# Control of rate and duration of speech movements

David J. Ostry and Kevin G. Munhall
*Department of Psychology, McGill University, 1205 Dr. Penfield Avenue, Montreal, PQ H3A 1B1, Canada*

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A computerized pulsed-ultrasound system was used to monitor tongue dorsum movements during the production of consonant-vowel sequences in which speech rate, vowel, and consonant were varied. The kinematics of tongue movement were analyzed by measuring the lowering gesture of the tongue to give estimates of movement amplitude, duration, and maximum velocity. All three subjects in the study showed reliable correlations between the amplitude of the tongue dorsum movement and its maximum velocity. Further, the ratio of the maximum velocity to the extent of the gesture, a kinematic indicator of articulator stiffness, was found to vary inversely with the duration of the movement. This relationship held both within individual conditions and across all conditions in the study such that a single function was able to accommodate a large proportion of the variance due to changes in movement duration. As similar findings have been obtained both for abduction and adduction gestures of the vocal folds and for rapid voluntary limb movements, the data suggest that a wide range of changes in the duration of individual movements might all have a similar origin. The control of movement rate and duration through the specification of biomechanical characteristics of speech articulators is discussed.

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## INTRODUCTION

A central problem in the study of motor control is the identification of the variables that are controlled by the nervous system to affect changes in the position of the limbs and other articulators (see Stein, 1982, for review). As movements differ greatly in their superficial complexity, an important aspect of this problem is whether a single set of principles is sufficient to account for the control of motor activities as diverse as single joint limb movements and speech (see Abbs, 1982; Kelso *et al.*, 1983; Ostry *et al.*, 1983; Tuller *et al.*, 1982). We have examined this problem in the present study by comparing the kinematic characteristics of tongue movements in speech with the known kinematic characteristics of other speech articulators and the limbs. The investigation involved the examination of changes in speech movement duration under conditions of rate, vowel, and consonant manipulation; movement duration was examined in this study as there is uncertainty as to whether the kinematic and physiological characteristics of durational change are comparable in speech and limb movements. Should similarities be observed in the kinematics of durational change in speech and limb movements it would suggest that both kinds of movement are controlled by the nervous system in similar ways. On the other hand, should the kinematic patterns for speech and limb movements differ, it could indicate that either the functional unit of control or the basis of control itself might differ in the movements of the speech articulators and the limbs.

Changes in movement rate, and, consequently, duration, have been shown to affect the dynamic characteristics of limb movements as well as their timing and interval durations. In rapid movements about the elbow, where both the amplitude and the velocity of the movement are free to vary, increases in rate are characterized both by decreases in movement amplitude and by increases in the dynamic stiffness of the limb (Cooke, 1982; Feldman, 1980b). In speech, on the other hand, there are suggestions that both the kinematics and the activity in muscles change in complex ways with differences in rate (Gay, 1981; Kuehn and Moll, 1976). For example, with increases in speaking rate, there have been reports of reduction in articulator movement amplitude with velocity unchanged (Kent and Moll, 1972) or increased (Gay, 1981), increases in peak velocity with amplitude unchanged (Abbs, 1973), and reductions in both amplitude and velocity (Kent and Moll, 1972). Further, while Tuller *et al.* (1982) have provided evidence for the preservation of the relative timing of average interval durations with rate changes in speech (as is the case in limb movements), Gay (1981) has shown that vowel and consonant related EMG activity change in different ways with variations in speech rate. Thus a consistent pattern has yet to emerge in the kinematic and physiological characteristics of rate control in speech.

In spite of apparent differences between speech and limb movements there are, as well, kinematic similarities which bear on the present examination of durational control. In both, there appear to be systematic changes in the slope of the relationship between maximum velocity and movement amplitude, a kinematic indicator of articulator stiffness (see below), with differences in movement rate and duration. In rapid elbow movements in humans, Cooke (1980) has shown that increases in rate result in increases in the slope of the maximum-velocity/movement amplitude relationship (with maximum velocity presented as a function of amplitude). In speech, increases in rate may likewise result in increases the slope of the maximum-velocity/amplitude relationship (Ostry *et al.*, 1983) though the magnitude of the effect does not appear to be as great as in the case of limb movements.

The slope differences between speech and limb movements may be due to the magnitude of the durational effect brought about by the rate manipulation. A useful way to look at this is to consider the slope changes in speech that result from the manipulation of both *rate* and *stress*. Ostry *et* *al.* (1983) reported that increases in speech rate resulted in an average decrease in gesture duration of 26% and only a slight increase in the slope of the maximum-velocity/movement amplitude regression. In contrast, with differences in stress, slope changes followed a pattern more similar to those observed in limb movements, with the slope of the maximum-velocity/movement amplitude regression being reliably greater for unstressed than for stressed vowels. In this case, an average reduction in movement duration of 58% was observed with decreases in stress. Thus it may be the case that changes in the slope of the maximum-velocity/movement amplitude regression are related primarily to differences in movement duration rather than to factors confounded with duration, such as movement amplitude or linguistic stress (cf. Ostry *et al.*, 1983). Consistent with this view is a recent demonstration by Ostry and Cooke (in press) that when movement rate and amplitude are varied orthogonally in rapid elbow movements, it is the differences in the duration of the movement, not its amplitude, that produce the observed changes in the slope.

