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Some Organizational Characteristics of Speech Movement Control

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The neuromotor organization for a class of speech sounds (bilabials) was examined to evaluate the control principles underlying speech as a sensorimotor process. Oral opening and closing actions for the consonants /p/, /b/, and /m/ (C1) in /s V1 C1 V2-C2/ context, where V1 was either /ae/ or /l/, V2 was /ae/, and C2 was /p/, were analyzed from 4 subjects. The timing of oral opening and closing action was found to be a significant variable differentiating bilabial consonants. Additionally, opening and closing actions were found to covary along a number of dimensions implicating the movement cycle as the minimal unit of speech motor programming. The sequential adjustments of the lips and jaw varied systematically with phonetic context reflecting the different functional roles of these articulators in the production of consonants and vowels. The implication of these findings for speech production is discussed.

KEY WORDS: speech motor control, coordination, timing, programming

As a motor process, speaking is an intricate orchestration of multiple effectors (articulators) coordinated in time and space to produce sound sequences. From a functional perspective, the speech production mechanism is a special purpose device modulating the aerodynamic and resonance properties of the vocal tract by rapidly creating constrictions, occlusions, or overall shape changes. These events provide the foundation for the categorically distinct sounds of the language. The functional task, driven by cognitive considerations, involves a number of sensorimotor processes that generate segmental units, specify the coordination among contributing articulators, scale articulator actions to phonetic and pragmatic contexts, and subsequently sequence these actions into meaningful units for communication. Assuming that the individual phonetic segments of a language are stored in some manner in the nervous system, a number of important issues can be identified. What are the production units, how are they differentiated for sounds, and how are they modified according to context? The present investigation is an attempt to answer some of these questions and identify some principles of speech motor organization used to scale, coordinate, and sequence multiple articulatory actions.

Movement Characteristics—Stop Consonants

One focus of the present investigation is to examine, in detail, the kinematic adjustments of lip and jaw motion associated with a class of English speech sounds, the bilabial stop consonants /p/, /b/, /m/, in different vowel contexts. These consonants are the same in their place of articulation (the lips), employing the same set of articulators to create an obstruction at the oral end of the vocal tract. One property distinguishing these sounds is the presence or absence of voicing; /p/ is a voiceless consonant because laryngeal vibration is briefly (100–200 msec) arrested during the oral closing. As the lips release the oral closure the vocal folds move back together and voicing for the next vowel is initiated (Lisker & Abramson, 1964). There are two other classes of stop consonants in English that

create temporary obstructions in different regions of the vocal tract and use different articulators: alveolar and velar stop consonants. In addition, each of the alveolar and velar voiced consonants can be produced with the velum lowered, creating the nasal resonances for the /n/ and /N/ sounds, respectively. Thus, English contains three characteristic sets of stop consonants that differ in the primary articulators used to create the obstruction and the location of the obstruction in the vocal tract.

It is not clear from previous investigations how articulatory movements within a class are modified by concomitant articulatory actions. That is, are the lip and jaw movements for all bilabial consonants similar, the acoustic distinctions between sounds in the class attributed solely to the laryngeal and velar actions? Examination of electromyographic (EMG), kinematic, and acoustic data reveal conflicting findings. Electromyographic activity from lip muscles for bilabial production has generally failed to reveal significant differences in measured variables such as peak EMG amplitude and EMG burst duration associated with the oral closing action (Fromkin, 1966; Harris, Lysaught, & Schvey, 1965; Lubker & Parris, 1970; Tatham & Morton, 1968). The one exception is the study by Sussman, MacNeilage, & Hanson (1973) in which the activity from one upper lip depressor muscle (depressor anguli oris) from one subject was found to be greater for /p/ than for /b/ and /m/. Kinematic studies have revealed a few movement differences for /p/ and /b/, most consistently a tendency for the oral closing movement velocity to be higher for /p/ than /b/ or /m/ (Chen, 1970; Summers, 1987; Sussman et al., 1973). Two of the above mentioned investigations (Sussman et al., 1973; Summers, 1987) have also reported kinematic and EMG differences in movements surrounding the oral closing action. Jaw opening for the vowel /a/ or /ae/ before /p/ was found to be higher than before /b/ (Summers, 1987), and the lower lip opening velocity and associated EMG activity (following the oral occlusion) was greater for /m/ than /p/ or /b/ (Sussman et al., 1973).

Acoustic studies have provided the most reliable findings associated with voicing differences. Closure durations for voiceless consonants are generally longer than closure durations for their voiced cognates and the preceding vowel is shorter in the voiceless context (Denes, 1955; House & Fairbanks, 1953; Luce & Charles-Luce, 1985). Integrating results from different empirical observations allows for some potential speculation on the voiced/voiceless differences. EMG results suggest that the form of the oral closing motor commands is not different in magnitude or duration because of the presence or absence of voicing. In contrast, the movement and acoustic studies suggest that differences may be focused on movement timing as evidenced by changes in movement velocity and vowel duration. Although the available data suggest that one difference between sounds within an equivalence class such as bilabials may be reflected in aspects of their timing, no detailed analysis has been conducted.

Another possibility is that articulatory motion may be governed by control principles that operate on combinations of kinematic variables reflecting important system parameters. For example, consonant-related movement differences may be specified by articulator stiffness, a construct with some potential as a motor control variable (Cooke, 1980; Ostry & Munhall, 1985; Kelso et al., 1985). If an effector such as the lower lip is modeled as a linear second order system, changing the static stiffness of the

system results in predictable changes in the velocity/displacement relationship; the velocity/displacement ratio varies directly with stiffness. Moreover, if resting stiffness is a variable being controlled by the nervous system, then changes in an effector's kinematics can be brought about by a single system parameter. It has been suggested that mass normalized stiffness, estimated from the ratio of a movement's peak velocity and displacement, may be an important control parameter for skilled actions, including speech (Kelso et al., 1985; Kelso, 1986). Although a number of studies have demonstrated consistent and systematic velocity/displacement relations for a range of speech movements (Kuehn & Moll, 1976; Ostry, Keller & Parush, 1983; Munhall, Ostry & Parush, 1985), to date it has not been demonstrated unequivocally that stiffness is an important control parameter, except as one of many possible alternatives (see Nelson, 1983, for example). One possibility is that /p/ with higher closing velocity might be differentiated from /b/ and /m/ by its stiffness specification, suggesting that speech sounds may be coded neurophysiologically by such a construct.

Articulator Interactions and Sequencing

It is becoming increasingly clear that individual articulators and their respective actions are not independent but functionally related by task. The empirical support for this view comes from two main sources. When the motions of the lips and jaw for bilabial closure are examined in detail, it appears that the individual articulators are not adjusted independently either in magnitude or relative timing (Hughes & Abbs, 1976; Gracco & Abbs, 1986; Gracco, 1988). Spatiotemporal adjustments to suprasegmental manipulations also suggest that stress and rate mechanisms act on all active regions of the vocal tract (Fowler, Gracco, V.-Bateson, & Romero, 1993). Changes in articulator movement patterns following mechanical perturbation are also consistent with the suggestion that the actions of individual articulators are not adjusted independently. Rather, disruptions to articulator movement during speech result in adjustments in the perturbed articulator as well as those (unperturbed) articulators that are actively involved in the production of the specific sound (Folkins & Abbs, 1975; Kelso et al., 1984; Kollia, Gracco, & Harris, 1992; Munhall, Löfqvist, & Kelso, in press; Shaiman, 1989; Abbs & Gracco, 1984; Gracco & Abbs, 1985, 1988). While many previous studies can be criticized on statistical grounds (see Folkins & Brown, 1987) it is not unreasonable to suggest that interactions among articulators are not random but systematic and integral to the overall speech production process. Together these observations suggest that speech movements are organized according to higher level principles that involve articulatory aggregates (similar to the principle of synergy defined by Bernstein, 1967).

