Erich von Holst* (Vol. 1) (R. Martin, trans.). London: Methuen, 1973.
- Kelso, J. A. S., Tuller, B., & Harris, K. S. A "dynamic pattern" perspective on the control and coordination of movement. In P. MacNeilage (Ed.), *The production of speech*. New York: Springer-Verlag, in press. (Also in *Status Report on Speech Research SR-65*. New Haven, Conn.: Haskins Laboratories, 1981.)
- Kent, R. D., & Moll, K. Articulatory timing in selected consonant sequences. *Brain and Language*, 1975, 2, 304-323.
- Kent, R. D., & Netsell, R. Effects of stress contrasts on certain articulatory parameters. *Phonetica*, 1971, 24, 23-44.
- Kewley-Port, D. An experimental evaluation of the EMG data processing system: Time constant choice for digital integration. In *Status Report on Speech Research SR-37/38*. New Haven, Conn.: Haskins Laboratories, 1974. (ERIC Document Reproduction Service No. ED 094 445)
- Kozhevnikov, V., & Chistovich, L. *Speech: Articulation and perception* (JPRS No. 30543). Washington, D.C.: Joint Publications Research Service, 1965.
- Lehiste, I. *Suprasegmentals*. Cambridge, Mass.: MIT Press, 1970.
- Lindblom, B. Spectrographic study of vowel reduction. *Journal of the Acoustical Society of America*, 1963, 35, 1773-1781.
- Löfqvist, A., & Yoshioka, H. Laryngeal activity in Icelandic obstruent production. *Nordic Journal of Linguistics*, in press. (Also in *Status Report on Speech Research SR-63/64*. New Haven, Conn.: Haskins Laboratories, 1980.)
- MacMillan, D. L. A physiological analysis of walking in the American lobster. *Philosophical Transactions of the Royal Society of London*, 1975, 270B, 1-59.
- Miller, J. L., & Grosjean, F. How the components of speaking rate influence perception of phonetic segments. *Journal of Experimental Psychology: Human Perception and Performance*, 1981, 7, 208-215.
- Miller, J. L., & Liberman, A. M. Some effects of later-occurring information on the perception of stop consonant and semivowel. *Perception & Psychophysics*, 1979, 25, 457-465.
- Møller, E. Action of the muscles of mastication. In Y. Kawamura (Ed.), *Physiology of mastication*. Basel, Switzerland: Karger, 1974.
- Moyers, R. E. An electromyographic analysis of certain muscles involved in temporomandibular movement. *American Journal of Orthodontics*, 1950, 37, 481-515.
- Öhman, S. E. G. Coarticulation in VCV utterances: Spectrographic measurements. *Journal of the Acoustical Society of America*, 1966, 39, 151-168.
- Perkell, J. S. *Physiology of speech production: Results and implications of a quantitative cineradiographic study*. Cambridge, Mass.: MIT Press, 1969.
- Peterson, G. E., & Lehiste, I. Duration of syllable nuclei in English. *Journal of the Acoustical Society of America*, 1960, 32, 693-703.
- Pickett, J. M., & Decker, L. R. Time factors in perception of a double consonant. *Language and Speech*, 1960, 3, 11-17.
- Port, R. F. The influence of tempo on stop closure duration as a cue for voicing and place. *Journal of Phonetics*, 1979, 7, 45-56.
- Rakerd, B., Verbrugge, R. V., & Shankweiler, D. P. Speaking rate, syllable stress, and vowel identity. In *Status Report on Speech Research SR-62*. New Haven, Conn.: Haskins Laboratories, 1980. (ERIC Document Reproduction Service No. ED 096 199)

- Raphael, L. J., & Bell-Berti, F. Tongue musculature and the feature of tension in English vowels. *Phonetica*, 1975, 32, 61-73.
- Shaffer, L. H. Intention and performance. *Psychological Review*, 1976, 83, 375-393.
- Shik, M. L., & Orlovskii, G. N. Neurophysiology of locomotor automatism. *Physiological Reviews*, 1976, 56, 465-501.
- Stein, P. S. G. Intersegmental coordination of swimmeret motoneuron activity in crayfish. *Journal of Neurophysiology*, 1971, 34, 310-318.
- Stein, P. S. G. Mechanisms of interlimb phase control. In R. M. Herman, S. Grillner, P. S. G. Stein, & D. Stuart (Eds.), *Neural control of locomotion*. New York: Plenum Press, 1976.
- Summerfield, A. Q. How a full account of segmental perception depends on prosody and vice versa. In A. Cohen & S. G. Nooteboom (Eds.), *Structure and process in speech perception*. New York: Springer-Verlag, 1975.
- Sussman, H. M., & MacNeilage, P. F. Motor unit correlates of stress: Preliminary observations. *Journal of the Acoustical Society of America*, 1978, 64, 338-340.
- Tiffany, W. R. Nonrandom sources of variation in vowel quality. *Journal of the Acoustical Society of America*, 1959, 58, 434-445.
- Tuller, B. *Coordination among articulators in speech*. Unpublished doctoral dissertation, University of Connecticut, 1980.
- Tuller, B., Harris, K. S., & Gross, B. An electromyographic study of the jaw muscles during speech. *Journal of Phonetics*, 1981, 9, 175-188.
- Tuller, B., Harris, K. S., & Kelso, J. A. S. Stress and rate: Differential transformations of articulation. *Journal of the Acoustical Society of America*, in press.
- Viviani, P., & Terzuolo, V. Space-time invariance in learned motor skills. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior*. Amsterdam: North-Holland, 1980.
- Wing, A. M. Response timing in handwriting. In G. E. Stelmach (Ed.), *Information processing in motor control and learning*. New York: Academic Press, 1978.

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