The slope changes associated with differences in movement rate and duration may be indicative of a similar basis for speech and limb control. Cooke (1980) has suggested that changes in the slope of the maximum-velocity/movement amplitude relationship can be interpreted with respect to the control of parameters of the biomechanical model of the limb. In this model, the position of the limb ($x$) over time ($t$) is described by the equation

$$M\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F, \tag{1}$$

where $M$, $b$, and $k$ are specifiable parameters of mass, viscosity, and stiffness, and $F$ indicates the force applied to the system. Cooke demonstrated that in rapid movements about the elbow, changes in the maximum-velocity/amplitude slope could be predicted on the basis of the stiffness parameter $k$, where increases in stiffness produced corresponding increases in the slope of the maximum-velocity/movement amplitude function. In this model, stiffness remains effectively constant for a given gesture but is specifiable by the nervous system and can therefore be altered between gestures to produce the desired kinematic effects. Thus, to the extent that the kinematic phenomena of speech control parallel in detail the phenomena in limb movements, increases in this slope may be related to underlying changes in the stiffness of either the limb or the speech articulator.

In the examples described here, the slope of the relationship between maximum velocity and movement amplitude has been found to vary with changes in rate in limb movements and possibly also in speech. The present study attempts to systematically evaluate this relationship in speech with the aid of pulsed ultrasound measurements of tongue dorsum movement. As changes in the duration of speech movements can be produced both by the manipulation of rate and by the selection of stimuli whose intrinsic movement durations differ, we have examined the effects of both factors on speech movement durations. This has been achieved through the manipulation of speech rate and back vowel height.

## I. METHOD

### A. Subjects

Three normal subjects were tested in the study. Subject SG was a native speaker of Canadian English; subjects CB and AD were native speakers of Quebec French and second-language speakers of English.

### B. Apparatus

Tongue dorsum movements were monitored using a computerized pulsed ultrasound system. Detailed descriptions of the system can be found in Keller and Ostry (1983) and Ostry *et al.* (1983).

A Picker model 104 ultrasonoscope with a 3.5-MHz single element transducer was used to generate and receive the ultrasound signals. An acoustic record was obtained simultaneously. The ultrasound and acoustic data were both recorded at a 1-kHz rate using a Cromemco CS2 microcomputer. Individual trials lasted 3.5 s each.

The ultrasound transducer was placed below the chin just anterior to the hyoid bone along the midline of the mandible. The transducer was oriented at about 90° to the Frankfurt horizontal, a maxillary reference line which runs approximately parallel to the line formed by joining the anterior and posterior nasal spines (Zemlin, 1981). This placement had the effect of directing the ultrasound signal in an orientation that was approximately perpendicular to the hard palate. The transducer was held in a fixed position during testing by means of a modified hockey helmet that was fitted with vertical and horizontal Plexiglas bars to secure the transducer (see Keller and Ostry, 1983; Ostry *et al.*, 1983, for schematics). The apparatus had no significant effect on the extent of vertical jaw movements (Keller and Ostry, 1983).

In monitoring the position of the tongue dorsum in speech, the ultrasound signal passes through soft tissue to the articulator surface. The distance from the crystal of the ultrasound transducer to the dorsum of the tongue is estimated by timing the interval between the emission of the ultrasound burst and the reception of the large amplitude echo from the dorsum of the tongue (Fig. 1). This interval is

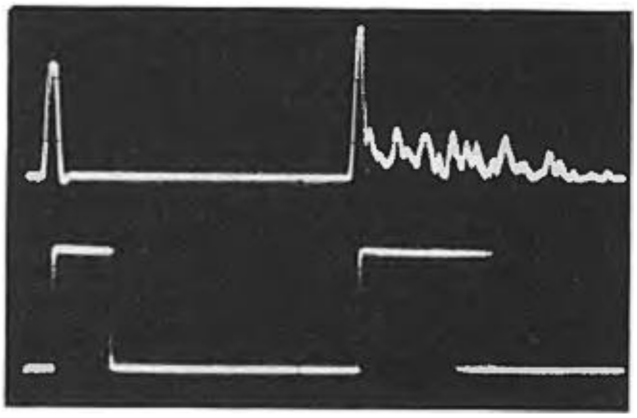

FIG. 1. Oscilloscope record of an emitted ultrasound pulse and the reflections from the tongue dorsum (upper trace). Corresponding signals from the peak detection circuitry are shown in the lower trace. The distance of the tonge dorsum from the crystal of the ultrasound transducer is indicated by the interval between the leading edges of the signals in the lower record.

converted to a distance estimate by assuming an average speed of ultrasound in soft tissue of 1540 m/s (Goss *et al.*, 1978). (The standard error due to system resolution is approximately 0.10 mm in this study.)

The transducer placement follows a standardized procedure that both maximizes the measured displacement of the tongue dorsum during repetitions of /ka/, and at the same time preserves the traditional order of back vowels /u, o, a/ in the ultrasound measurement (Keller and Ostry, 1983). The lateral orientation of the transducer coincides with the axis connecting the nasion to the gnathion. The placement is verified by examining several test recordings of the sequence of /kukoka/. Keller and Ostry have shown that the optimal placement position differs somewhat between subjects; however, it is usually possible to satisfy both of the placement criteria within a range of approximately 4° about the perpendicular to the Frankfurt line.