Speaking is also a continuous process involving articulatory motion generating acoustic and aerodynamic events. Lip and jaw motion can be classified as either opening or closing depending on the direction of the motion relative to an occlusion/constriction or characteristic vocal tract shape. Oral opening is most often associated with vowel production, whereas oral closing is most often associated with consonant production. Different relative timing patterns for oral articula-

tory motions depending on direction have been interpreted as manifestations of separate and distinct synergistic actions fundamental to the speech production process (Gracco, 1988). Moreover, the opening phase of an articulatory action shows greater variation in spatiotemporal adjustment that is due to stress (Kelso, V.-Bateson, Saltzman, & Kay, 1985; Ostry, Keller, & Parush, 1983) than the corresponding closing phase. Similarly, oral opening and closing movement duration show differential effects to changes in speaking rate (Adams, Weismer, & Kent, 1993). These differential patterns associated with movement direction are also influenced by phonetic context. The context in which a sound is produced is known to affect the acoustic and kinematic properties associated with its production (Daniloff & Moll, 1968; Sussman, MacNeilage, & Hanson, 1973; Parush, Ostry, & Munnhall, 1983; Perkell, 1969). It seems that articulatory adjustments for context may have differential effects on the different movement phases. In order to understand the organizational principles and control processes that govern speech production, evaluation of speech movement differences must include the articulatory adjustments within as well as across articulators and movement phases.

Examining kinematic changes across movement phases has additional implications for understanding speech as a serial process. As pointed out by Lashley (1951), serial actions, such as those found in speech, locomotion, typing, and the playing of musical instruments, cannot be explained in terms of successions of external stimuli or reflex chaining. Rather, the apparent rhythmicity found in all but the simplest motor activities suggests that some sort of temporal patterning or temporal integration may form the foundation for motor as well as perceptual activities (Lashley, 1951). Lashley further suggested that skilled action involves the advanced planning of entire sequences of action. More recently, Sternberg and colleagues have developed a model of speech timing that incorporates the concept of an advanced plan of action, an utterance program, which is used to control the execution of the elements in sequence (Sternberg, Knoll, Monsell, & Wright, 1988). The elements of the utterance program are action units defined abstractly on the basis of a single selection process but may contain multiple distinguishable actions (Sternberg et al., 1988). That is, speech production is considered a hierarchical process with advanced planning of what is to be said (utterance program) followed by the execution of the program using smaller sequenced elements (action units) on the order of stress groups (Fowler, 1983; Sternberg et al., 1988).

Although this model provides a framework for the speech motor process, a number of unresolved issues remain. Previous work has focused on evaluating the latency and duration of words or syllables rapidly produced by subjects. Examination of articulatory movement has not been undertaken and thus identification of the articulatory correlates of the action unit is lacking. If an action unit or unit of speech production is to have any theoretical significance, identification of the physiological (articulatory) instantiation of the construct is crucial. Further, in order to fully understand the speech production process, the mechanism by which elemental units are sequenced and modified is also of central import. In the present investigation, serial speech move-

ments within and across movement sequences were examined for evidence of articulatory cohesiveness that may reflect the production unit as well as the manner in which phonetic context may modulate the underlying temporal patterning.

Articulatory Coordination

A final focus of the present investigation is the coordination patterns of the lips and jaw as they cooperate to occlude and open the oral end of the vocal tract for the different bilabial consonants. A number of previous investigations suggest that task-related articulatory movements, such as the lip and jaw motion for bilabial closing, are interdependent in their timing (Gracco & Abbs, 1986; Gracco, 1988). Results presented by Löfqvist and Yoshioka (1981, 1984) similarly suggest a number of consistent timing patterns for different laryngeal-oral interactions following stress, rate, and consonantal manipulations. Observations of timing coherence among articulatory actions have been extended to include the lip, jaw, and larynx associated with the initiation of voicing and devoicing in a variety of phonetic contexts (Gracco, 1990; Gracco & Löfqvist, 1989; Gracco & Löfqvist, in preparation). Such observations reflect a potential principle of speech movement organization. For speech movement coordination, as for motor coordination in general (see Bernstein, 1967), the timing or patterning of the potential degrees of freedom for task-related actions are constrained, thereby reducing the overall motor control complexity (Gracco, 1988).

Although the available evidence suggests that constraining the degrees of freedom may be a general principle underlying the coordination of task-related speech articulators, it has recently been suggested that lip and jaw coordination is not invariant (DeNil & Abbs, 1991). Rather, variations in the temporal sequencing of lip and jaw closing movements for /b/ at fast and slow speaking rates have been interpreted to reflect fundamentally different patterns requiring different coordinative patterns. With the exception of the DeNil and Abbs (1991) investigation, previous studies examining the relative timing of the lips and jaw during oral closing have focused on voiceless /p/ (Caruso, Abbs, & Gracco, 1988; Gracco & Abbs, 1986, 1988; Gracco, 1988; McClean, Kroll, & Loftus, 1990). It is possible that lip and jaw actions for voiced and voiceless sounds differ in their relative timing, reflecting different coordinative relations. Further, one previous study has examined the relative timing of the lips and jaw for oral opening, and reported fundamentally different timing patterns among the articulators for oral opening than for oral closing (Gracco, 1988). As such, extended examination of interarticulatory timing across movement phases may be informative regarding the extent and generality of any coordinative principles governing speech motor actions.

Method

Subjects and Movement Task

Four females between the ages of 21 and 28 years were subjects in the present study. None had a history of neuro-

logical disorder and all were native speakers of American English. Subjects were asked to repeat one of six utterances following the onset of an experimenter-controlled tone. The utterances were of the form /s V1 C V2/ where V1 was either /ae/ or /i/, C was /p/, /b/, or /m/ and V2 was /ae/. The specific utterances were as follows:

sapapple
seepapple
sabapple
seebapple
samapple
seemapple

Each word was repeated, in isolation, a total of 40 times, 10 or 20 consecutive times for each word on the list in the presented order, followed by subsequent repetition(s) of the entire list. A total of 240 tokens were obtained for each subject with the exception of Subject 4, whose total was 238 (one sapapple and one seemapple missing). The stimulus to respond (auditory tone) was presented at approximately 3-sec intervals. Subjects were instructed to produce each word with equal stress at a comfortable speaking rate following the tone and to use an effort level appropriate for speaking to someone 10–15 feet away.

Instrumentation and Data Acquisition

Single dimensional midsagittal movements of the upper lip (UL), lower lip (LL), and jaw (J) were transduced using a head-mounted strain gage system previously described (Barlow, Cole, & Abbs, 1983). Briefly, movements of the upper lip, lower lip, and jaw were transduced using ultra-light weight cantilever beams instrumented with strain gages attached to a lightweight head-mounted frame. Transducers were attached midsagittally at the vermillion border of the upper and lower lips and on a region of the chin that yielded minimal skin movement artifact (see Barlow et al., 1983; Folkins, 1981; Kuehn, Reich, & Jordan, 1980; Müller & Abbs, 1979). Transducers were visually aligned to capture the major movement axis for oral opening/closing for each subject with the resultant orientation rotated approximately 100 to 110 degrees posterior to the vertical. Movement signals were digitized at a sampling rate of 500 Hz with 12-bit resolution except for Subject 4 in which movement signals were sampled at 400 Hz. The acoustic signal was sampled at 500 Hz to indicate the onset and offset of the stimuli only.

Data Analysis

Prior to data analysis, all movement signals were digitally low-pass filtered (Butterworth implementation, two-pole zero phase lag, 20 Hz cutoff). As transduced, the lower lip signal reflects the combined movement of the lower lip and jaw. In order to obtain lower lip movement only, the jaw signal was software subtracted from the lower lip signal, yielding net lower lip movement. First derivatives were obtained using a 3-point numerical differentiation routine (central difference) and stored as part of the data file. From these instantaneous velocity signals, movement onsets and offsets were deter-