The pulsed ultrasound measurement produces a unidimensional approximation to the vertical movement of the tongue dorsum. Hence, the terms "displacement" and "maximum velocity" indicate positions and rates of change along the measurement axis, not the displacement of individual tissue points. Parush *et al.* (1983) provide several lines of evidence on the validity of this approximation. Further, Keller and Ostry (1983) have shown that if stimuli are restricted to consonants and vowels that are articulated primarily in the back cavity, then tongue dorsum movements monitored with this procedure can be interpreted in a maxillary reference frame.

### C. Data analysis

The data were analyzed by dividing the duration of the trial into equal intervals and fitting natural cubic spline functions to the set of values, termed knots, formed by the interval averages at their midpoints (the algorithm used here can be found in Johnson and Riess, 1977). Natural cubic spline functions are a set of piecewise polynomial functions which pass through each of the knots and have first and second derivatives that are continuous at the knots. Spline functions were selected for this application because they are differentiable numerically, they make no *a priori* assumptions about the overall form of the function, and their piecewise form enables them to follow trends in the data with considerable accuracy. Keller and Ostry (1983) have shown that the use of interval widths of 45 ms or less results in an average absolute difference between the raw data and the spline function of about 0.03 cm per measurement. Parush *et al.* (1983) report that for interval widths as large as 50 ms, estimates of the point of initiation or termination of lingual gestures have standard errors of less than one ms. In the present study, a 45-ms interval width for averaging was selected; this results in a bandwidth for tongue dorsum measurements of approximately 11.5 Hz.

### D. Stimuli

The stimuli were consonant–vowel (CV) pairs formed by taking all combinations of the back vowels /u/, /o/, and /a/ and the velar consonants /k/ and /g/. The stimuli were produced either at a fast or slow speech rate. A given CV sequence was repeated continuously during a recording trial. Subjects were able to produce about three tokens per trial at the slow rate and as many as eight or nine tokens per trial at the fast rate. The order of testing was randomized with respect to vowel, consonant, and rate. Back vowels and velar consonants were used in this study because of the ease of ultrasound recording in the back cavity.

### E. Procedure

The transducer was positioned and the placement was verified in the manner described in the previous sections. The subjects were tested in blocks of 12 trials with each of the stimulus combinations formed by the 3 vowels × 2 consonants × 2 rates tested once in each block. In total, nine blocks of 12 trials were recorded for each subject. An additional three blocks of six trials (3 vowels × 2 consonants) were obtained in the slow condition only. The purpose of this procedure was to ensure that in total there were an equal number of fast and slow tokens. The testing was divided into two sessions. After the initial placement of the transducer at the beginning of the session, all trials were recorded without changing its position.

In scoring the data, tokens were rejected if either oral release or voice onset was not clearly distinguishable in the acoustic record or if multiple peaks in the position record made it difficult to identify either the point of initiation or termination of a gesture. The data rejection rate tended to be higher in the slow condition than in the fast condition but was otherwise unaffected by differences in vowel or consonant. The results reported below are based on approximately 20 to 30 tokens per subject in each of the 12 conditions tested.

## II. RESULTS

The pattern of tongue dorsum movements observed in this study is shown in Fig. 2 for repetitions of /ka/ at both fast and slow speech rates. The upper panel of the figure gives the tongue position, velocity, and acoustic records for one recording trial at the slow rate; the lower panel shows one recording trial at the fast rate. Figure 3 presents an enlargement of the record obtained in the fast condition, showing both the raw data and the approximating solution provided by the spline. Note that scale on the position record gives the distance in cm from the crystal of the ultrasound transducer to the dorsum of the tongue. Values in the velocity record are shown in cm/s with positive values indicating tongue dorsum raising movements and negative values indicating lowering movements.

The kinematics of tongue dorsum movement were analyzed by partitioning the lowering gesture of each token (Fig. 4) to give estimates of movement amplitude or displacement ($D$), duration ($T$), and maximum velocity ($V_{max}$). The estimates for each token were obtained by assuming that the movement was initiated at points of zero velocity and terminated at velocities equal to 5% of the average maximum velocity in a given condition. The reason for adopting a nonzero velocity as a criterion for movement termination was to eliminate artifactual estimates of movement duration which can occur as a result of periods of very slow movement at the

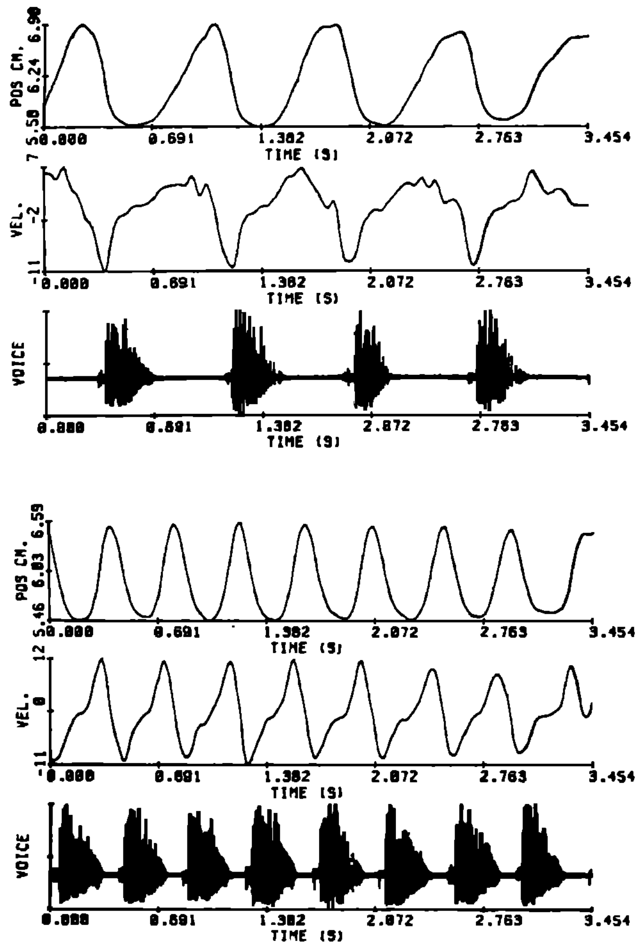


FIG. 2. Ultrasound records of the position of the tongue dorsum during repetitions of /ka/ at both slow (upper panel) and fast (lower panel) speech rates. The records are shown at a bandwidth of 11.5 Hz. Both panels are divided into three parts. Top: The upper peaks correspond to the position of the tongue dorsum for linguo-palatal closure, points at the bottom of the trace give the position of the tongue dorsum for the back vowel /a/. Values on the ordinate correspond to the distance in cm from the crystal of the ultrasound transducer to the dorsum of the tongue. Middle: Velocity record showing the rate of tongue dorsum raising (positive values) and lowering (negative values). Bottom: Corresponding acoustic record. Subject: Male native speaker of Quebec French.

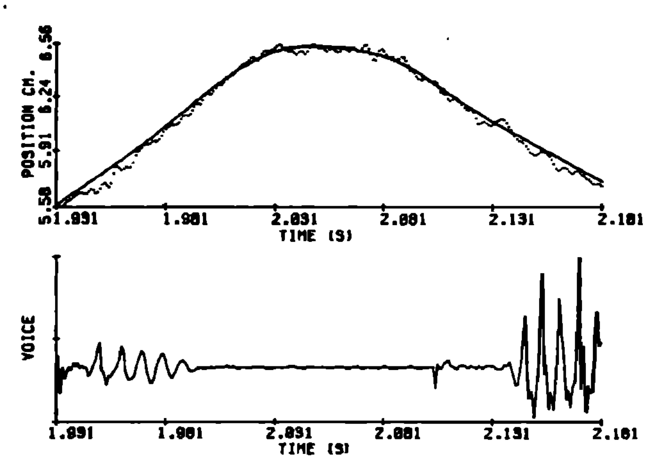


FIG. 3. Ultrasound record of the movement of the tongue dorsum during the production of /ka/ at a fast speech rate. Top: Raw data points and the corresponding natural cubic spline function are given for a 250-ms segment involving a closure for /k/. The spline function shown here represents a tongue displacement bandwidth of 11.5 Hz. Bottom: Corresponding acoustic signal.

end of a gesture. This decision resulted in the scoring of movement termination at velocities of 0.6, 0.4, and 0.3 cm/s for /a/, /o/, and /u/, respectively. Tongue dorsum raising movements were not scored in this study.

### A. Tongue dorsum kinematics

Differences in the duration, movement amplitude, and maximum velocity of tongue dorsum lowering movements were assessed by analysis of variance as a function of the vowel, consonant, and rate, for each subject separately. The vowel was found to affect tongue dorsum movement amplitude, duration, and maximum velocity, with all subjects showing greater amplitude (maxillary reference), duration, and maximum velocity as the vowel changed from /u/ to /o/ to /a/ (Table I). The tests of significance of the main effect of the vowel were reliable at $p < 0.001$ for the duration, amplitude, and maximum velocity measures for all subjects.

The rate manipulation yielded changes in the duration of the tongue lowering gesture for all subjects ($p < 0.001$). But, as reported elsewhere (e.g., Kuehn and Moll, 1976), the average rate changes were produced differently by the different subjects. Subjects SG and AD reduced average tongue dorsum movement amplitude in the fast condition ($p < 0.01$), whereas movement amplitudes were comparable at both rates for subject CB. Amplitude effects were accompanied by an increase in average maximum velocity for subject CB ($p < 0.01$) and no change in maximum velocity for subjects SG and AD ($p > 0.05$).

There were also systematic differences in the kinematic patterns for the voiced and voiceless stop consonant; however, these differed for the three subjects and did not appear to be related in any consistent way to whether the subjects were native French or English speakers (see Table I). There were, as well, a number of interactions as a function of the vowel, consonant, and rate variables. However, no consistent patterns were observed across subjects.

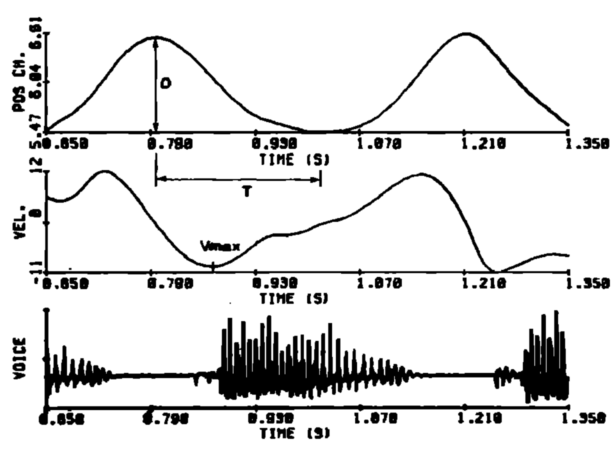


FIG. 4. Ultrasound record of the position and velocity of tongue dorsum and corresponding acoustic signal during the production of /ka/. As in Fig. 2, the upper peaks correspond to the position of the tongue dorsum during oral closure. The numerical values for tongue dorsum position indicate the distance in cm between the ultrasound transducer and the dorsum of the tongue. Duration: $T$; displacement: $D$; maximum velocity: $V_{max}$.