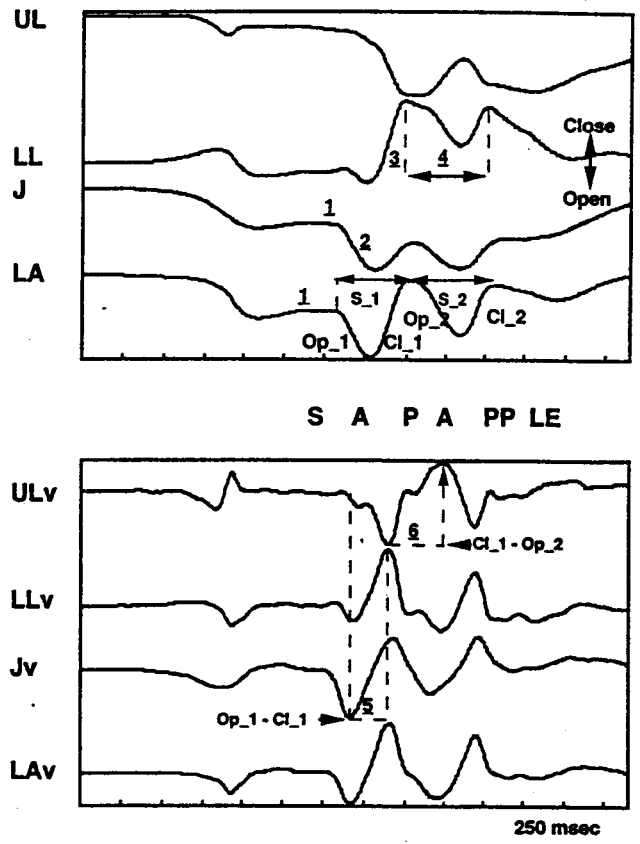


FIGURE 1. A representative example of upper lip (UL), lower lip (LL), jaw (J), and lip aperture (LA) displacement (above) and velocity (below) signals for one of the stimulus words, "sapapple." All trials were initiated from a rest position with the lips together and teeth lightly touching. Each production included two opening/closing sequences identified from the LA signal as S₁ and S₂. Within each sequence or cycle, opening and closing phases were also identified (Op₁, Cl₁, Op₂, Cl₂). Measurements are indicated by the numbers in the figure (see text for details).

mined for the individual closing movements. Computer software was used to identify zero crossings in the velocity traces of the respective upper lip, lower lip, and jaw signals and movement onset and offsets were marked. In addition, the movements of the upper lip, lower lip, and jaw were combined to yield a measure of the overall lip aperture (LA).

For the present experiment, subjects had been instructed to start each utterance from a position of rest with the lips in contact, and the upper and lower teeth lightly touching. Using this relatively consistent starting point it was possible to evaluate the relative position of the different articulators for the /s/ and the following vowel.

Each acquired token consisted of eight signals illustrated in Figure 1. Two complete movement cycles or sequences were identified from the lip aperture signal (LA) and indicated as sequence 1 and 2 (S₁, S₂) in the figure. Each sequence consists of two phases, an opening and closing phase. Sequences were defined as the time interval between the onset of the opening movement and the offset of the closing movement in the LA signal using a zero velocity criterion. Onsets of the opening and closing movements for the lips

and jaw were also determined from zero crossings in the first derivatives of the respective articulator motions. Maximum displacement and duration were defined as the distance and time, respectively, between the onset and offset of each movement; peak instantaneous velocity was also obtained for each movement. As with previous studies (Gracco & Abbs, 1986; Gracco, 1988) a measure of upper lip, lower lip, and jaw coordination during oral closing was obtained from the timing of each articulator's peak velocity relative to the same preceding articulatory event (jaw opening for the vowel). From the identified events of interest, the following measures were made (see Figure 1):

1. extent of oral opening and associated jaw position for /s/, relative to the subjects' rest position,
2. extent of oral opening for the first vowel (Op₁) and the associated jaw opening movement characteristics,
3. lip and jaw closing movement characteristics for the first closing,
4. oral opening (Op₂) and closing (Cl₂) movement characteristics for the second cycle (S₂) for the /aep/ in "apple,"
5. time of upper lip, lower lip, and jaw peak closing velocity relative to the peak jaw opening velocity for the first vowel opening,
6. time of upper lip, lower lip, and jaw peak opening velocity for the second opening relative to the peak upper lip closing velocity for the first oral closing.

Statistical Analysis

The data were analyzed using two-factor repeated-measures ANOVA with vowels and consonants as factors. When there were significant interactions, post hoc analyses were conducted using Scheffe's F-test with alpha level set to .01 for all comparisons.

Results

Context-dependent changes in the opening and closing movements will be examined for the first movement sequence. Next, movement parameters of the second sequence will be examined for carryover effects from the phonetic context of the first sequence. Finally, the coordination of lip and jaw motion will be examined for closing and opening effects and phonetic context. Individual articulator adjustments will be concurrently examined to evaluate their functional role in the speech production process.

SEQUENCE 1: MOVEMENT CHARACTERISTICS

Cycle Duration

One of the most robust findings in the present study was a change in the duration of the first movement cycle. For the group, the cycle duration obtained from the lip aperture signal was, on average, shorter for the /i C/ than /ae C/ context (191.8 msec vs. 227.3 msec). In addition, the cycle duration was shorter when the

consonant was /p/ than /b/ or /m/ (203.3 vs. 210.2 vs. 215.1 msec, respectively). Shown in Figure 2 are three examples of the lower lip and jaw movements for "sapapple," "sabapple," and "samapple" from a single subject. All movements in the figure were aligned to the same articulatory event: jaw opening peak velocity for the first vowel /ae/ (dotted line). As illustrated by the arrows in Figure 2, the interval between the J opening peak velocity for /ae/ and the time of maximum lip and jaw closing velocity and displacement is shortest when the consonant is /p/. Because the jaw opening peak velocities are aligned in these examples, it can also be seen that the adjustment within the cycle was localized to the interval spanning the terminal phase of the opening action and the time of the peak velocity for the closing action. This interval for all phonetic contexts and subjects for the first movement cycle is presented in Figure 3. Because there were no articulator specific differences, only the LL will be considered.

Within-vowel and consonant comparisons revealed a significantly shorter interval when the consonant was /p/ than /b/ and /m/ in both vowel contexts, and a longer interval when the vowel was /ae/ compared to /i/. These effects were reliable for all subjects except for S1 whose consonant effect did not reach significance. Inspection of the data from S1 indicated that for the first block of 10 repetitions the same trend as seen in the other subjects was present. However, for the subsequent blocks, the overall speech rate was increased resulting in a reduction in the /p/ -/b/ - /m/ interval differences. In contrast to the interval results, the LL closing movement durations were not consistently affected by the consonant or vowel identity. Table 1 presents the average Op₁ Cl₁ interval and movement duration differences for the LL for each subject and the associated F statistic (see Table 1).

Oral Opening-Position/Displacement/Velocity

Since the subjects began each experimental trial with their lips together and teeth lightly touching, the opening position for the first sound (/s/) in the movement sequence could be examined for anticipatory adjustments associated with the different phonetic context (upcoming vowel and/or consonant). The vertical oral opening for /s/ obtained from the lip aperture signal averaged 6.78 mm (S1) to 9.38 mm (S2) across subjects and conditions and was not affected by subsequent phonetic context ($p > .2$). In contrast, the maximum oral opening for the vowel was highly dependent on vowel identity. Figure 4 presents the average oral opening for the group and the individual lip and jaw contributions to the opening for the different vowel-consonant contexts. The oral opening was significantly larger for /ae/ compared to /i/ for all subjects (S1[F(1,238) = 230.81, $p = .0001$]; S2[F(1,238) = 2188.6, $p = .0001$]; S3[F(1,238) = 796.51, $p = .0001$]; S4[F(1,236) = 343.96, $p = .0001$]). Oral opening for /ae/ averaged 15.2, 17.6, 17.9, and 13.3 mm, while oral opening for /i/ averaged 12.2, 9.8, 11.5, and 10.0 mm for S1-4 respectively. As can be seen from the consistent UL plus LL contribution to the oral opening in Figure 4, the jaw is the articulator solely responsible for the oral opening changes. Jaw position was consistently higher for /i/ than /ae/ for all

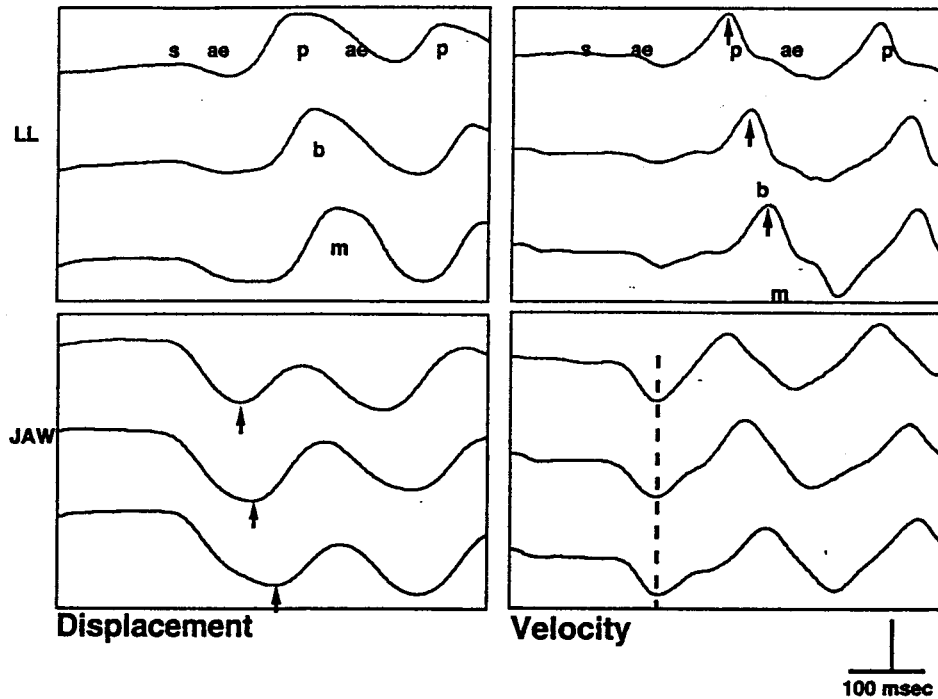


FIGURE 2. Three representative lower lip (LL) and jaw movements (displacement and velocity) from S2 for "sapapple," "sabapple," and "samapple." All signals were aligned to the jaw opening peak velocity (dotted line). Opening is toward the bottom; closing is toward the top. Arrows in jaw opening displacement panel (lower left) indicate the shortening of the jaw opening movement duration for the different consonants. Similarly, the LL closing movement for /p/ achieves both peak velocity (arrows, upper right panel) and peak displacement (upper left panel) earlier for /p/ than /b/ and /m/. Vertical calibration is 6 mm (displacement) and 150 mm/sec (velocity).

subjects ($S1[F(1,238) = 535.41, p = .0001]$; $S2[F(1,238) = 2067.8, p = .0001]$; $S3[F(1,238) = 610.89, p = .0001]$; $S4[F(1,236) = 505.12, p = .0001]$). Collapsed across consonants, jaw opening position averaged 3.4, 7.0, 6.1, and 3.5 mm higher for /i/ than /ae/ (S1–4 respectively). The voicing character of the consonant had no consistent effect on the jaw opening position. No significant vowel or consonant effects were noted for the UL + LL.

In the present phonetic context, it was often not possible to unambiguously identify UL or LL opening movement associated with the vowel from movements associated with /s/. Thus, the opening velocity for the first movement sequence focused exclusively on the jaw. Because of the large vowel-related jaw opening displacement effect, jaw opening characteristics were examined for consonant-related effects only. Figure 5 presents the jaw opening velocity results for the 4 subjects. Post hoc testing revealed significant consonant effects in the /ae/ context only with jaw opening velocity higher before /p/ than /m/ for all subjects ($S1[F(2,117) = 8.11, p < .01]$; $S2 F = 30.97, p < .01]$; $S3 F = 29.88, p < .01]$; $S4[F(2,116) = 9.0, p < .01]$); /p/ - /b/ differences were only significant for S2 ($F = 9.0, p < .01$).

Oral Closing—Displacement

As a consequence of changes in oral opening displacement for the different vowels, oral closing movements were

modified in their extent. As shown in Figure 6 for the group, movement extent for each articulator is greater for the more open vowel /ae/. Presented in Table 2 are the individual subject comparisons for the upper lip, lower lip, and jaw closing displacements. There was a highly significant vowel effect for the J for all subjects with larger closing movement displacements in the /ae/ context compared to /i/. Results for the UL were in general agreement with those of the J but to a lesser degree; S2, S3, and S4 demonstrated significantly larger closing displacements in the /ae/ context compared to /i/. The LL results were less consistent with fewer comparisons reaching significance. No significant UL or LL differences related to vowel identity were noted for S1. Consonant-related movement adjustments were much less consistent for all articulators. The J displacement for /p/ was larger than /m/ for 3 subjects: S1, S3, S4 in the /ae/ context.

Oral Closing—Velocity/Stiffness

Lower lip closing velocity has previously been shown to be higher for /p/ than /b/ (Sussman et al, 1973; Summers, 1987). A similar result for the LL was found in the present investigation although the differences, with few exceptions, were small. Shown in Figure 7 is a summary of the LL closing movement velocities for all subjects for the different phonetic contexts. The closing velocity for /p/ was higher for /b/ for 3 subjects (S2, S3, S4) and higher than /m/ for 2 subjects (S3,

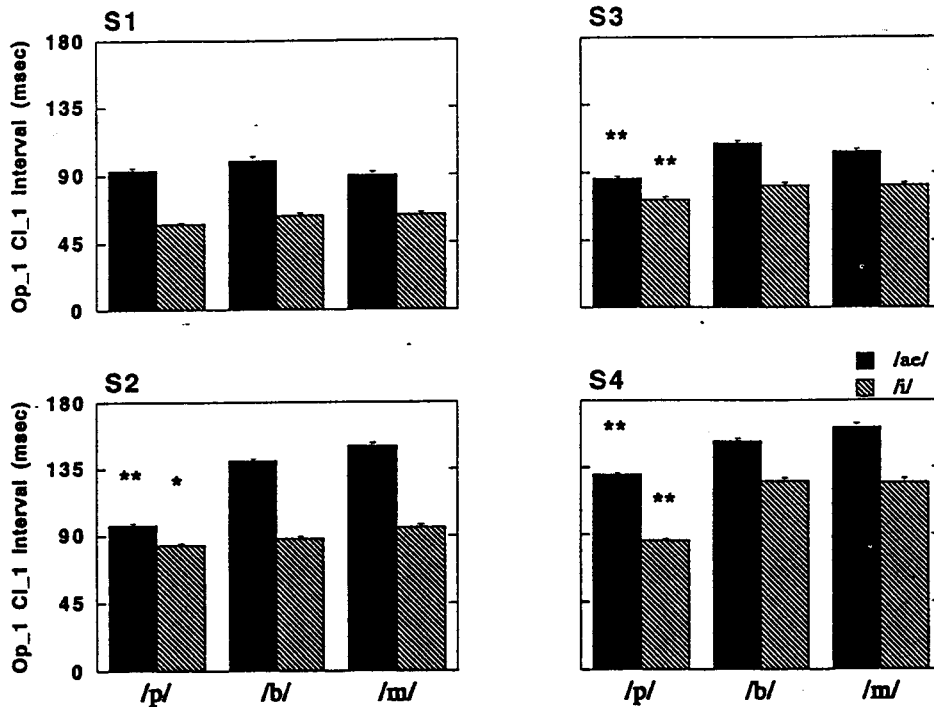


FIGURE 3. Average interval (in milliseconds) between the jaw opening peak velocity for the first vowel (Op₁) and the time of the LL peak velocity for the first oral closing (Cl₁) for the different phonetic contexts for all subjects. Single asterisk reflects a significant /p/ - /b/ or /p/ - /m/ difference; a double asterisk indicates that both comparisons were reliable ($p < .01$).

S4) in the /ae/ context. For S1 the LL closing velocity was significantly reduced for /p/ compared to /m/ in the /ae/ context ($p < .01$). Table 3 is a summary of the post hoc

comparisons for each articulator and subject. As shown, the UL results are generally similar to the LL with S2, S3, and S4 showing small increases in closing velocity for certain com-

TABLE 1. Mean difference (x_d) and associated F-value (Scheffe's F-test) for within-vowel (/aep-aeb/, /aep-aem/, /ɪp-ɪb/, /ɪp-ɪm/) consonant comparisons and across-vowel (/aep-ɪp/, /aeb-ɪb/, /aem-ɪm/) consonant comparisons for the Op₁ Cl₁ interval and lower lip closing movement duration for all subjects. Degrees of freedom for S1-3 (5,234), S4 (5,232); asterisk indicates a significant difference at $p < .01$.