TABLE I. Average duration ($T$), movement amplitude or displacement ($D$), and maximum velocity ($V_{max}$) of tongue dorsum gestures as a function of speech rate and back vowel height. Probability values indicating the reliability of the various main effects are shown to the right of the respective consonant, vowel, and rate means. Standard errors are shown below.

| | Consonant | | | Vowel | | | | Rate | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | /k/ | /g/ | $p$ | /a/ | /o/ | /u/ | $p$ | Slow | Fast | $p$ |
| Subject SG | | | | | | | | | | |
| $T$ (ms) | 192 | 182 | a | 217 | 180 | 163 | c | 210 | 171 | c |
| $D$ (cm) | 0.88 | 0.84 | a | 1.25 | 0.83 | 0.49 | c | 0.97 | 0.79 | c |
| $V_{max}$ (cm/s) | 8.60 | 8.99 | b | 11.47 | 8.93 | 5.91 | c | 9.57 | 8.26 | c |
| Subject CB | | | | | | | | | | |
| $T$ (ms) | 215 | 204 | b | 248 | 208 | 174 | c | 219 | 202 | c |
| $D$ (cm) | 0.85 | 0.77 | c | 1.06 | 0.86 | 0.52 | c | 0.81 | 0.81 | ... |
| $V_{max}$ (cm/s) | 7.65 | 7.43 | ... | 9.00 | 8.15 | 5.56 | c | 7.28 | 7.72 | b |
| Subject AD | | | | | | | | | | |
| $T$ (ms) | 158 | 167 | a | 200 | 148 | 139 | c | 184 | 148 | c |
| $D$ (cm) | 0.75 | 0.84 | c | 1.28 | 0.69 | 0.44 | c | 0.94 | 0.72 | c |
| $V_{max}$ (cm/s) | 8.45 | 9.86 | c | 12.77 | 8.63 | 5.98 | c | 9.85 | 8.72 | c |
| | | | | | Standard errors | | | | | |
| Subject SG | | | | | | | | | | |
| $T$ (ms) | 4 | 3 | | 4 | 3 | 2 | | 4 | 3 | |
| $D$ (cm) | 0.02 | 0.02 | | 0.01 | 0.01 | 0.01 | | 0.02 | 0.02 | |
| $V_{max}$ (cm/s) | 0.13 | 0.15 | | 0.11 | 0.10 | 0.10 | | 0.16 | 0.12 | |
| Subject CB | | | | | | | | | | |
| $T$ (ms) | 3 | 3 | | 4 | 3 | 3 | | 4 | 2 | |
| $D$ (cm) | 0.03 | 0.03 | | 0.02 | 0.01 | 0.01 | | 0.03 | 0.02 | |
| $V_{max}$ (cm/s) | 0.19 | 0.24 | | 0.17 | 0.17 | 0.12 | | 0.25 | 0.19 | |
| Subject AD | | | | | | | | | | |
| $T$ (ms) | 3 | 3 | | 3 | 3 | 3 | | 3 | 3 | |
| $D$ (cm) | 0.03 | 0.03 | | 0.02 | 0.02 | 0.01 | | 0.04 | 0.02 | |
| $V_{max}$ (cm/s) | 0.24 | 0.30 | | 0.27 | 0.21 | 0.18 | | 0.35 | 0.22 | |

[a] $p<0.05$.
[b] $p<0.01$.
[c] $p<0.001$.

### B. Maximum velocity-movement amplitude relationship

All subjects showed reliable correlations between the tongue dorsum movement amplitude and its maximum velocity; ten of 12 within condition tests (3 vowels $\times$ 2 consonants $\times$ 2 rates) of this relationship were reliable at $p<0.01$ for SG; all 12 correlations were reliable for AD and CB. The proportion of variance accounted for by the within condition correlations averaged 0.48, 0.40 and 0.68 for SG, CB, and AD, respectively.

Scatterplots of the relationship between maximum velocity and movement amplitude are presented in Fig. 5 for the three subjects separately. The figure shows the individual observations for all combinations of rate and vowel height. A strong correlation between maximum velocity and movement amplitude is evident. The proportion of variance accounted for by this relationship is 0.81, 0.77, and 0.86 for subjects SG, CB, and AD, respectively. For subjects SG and CB, the quadratic term in the polynomial regression is also reliable, $F(1,350)=36.98$, $p<0.01$; $F(1,357)=22.10$, $p<0.01$. It can be seen from the figure that there is extensive overlap between the movement amplitudes and maximum velocities for the different combinations of speech rate and vowel height. However, the vowel height observations seem to occupy different regions of the function with both the amplitude and maximum velocity increasing as the vowel goes from /u/ to /a/.

### C. Relationship between duration, maximum velocity, and amplitude

The relationship between maximum velocity and movement amplitude was examined as a function of the duration of the gesture. The aim was to assess changes in the slope of the maximum-velocity/movement amplitude relationship, and, hence, articulator stiffness, with differences in the duration of the movement. Tests were conducted for each condition separately and also across all observations for a given subject. The analyses were based on the measurement of individual tokens to obtain both a ratio measure ($V_{max}/D$) and a duration measure ($T$). This ratio is a point estimator of the maximum velocity/movement amplitude slope and thus a point estimate of stiffness. For each token, the ratio of maximum velocity to movement amplitude was plotted as a function of the duration of the corresponding gesture. Figure 6 shows scattergrams of this relationship for the 2 rate by 3 vowel height combinations for each of the three subjects.

For all subjects, the ratio of maximum velocity to tongue dorsum amplitude varied systematically with the duration of the gesture; as the gesture duration increased, the ratio decreased. On a within condition basis eight of 12 tests of this relationship (3 vowels $\times$ 2 consonants $\times$ 2 rates) were reliable at $p<0.01$ for SG, ten of 12 for AD, and 11 of 12 for CB. The proportion of variance accounted for by these within condition relationships averaged 0.44, 0.42, and 0.57 for

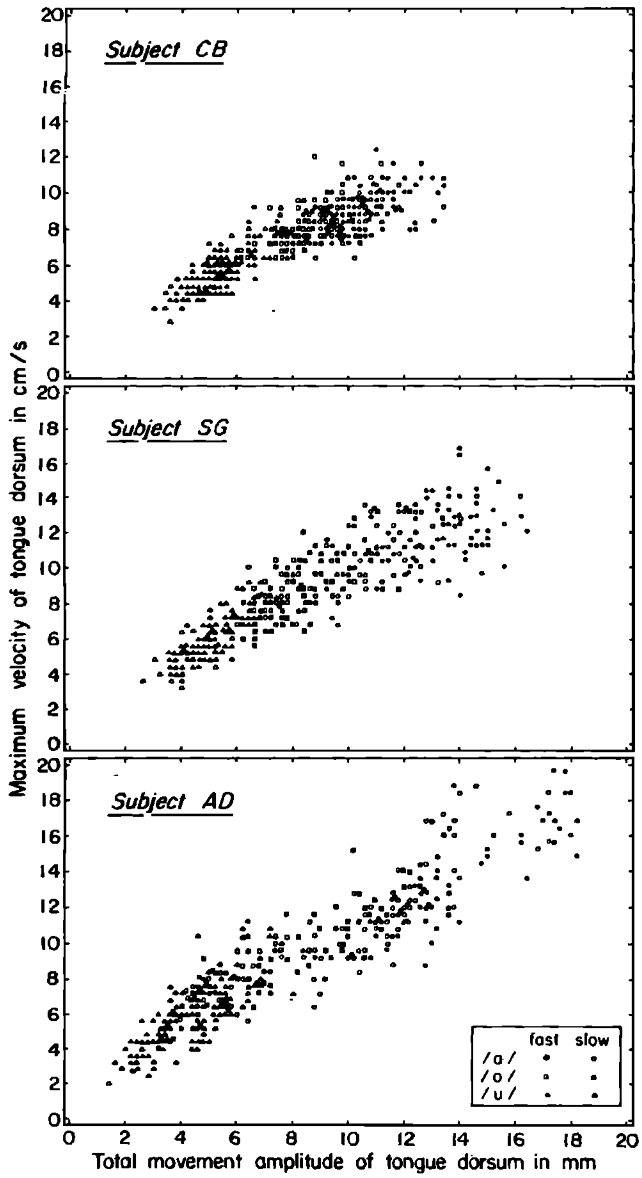


FIG. 5. Relationship between tongue dorsum movement amplitude and maximum velocity showing individual data points for all combinations of speech rate and back vowel height.

CB, SG, and AD, respectively. Since systematic relationships between $V_{max}/D$ and $T$ are present on a within condition basis, the patterns reported here presumably reflect the mechanisms by which the nervous system actually affects changes in movement duration. That is, the patterns do not appear to arise simply as a consequence of manipulating variables such as rate, vowel, or consonant.

The rate by vowel combinations shown in Fig. 6 also indicate a consistent relationship across conditions between the ratio of maximum velocity to movement amplitude and the duration of the gesture. The linear and quadratic terms of the polynomial regression were reliable ($p < 0.01$) for all subjects, with an overall proportion of variance accounted for of 0.66, 0.57, and 0.80, for CB, SG, and AD, respectively. Since the ratio measure is an index of articulator stiffness, these data are consistent with other observations that stiffness increases with decreases in gesture duration. As in the analysis of the maximum-velocity/movement amplitude relationship, the individual rate by vowel height combinations can be seen to occupy different regions of the function, with the fast speech conditions having higher ratios, greater stiffness, and shorter movement durations and the slow speech conditions having lower ratios, less stiffness, and longer movement durations.

Note that this trial by trial analysis suggests that stiffness changes continuously with movement duration; it does not appear to be set at a constant value for a given equivalence class of movements. Ostry *et al.* (1983) assessed the slope of the maximum-velocity/ movement amplitude relationship within a given condition and thus, in effect, were taking average values for stiffness rather than assessing the stiffness of the articulator for individual gestures as is the case here.