		Op ₁ Cl ₁ Interval						
		/aep-aeb/	/aep-aem/	/ɪp-ɪb/	/ɪp-ɪm/	/aep-ɪp/	/aeb-ɪb/	/aem-ɪm/
S1	x_d	-6.75	3.25	-5.4	-5.75	35.55	36.9	26.55
	F	1.15	.27	.73	.83	31.8*	34.26*	17.73*
S2	x_d	-43.5	-53.55	-4.4	-12.1	13.5	52.6	54.95
	F	75.99*	115.16*	.78	5.88*	7.32*	111.11*	121.26*
S3	x_d	-22.95	-17.5	-10.05	-9.75	14.6	27.5	22.35
	F	18.9*	10.99*	3.62*	3.41*	7.65*	27.14*	17.93*
S4	x_d	-22.1	-31.29	-39.69	-38.99	44.71	27.12	37.01
	F	12.88*	25.81*	42.06*	40.09*	52.71*	19.65*	36.11*
		Movement duration						
		/aep-aeb/	/aep-aem/	/ɪp-ɪb/	/ɪp-ɪm/	/aep-ɪp/	/aeb-ɪb/	/aem-ɪm/
S1	x_d	-5.05	-3.35	.3	-5.1	-2.8	2.55	-4.55
	F	1.93	.85	.01	1.97	.59	.49	1.57
S2	x_d	-19.2	-11.8	-.15	-13.2	-18.25	.8	-19.65
	F	11.74*	4.44*	.00	5.55*	10.61*	.02	12.3*
S3	x_d	-20.2	-22.45	-3.65	-6.35	-13.1	3.45	.3
	F	9.98*	12.32*	.33	.99	4.2*	.29	.22
S4	x_d	-4.66	-5.16	-.94	-15.38	-3.6	.12	-13.81
	F	.51	.63	.02	5.59*	.31	.0003	4.51*

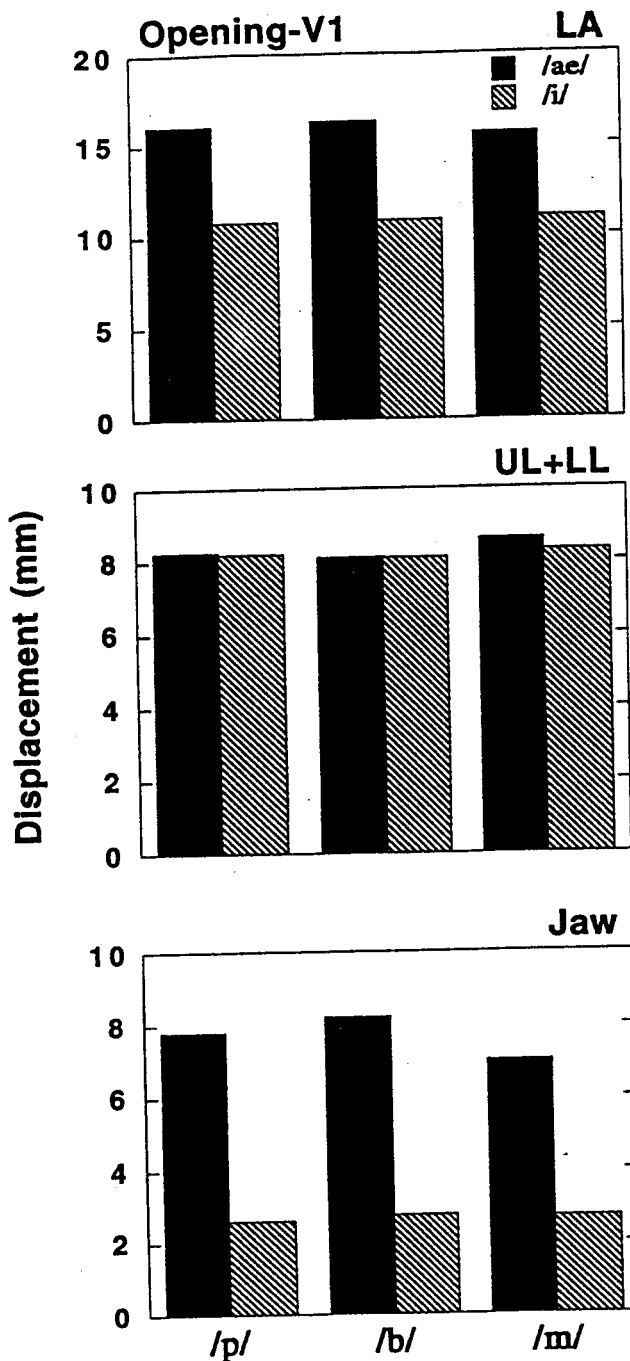


FIGURE 4. Group lip aperture (LA) opening, in millimeters (mm) relative to the rest position, for the first vowel (V1) and consonant contexts. Below the LA data are the contributions of the UL plus LL (UL + LL) and jaw to the oral opening. Vertical bars indicate one standard deviation.

comparisons in the /ae/ context. Only 2 subjects (S3, S4) showed higher J closing velocities for /p/ compared to /b/ or /m/ in the /ae/ context. Jaw closing velocity for all subjects was significantly higher in the /ae/ context. A similar tendency was noted for the UL and LL although the results were not as robust as those for the J.

It appears that the magnitude of the LL closing velocity provides a fairly robust metric differentiating voiceless from voiced consonants. However, it was of interest to determine if a combination of kinematic variables, especially those for the UL and J, might provide a more reliable measure. One construct that has been used to describe speech movements and is suggested as an important control variable for speech is mass-normalized stiffness, expressed as the ratio of peak velocity to peak displacement (Kelso et al., 1985; Ostry & Munhall, 1985). Changes in derived stiffness have been shown to co-occur with changes in movement duration, speaking rate, and emphasis. The correlation of velocity to displacement was generally high for all subjects and articulators with the correlation magnitudes ordering $J > LL > UL$. Velocity/displacement correlations were generally high across subjects for the LL and J ranging from $r = .49$ to $r = .79$ for the LL and from $r = .91$ to $r = .96$ for the jaw; the upper lip was less robust with correlations ranging from $r = .16$ to $r = .86$. Presented in Figure 8 are the UL, LL, and J stiffness values for the different consonants for the group. The LL values are generally higher for /p/, a finding consistent with the peak velocity measures presented in Figure 7. For the UL and J, the ratios of peak velocity to peak displacement suggest that in the /ae/ context, /p/ is less stiff than /m/, a result opposite to that for the LL. Vowel-related differences were also inconsistent across subjects with the exception that J stiffness was always higher for /i/ than /ae/. The data from the individual subjects reflected the group trend and are presented in Table 4.

Opening/Closing Interactions

Inspection of the oral opening and closing movement relations collapsed across consonants revealed some interactions that were not phonetically related but apparently reflect more general characteristics of speech movement organization. As indicated above, the positions of the lips and jaw for the first vowel were not reliably related to phonetic context. However, vowel-related positions of the different articulators did vary and those variations influenced the extent of articulator displacement for the closing movement. Shown in Figure 9 are results from the LL (left side) and J (right side) opening position-closing displacement relations for the individual subjects. As shown, the relative articulatory positions for the vowel produced systematic variations in the magnitude of the oral closing movement. The LL data (left panel) reflect all consonant and vowel combinations; because of the large movement difference for the J, only the data for the /ae/ context are included (right panel). Including /i/ in the /ae/ data created a range effect that artificially inflated the correlation.

As shown in Figure 9, correlation coefficients for the LL range from $r = .37$ to $r = .66$. The J closing displacement was even more strongly related to the preceding J opening position with correlation coefficients ranging from $r = .50$ to $r = .73$; the UL (not shown) was less consistent (correlation coefficients ranging from $r = .05$ to $r = .55$). As indicated, the lower the position of the lips and jaw from the subjects' defined rest position prior to closure, the greater the resulting displacement.