In models of movement control of the general form of

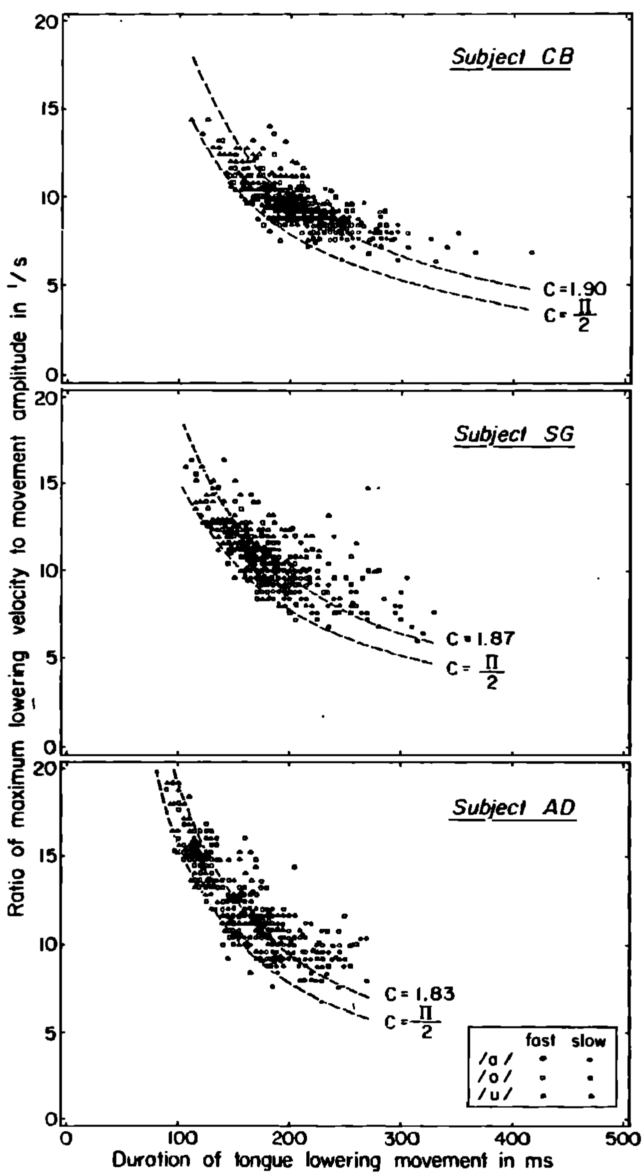


FIG. 6. Relationship between the maximum-velocity/movement amplitude ratio and gesture duration showing individual data points for all combinations of speech rate and back vowel height. The relationship predicted by a mass-spring system without damping and the best fit functions for the relationship $V_{max}/D = c/T$ are also shown (see text for details).

Eq. (1), in which changes in duration can be produced by altering the value of the stiffness coefficient ($k$), it can be shown that the ratio of maximum velocity to movement amplitude is related to gesture duration by the following expression (see Munhall, 1984; Ostry and Cooke, in press; Soechting, 1984, for details):

$$V_{max}/D = c/T. \quad (2)$$

In this equation changes in the ratio measure and, hence, stiffness are related to differences in movement duration by a constant $c$ whose value is characteristic of the system's velocity pattern over time (Munhall, 1984; Ostry and Cooke, in press; Soechting, 1984). For example, in the case of the mass-spring system, the value of the constant $c$ is equal to $\pi/2$ or 1.57; the constants appropriate to the present data are 1.90, 1.87, and 1.83 for CB, SG, and AD, respectively (see Fig. 6). The proportion of variance accounted for by Eq. (2) with $c$ equal to these values is 0.43, 0.41, and 0.71, respectively.

The data in Fig. 6 lie above the function predicted for an undamped mass-spring system. Nevertheless, the mechanisms of durational change may be based at least in part on specification of the biomechanical characteristics of the articulator. For a particular best fit function, that is, a particular value of the constant $c$, changes in the operating point along the curve may result from specifiable changes in the stiffness parameter $k$. Thus, when stiffness is increased, gesture duration is reduced and there is a corresponding increase in the ratio of maximum velocity to movement amplitude. The value of $c$, however, remains constant.

The possibility that the findings presented in Figs. 5 and 6 are attributable to the unidimensional measurement technique should be considered. Since the tongue dorsum movements associated with the consonants used in this study have horizontal as well as vertical components (Kent and Moll, 1972) it could be argued that the changes in the maximum-velocity/movement amplitude ratio observed here result from error introduced by using a measurement axis that is not strictly coincident with the trajectory of the tongue. While our instrumentation does not enable the evaluation of this possibility, there are at least two reasons to believe that the obtained results are not due to the measurement technique. First, there is some question about the proportionality of horizontal and vertical components of tongue movements (Kent and Moll, 1972, p. 459). In the absence of such a correlation there is no reason to suggest that the relationship seen in Fig. 6 is artifactual. Equally important is converging evidence from other articulators; the pattern reported here for tongue dorsum movements has also been observed in the adduction and abduction movements of the vocal folds (Munhall and Ostry, in press; see discussion) and also for movements of the limbs. In these cases it cannot be argued that the relationship between amplitude, velocity and duration is based on measurement orientation artifact.