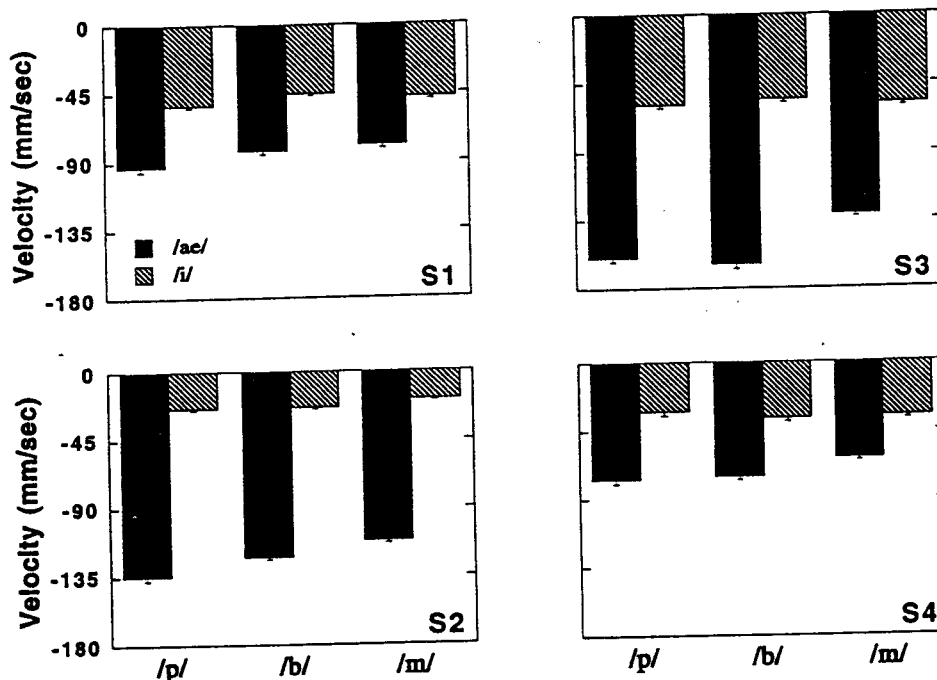


FIGURE 5. Average jaw opening velocity, in millimeters per second (mm/sec), for the different phonetic contexts for each of the 4 subjects. Vertical bars indicate one standard error.

In addition to the apparent dependence of articulator displacement on articulator position, other characteristics of oral opening and oral closing were found to covary. For example, the jaw opening velocity for /ae/ and the subsequent closing velocity for the consonant demonstrated a covariation with correlations ranging from $r = .47$ to $r = .67$ for the 4 subjects (Figure 10). It should also be noted that there was a trend for jaw opening and closing velocity for /p/ and /b/ to be faster than for /m/. It appears that there are systematic spatiotemporal variations in oral opening and closing and such interactions are not necessarily phoneme-specific.

Articulator Interactions

In previous studies it has been suggested that the movement of individual articulators are subordinate to the combined movement of the contributing parts (Hughes & Abbs, 1976; Gracco & Abbs, 1986; Saltzman, 1986). That is, there appears to be a higher level motor plan in which the action of individual articulators is partially dependent on the action of the other articulators contributing to a multiarticulator goal. In the present study, separate stepwise regressions were done on the individual UL, LL, and J displacements for oral closing, using the positions of the three articulators for the preceding vowel as independent variables, to examine for evidence of articulatory interactions. In all cases, the position of a particular articulator for the preceding vowel was found to have the strongest influence on the movement displacement for this articulator. However, in all cases, significant increases in the amount of explained variance were noted when the position of at least one other articulator was included in the regression model. A summary of the regression results is presented in Table 5.

SEQUENCE 2: MOVEMENT CHARACTERISTICS

Cycle Duration

In the present investigation, the stimuli required two complete movement sequences: two opening and two closing. Following the first sequence in which the vowel and consonant varied, the remaining sequence for "apple" was similar in phonetic context: an opening for the vowel /ae/ and a closing for /p/. Thus the data could be examined for carryover effects of the first syllabic context on the second movement sequence. Examination of the duration of the second movement cycle presented in Figure 11 revealed significant differences as a function of the preceding consonant. For subjects S1, S3, and S4, the duration of the second movement sequence, obtained from the lip aperture signal, was longer when the preceding oral closing consonant was /p/ than when it was /b/ or /m/ (S1 [$F = 52.06, p = .0001$]; S3 [$F = 42.23, p = .0001$]; S4 [$F = 49.13, p = .0001$]). There were no consistent vowel related effects for these subjects ($p > .05$). For S2 the duration of the second movement sequence was only longer for /p/ when the preceding vowel was /i/ ($[F(5,234) = 6.92, p < .01]$); a significant vowel effect was noted in the /p/ context ($F = 14.06, p < .01$).

To determine whether the longer cycle duration was localized to a single phase of the movement sequence and a single articulator or distributed across the opening and closing phases and contributing articulators, the movement characteristics of the respective phases for all three articulators were examined. Shown in Figure 12 are the group averaged

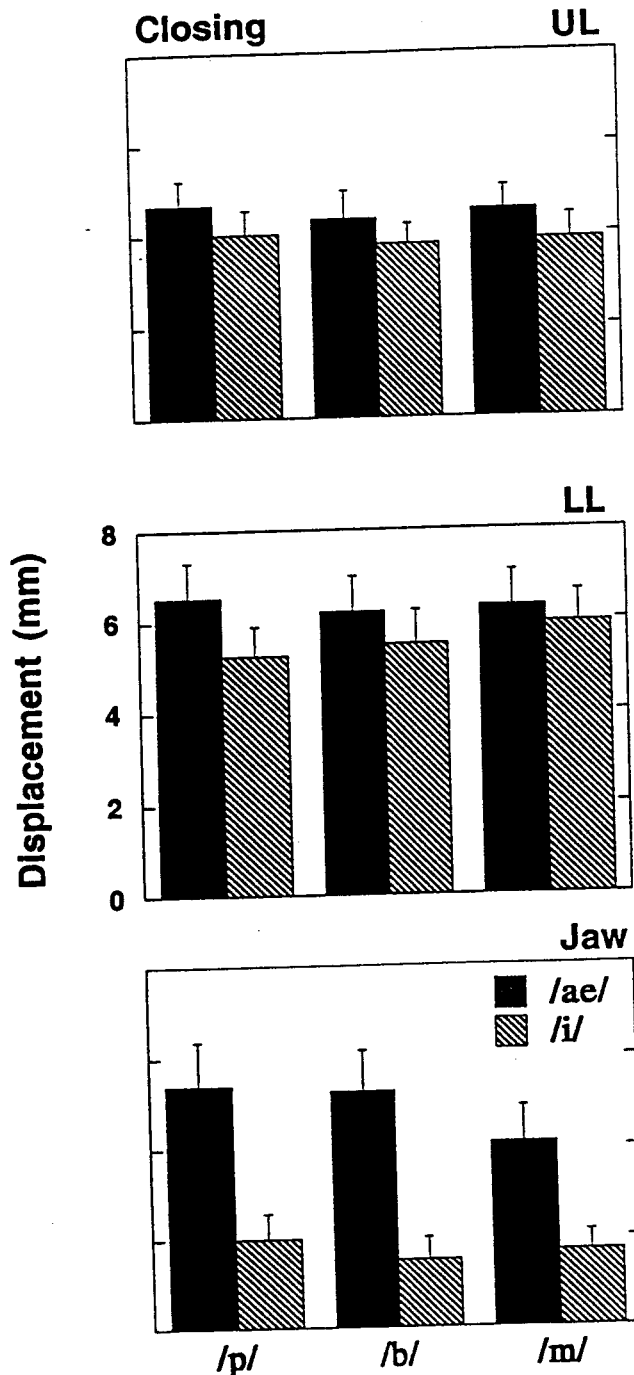


FIGURE 6. Average upper lip (UL), lower lip (LL), and jaw (J) closing displacement (in millimeters) for the phonetic contexts for the group. Vertical bars indicate one standard deviation.

upper lip, lower lip, and jaw opening and closing movement durations for the second movement sequence. As can be seen, the opening movements account for the changes in cycle duration associated with the preceding phonetic context noted in Figure 11. For the group the opening movement duration was longer following /p/ than /b/ or /m/ for the UL ($[F(2,956) = 47.07, p = .0001]$) the LL ($[F(2,956) = 95.9, p = .0001]$) and the J ($[F(2,956) = 31.53, p = .0001]$). There were

no significant closing movement duration changes for any articulator or context ($p > .05$). In addition, vowel-related differences were noted that were obscured by examining the sequence duration from the lip aperture signal. For the UL and LL, the opening movement was shorter for /i/ compared to /ae/ ($[F(1,957) = 212.02, 125.01, p = .0001]$) for the UL and LL respectively). For the J just the opposite was found; jaw opening duration was longer for /i/ compared to /ae/ ($[F(1,957) = 160.45, p = .0001]$). Opposing vowel-related effects for the lips and jaw apparently offset one another in the combined lip aperture signal resulting in no net change to the second movement cycle.