## III. DISCUSSION

The kinematics of tongue dorsum lowering movements were assessed under conditions of rate, vowel, and consonant manipulation. Within individual conditions, the extent of the tongue lowering gesture was positively related to the corresponding maximum velocity. Across conditions, the relationship appeared to be nonlinear for two of the subjects with the slope decreasing with increases in tongue dorsum displacement. In a further analysis, the ratio of maximum velocity to movement amplitude was examined as a function of the duration of the gesture. Overall, the ratio was found to increase with decreases in movement duration. This relationship held both within and across conditions. In this analysis, the two speech rates occupied different regions of the overall function. Fast speech rates tended to be characterized by larger ratios, whereas slow speech rates were characterized by smaller ratios.

A significant feature of these findings is that changes in movement duration associated with differences in back vowel height, consonant, and speech rate can all be accommodated by a single function of the form of Eq. (2). A similar demonstration of the case in laryngeal abduction and adduction gestures (Munhall and Ostry, in press) and related findings in limb movement (Ostry and Cooke, in press; Soechting, 1984) raise the possibility that a single set of principles can account for a wide range of changes in the duration of movements. In studies of rate control in rapid limb movement, both Cooke (1980, 1982) and Feldman (1980b) have shown that increases in the rate of rapid elbow flexions (and, hence, decreases in the duration) are accompanied both by increases in slope of the maximum-velocity/movement amplitude relationship and corresponding increases in the static and the dynamic stiffness of the elbow joint. In speech, Munhall and Ostry (in press) have shown that the ratio of maximum-velocity to movement amplitude varies inversely with gesture duration for both abduction and adduction gestures of the vocal folds across manipulations of rate, stress, and consonant. Taken together these findings are consistent with the view that changes in the duration of individual movements all have a similar origin (cf. Lindblom, 1963).

The present findings differ from those of earlier reports (Ostry *et al.*, 1983; Ostry *et al.*, 1984) in which the slope of the maximum-velocity/movement amplitude regression was found to vary with stress and only slightly with rate. We believe that the relatively small effects of rate are the result of the relatively small durational changes produced by altering speech rate and by the variability in the way speakers alter rate in speech production experiments; speaking rate is not well controlled experimentally or, characteristically, in natural speech. However, as demonstrated in the present study, when durational differences associated with rate are taken into account, it can be shown that rate influences the maximum-velocity/movement amplitude relationship in a systematic manner.

The data relating the maximum-velocity/movement amplitude ratio to the rate and duration of tongue lowering gestures can be modeled in terms of changes produced by the nervous system in the biomechanical characteristics of the speech articulator. Specifically, increases in the ratio with decreases in movement duration could be produced by a second-order system in which stiffness (the coefficient of the zero-order term) is increased to affect the kinematic changes (see Cooke, 1980; Nelson, 1983).

The idea that voluntary movements are produced, at least in part, by the control of biomechanical characteristics of the movement articulator is consistent with the so-called mass-spring model of motor control. The essence of this model is that muscles acting antagonistically are controlled so as to exhibit many of the characteristics of a damped spring with an inertial load. In such a system, the end point and the duration of the movement are determined by the specification of one or more of the spring constant [the parameter $k$ in Eq. (1)], the viscosity [$b$ in Eq. (1)], and the zero length or resting length of the spring. In the context of this model, Cooke (1980) has suggested that movements are produced by changes in stiffness rather than zero length. However, Feldman (1980a, b) has shown that in the lumped model of the limb changes in overall stiffness can be produced by setting the zero lengths of agonist and antagonist muscles without controlling the individual muscle stiffnesses.

A point that should be emphasized is that, in the model proposed here, duration *per se* is not represented in the nervous system. Rather, durational change is brought about indirectly through the specification of biomechanical parameters of articulators. Although the issue of whether the nervous system has an explicit temporal representation may be of little consequence at the behavior level, (where it appears appropriate to say that duration is the controlled variable), the form of models of the motor system is greatly affected by the presence or absence of a temporal variable (see Tuller and Kelso, in press, for a discussion of this issue).

In contrast to the systematic relationship observed between the maximum-velocity/movement amplitude ratio and the duration of the speech gesture, we noted that changes in speech rate, as measured by average displacement and average maximum velocity, were produced differently by the three subjects in the study (also see Abbs, 1973; Gay, 1981; Kent and Moll, 1972; Kuehn and Moll, 1976). Subjects SG and AD reduced average displacement in the fast speech condition, whereas CB showed no change. However, CB reliably increased average maximum velocity at fast speech rates ,whereas SG and AD showed no change. The apparent lack of consistency observed across subjects may be the result of monitoring the individual components (amplitude and maximum velocity) of a variable such as stiffness, whose values are not directly reflected in either the amplitude or the maximum velocity alone. While the average maximum velocities appear to have no consistent pattern across subjects with changes in rate, an orderly pattern is shown to be present when velocities are examined in the context of amplitude and movement duration.

Durational changes in speech production have been reported for manipulations of rate, stress, and phonetic context. These changes appear in both the acoustical intervals, which were not studied here, and in the duration of the movements. The relationship between movement durations and acoustical durations under the conditions of this study is somewhat uncertain as the articulatory period and the acoustical period presumably differ in duration (Bell-Berti and Harris, 1981). Furthermore, as changes in acoustical durations may involve inter-articulator patterns rather than the intra-articulator pattern studied here there may not be any systematic relationship between the acoustical and articulatory measures of duration.


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