Velocity/Displacement

Other characteristics of the opening phase of the second sequence revealed articulator-specific contextual differences in movement extent and movement velocity consistent with these results. In the opening phase, the most significant effects were vowel-related for the J and consonant-related for the LL. As summarized in Figure 13 for the 4 subjects, the J opening movement for the /ae/ went farther (S1-S3 $[F(1,238) = 179.72, 65.1, 709.07]$ respectively, $p = .0001$); S4 $[F(1,237) = 298.2, p = .0001]$ and faster when following /i/ (S1-S3 $[F(1,238) = 78.06, 12.01, 419.24]$ respectively, $p = .0001$); S4 $[F(1,237) = 306.88, p = .0001]$). The effect for the LL was less robust (displacement; S3 $F = 290.46, p = .0001$; S4 $F = 52.05, p = .0001$; velocity S2 $F = 6.93, p = .009$; S3 $F = 21.7, p = .0001$) and when significant went in the opposite direction to that observed for the J. The greater J opening displacement, duration, and velocity for /ae/ following /i/ appears to be due to the higher jaw position prior to the second opening movement following /i/. The jaw position for /i/ is higher than when the first vowel is /ae/ and, as a consequence, the jaw opening displacement starts from a significantly higher position. The higher J position results in larger opening movement displacements, longer opening movements, and higher opening velocities for the subsequent vowel opening.

In contrast to the vowel-related opening differences, consonant-related differences were noted but only for the LL. The magnitude of the opening velocity following closure was found to order according to consonant identity with /p/ < /b/ < /m/ for all subjects. As can be seen in Figure 14, this result was reliable for all subjects for the LL (S1-S4 $F = 52.95, 237.76, 54.44, 160.85]$ respectively, $p = .0001$). For the J post hoc testing revealed only two significant differences; /b/ - /m/ for S1 ($F = 6.01, p < .01$) and /p/ - /m/ for S2 ($F = 31.52, p < .01$).

LIP-JAW COORDINATION

Oral Closing

Starting from a relatively steady state for the /s/ in the six stimulus words, the upper lip, lower lip, and jaw attained some open posture for the vowel and subsequently closed the oral opening cooperatively. Using the jaw opening peak velocity for the vowel as a reference point (see Figure 2), the

TABLE 2. Mean difference (x_d) and associated F-value (Scheffe's F-test) for within-vowel (/aep-aeb/, /aep-aem/, /ip-ib/, /ip-im/) consonant comparisons and across-vowel (/aep-ip/, /aeb-ib/, /aem-im/) consonant comparisons for the upper lip, lower lip, and jaw closing displacement (mm) for all subjects. Degrees of freedom for S1-3 (5,234), S4 (5,232); asterisk indicates a significant difference at $p < .01$.

Upper Lip							
	/aep-aeb/	/aep-aem/	/ip-ib/	/ip-im/	/aep-ip/	/aeb-ib/	/aem-im/
S1 (x_d)	.75	.56	.2	.26	.4	-.14	.1
F	8.32*	4.61*	.61	.99	2.4	.31	.16
S2	.58	.18	.32	.4	.77	.51	.99
	6.86*	.69	2.06	3.26*	12.2*	5.33*	19.95*
S3	-.55	-.07	-.01	-.07	.51	1.04	.5
	7.26*	.11	.003	.14	6.24*	26.41*	6.09*
S4	.58	-.03	.34	-.06	1.06	.82	1.04
	1.95	.01	.67	.02	6.59*	4.0*	6.3*
Lower Lip							
	/aep-aeb/	/aep-aem/	/ip-ib/	/ip-im/	/aep-ip/	/aeb-ib/	/aem-im/
S1 (x_d)	-.24	-.36	-.03	-.34	.26	.47	.27
F	.66	1.42	.01	1.33	.77	2.49	.84
S2	.06	-.28	-1.17	-1.45	2.0	.77	.82
	.02	.59	10.05*	15.49*	29.17*	4.33*	4.98*
S3	.33	.97	.08	-.21	1.76	1.51	.58
	.7	6.0*	.04	.28	19.81*	14.59*	2.17
S4	1.1	.48	.08	-.75	1.04	.03	-.18
	7.09*	1.34	.04	3.26*	6.4*	.01	.19
Jaw							
	/aep-aeb/	/aep-aem/	/ip-ib/	/ip-im/	/aep-ip/	/aeb-ib/	/aem-im/
S1 (x_d)	.48	.87	.46	.2	2.47	2.44	1.79
F	1.06	3.49*	.96	.18	27.81*	27.31*	14.68*
S2	-.46	.46	.99	.28	3.93	5.38	3.75
	1.25	1.26	5.82*	.47	91.51*	171.59*	83.32*
S3	-.22	1.97	.09	.18	4.58	4.88	2.79
	.38	31*	.06	.26	167.02*	190.02*	61.92*
S4	.77	1.84	.47	.57	2.25	1.95	.98
	11.93*	68.34*	4.61*	6.61*	102.3*	78.32*	19.53*

consistency of the relative timing of the three articulators was examined. Consistent with previous studies the timing of the UL, LL, and J covaries during oral closing (Gracco, 1988; Gracco & Abbs, 1986). The UL-LL relative timing for the 4 subjects is presented in Figure 15 with the corresponding correlations shown at the bottom. Similar results were obtained for the LL-J with all within-vowel correlations ranging from $r = .86$ to $r = .99$.

Oral Opening

In contrast to the UL, LL, and J timing relations for the oral closing, the timing of the three articulators for oral opening was less consistent. Figure 16 presents the UL-LL relative timing for oral opening for the 4 subjects. For these data the UL-LL opening velocity timing is referenced to the time of the preceding UL peak closing velocity. While it appears that the two lips are certainly related in their timing, they do not display the same consistency seen for the oral closing (Figure 15). Similar results were obtained for the LL-J with correlations ranging from $r = .57$ to $r = .80$.

Context Effects

A final issue related to the lip-jaw coordination for oral closing focused on whether the coordinative relations among the articulators are fundamentally the same or different for the different contexts. To examine the articulatory relations in detail, the intervals between the UL-LL and LL-J peak velocities were examined. The interpeak interval is a measure of the absolute time difference between articulator pairs, and the sign of the difference (positive or negative) indicates whether one articulator leads or lags another. Figure 17 presents the averages of the UL-LL (right side) and LL-J (left side) interpeak intervals for oral closing for the 4 subjects. The most significant effects were vowel-related. For the UL-LL, the tendency was for the interpeak interval to decrease in the /i/ context with 4 of the 12 possible within-vowel comparisons (3 comparisons \times 4 subjects) reaching significance (S2 $F = 6.88$ for /b/; S3 $F = 4.25$ for /p/; S4 $F = 5.32$ and $F = 9.91$ for /p/ and /b/ respectively, $p < .01$). The LL-J interval also displayed vowel related effects for all subjects; however, the trend was the opposite of that seen for the

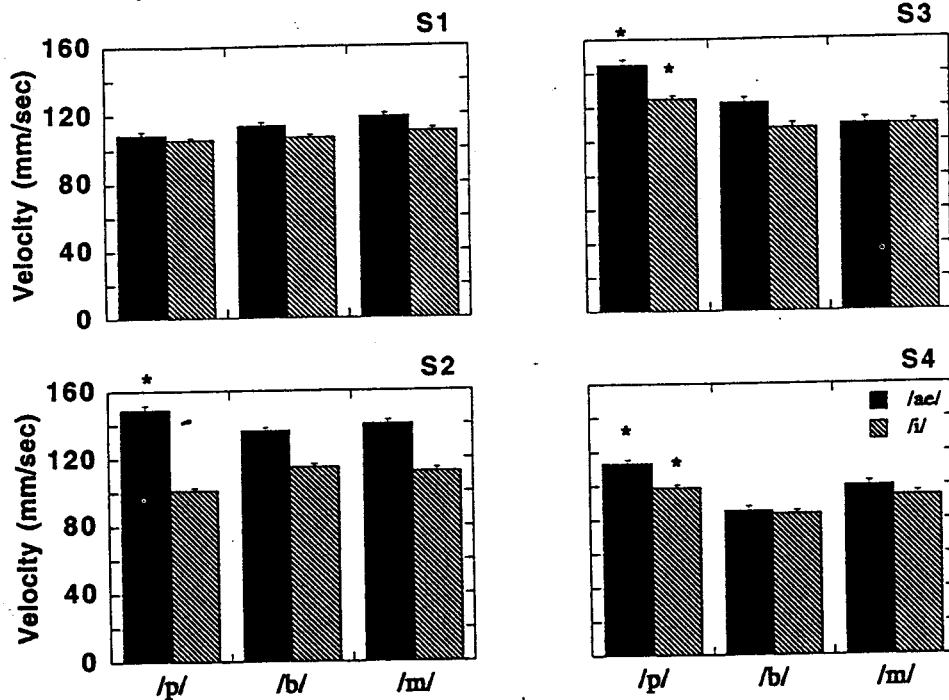


FIGURE 7. Mean lower lip peak closing velocity (in millimeters per second) for the different phonetic contexts for the 4 subjects. Vertical bars indicate one standard error; asterisks indicate significantly higher closing velocity ($p < .01$) for /p/ compared to /b/ and /m/.

UL-LL. Of the 12 possible differences, 5 were found to be reliable (S2 $F = 3.82$ and 3.82 for /b/ and /m/ respectively; S3 $F = 6.12$ for /m/; S4 $F = 20.66$ and 4.52 for /p/ and /m/ respectively, $p < .01$). For the /i/ context, the LL-J interval tended to increase, indicating that the J timing was not being adjusted to the vowel context. Consonant-related effects for the UL-LL were essentially absent with only two /p/ comparisons reaching significance (S3 $F = 8.51$ and S4 $F = 5.5$, $p < .01$). For the LL-J, there was a trend for the interval for /p/ closure to be longer than /b/ and/or /m/ with reliable differences found for 3 subjects (S2 $F = 18.99$ for /p/ - /b/ in the /ae/ context and $F = 45.27$ in the /i/ context; S3 $F = 7.48$ for /p/ - /m/; S4 $F = 14.36$ for /p/ - /b/ in the /ae/ context and $F = 48.29$ for /p/ - /b/ in the /i/ context; $p < .01$). Again it appears that the J timing is less related to the phonetic context than are the lips.

It can also be seen that the sequence of velocity events varied across subjects and articulator pairs. Positive values for the two interpeak intervals indicate that the average sequence of articulator velocity peaks was UL-LL-J. For S2 and S4, negative values were obtained for /b/ and /m/ for the LL-J and UL-LL respectively, indicating that the sequence of events reversed from UL-LL-J to either UL-J-LL or LL-UL-J. In general, the UL-LL timing for the different phonetic contexts suggests that the coordinative relations among these articulators remain similar for different consonants. When the movement characteristics are substantially modified, as occurred for the different vowels, there is a tendency for the relative timing of the articulators to change with differences noted for the lips.

Discussion

The present study investigated characteristics of the lip and jaw movements associated with a class of consonants (bilabials). A number of observations were made that reflect on certain speech movement principles and the manner in which such principles are modulated for phonetic context. The most consistent finding of the present investigation is that the timing or phasing of contiguous movement phases is an important mechanism for modifying speech movements for certain phonetic differences (see also Browman & Goldstein, 1989, 1990; Edwards, Beckman, & Fletcher, 1991; Saltzman & Munhall, 1989). Speech movements appear to be organized and hence controlled at a level in which multiple articulatory actions and contiguous movement phases are the functional units of control and coordination. These conclusions will be discussed below.

Movement Adjustments

The two vowels used in the present study resulted in articulatory changes in position, extent, and speed because of greater movement requirements for the jaw (Lindblom, 1967; Lindblom, Lubker, & Gay, 1979). As such, the size of the oral opening, determined predominantly by jaw position, is a significant factor in determining movement adjustments for different vowel contexts. In contrast, the upper and lower lips were not affected by the identity of the two vowels. Similar findings have been reported by Macchi (1988) in which lip position for /p/ was not affected by the vowel environment while the jaw was, because of tongue height. It

TABLE 3. Mean difference (x_d) and associated F-value (Scheffe's F-test) for within-vowel (/aep-aeb/, /aep-aem/, /ip-ib/, /ip-im/) consonant comparisons and across-vowel (/aep-ip/, /aeb-ib/, /aem-im/) consonant comparisons for the upper lip, lower lip, and jaw closing velocity (mm/sec) for all subjects. Degrees of freedom for S1-3 (5,234), S4 (5,232); asterisk indicates a significant difference at $p < .01$.

Upper Lip							
	/aep-aeb/	/aep-aem/	/ip-ib/	/ip-im/	/aep-ip/	/aeb-ib/	/aem-im/
S1 (x_d)	4.52	-1.16	3.11	3.43	-2.18	-3.59	2.42
F	1.36	.09	.64	.78	.32	.86	.39
S2	2.26	8.6	4.34	-5.64	10.46	8.38	24.7
	.4	5.87*	1.49	2.53	8.68*	5.57*	48.43*
S3	5.96	5.92	-.27	-2.24	.24	6.47	8.4
	4.26*	4.2*	.01	.6	.01	5.02*	8.45*
S4	13.76	2.86	8.47	10.66	9.49	-4.27	17.29
	4.64*	.2	1.78	2.79	2.21	.45	7.34*
Lower Lip							
	/aep-aeb/	/aep-aem/	/ip-ib/	/ip-im/	/aep-ip/	/aeb-ib/	/aem-im/
S1 (x_d)	-4.9	-10.14	-.92	-4.34	2.99	6.97	8.79
F	.79	3.38*	.03	.62	.29	1.6	2.54
S2	12.45	8.62	-13.88	-11.08	47.79	21.46	28.09
	3.43*	1.64	4.26*	2.71	50.49	10.18*	17.45*
S3	22.22	35.05	17.33	15.06	20.26	25.37	.27
	6.26*	15.57*	3.81*	2.87	5.2*	2.99	.0001
S4	23.87	13.6	15.46	4.93	14.5	1.59	5.84
	14.85*	3.41*	4.47*	.45	3.88*	.05	.63
Jaw							
	/aep-aeb/	/aep-aem/	/ip-ib/	/ip-im/	/aep-ip/	/aeb-ib/	/aem-im/
S1 (x_d)	2.53	4.3	6.32	4.52	34.16	37.95	34.37
F	.11	.32	.69	.35	19.99*	24.68*	20.24*
S2	-1.33	10.76	14.1	1.82	68.36	83.81	59.44
	.03	2.26	3.87*	.06	91.11*	136.87*	68.85*
S3	-8.13	32.21	2.11	4.13	80.43	90.67	52.35
	1.43	22.53*	.1	.37	140.5*	178.56*	59.53*
S4	14.62	27.33	6.23	8.93	35.67	27.27	17.26
	18.67*	65.2*	3.43*	6.96*	111.03*	65.75*	26.02*

should be noted that transducing lip motion in only one dimension (inferior-superior) limited any observations of anterior-posterior lip spreading, often assumed to accompany /i/. However, although there may have been some differences in the anterior-posterior dimension, it seems clear that lip motion is not the major factor in differentiating the vowels /ae/ and /i/.

The vowel-related jaw opening movements resulted in systematic and distributed differences in oral closing movement characteristics. As jaw opening was modified for the high or low vowel, the extent and speed of lip and jaw oral closing characteristics were similarly adjusted; vowel-related oral closing movement adjustments were distributed to all the contributing articulators. These vowel-related adjustments suggest that oral opening and oral closing are not independent events. Rather, oral closing actions are dependent on characteristics of the preceding oral opening action. Other evidence for systematic movement relations between oral opening and oral closing can be found in results reported by Folkins and Canty (1986), Folkins and Linville (1983), Hughes and Abbs (1976), and Kozhevnikov and Chistovich (1965).

Some of the opening/closing interactions observed were apparently consonant-related such as higher opening and closing velocities for the voiceless consonant /p/. Jaw opening velocity for /ae/ was faster when the subsequent closing movement was the voiceless /p/ compared to /b/ or /m/ (Summers, 1987). In addition, LL closing velocity was generally higher for /p/ than /b/ or /m/ independent of the preceding vowel, and, LL opening velocity following closure was always lowest for /p/ and highest for /m/. Previous investigations have demonstrated faster lower lip or jaw closing velocity for voiceless compared to voiced consonants (Chen, 1970; Fujimura & Miller, 1979; Sussman et al., 1973; Summers, 1987), and slower lip opening velocity for the voiceless consonant (Sussman et al., 1973). It has been suggested that the higher LL closing velocity is to accommodate the higher intraoral pressures for /p/ compared to /b/ (Chen, 1970; Sussman et al., 1973). That is, higher intraoral air pressure may require greater lip force, manifest as higher lip closing velocity, to maintain lip contact during the closure interval. Although it is generally observed that oral pressure for a voiceless sound is higher than for its voiced counterpart that is higher than its voiced nasal counterpart (Arkebauer,

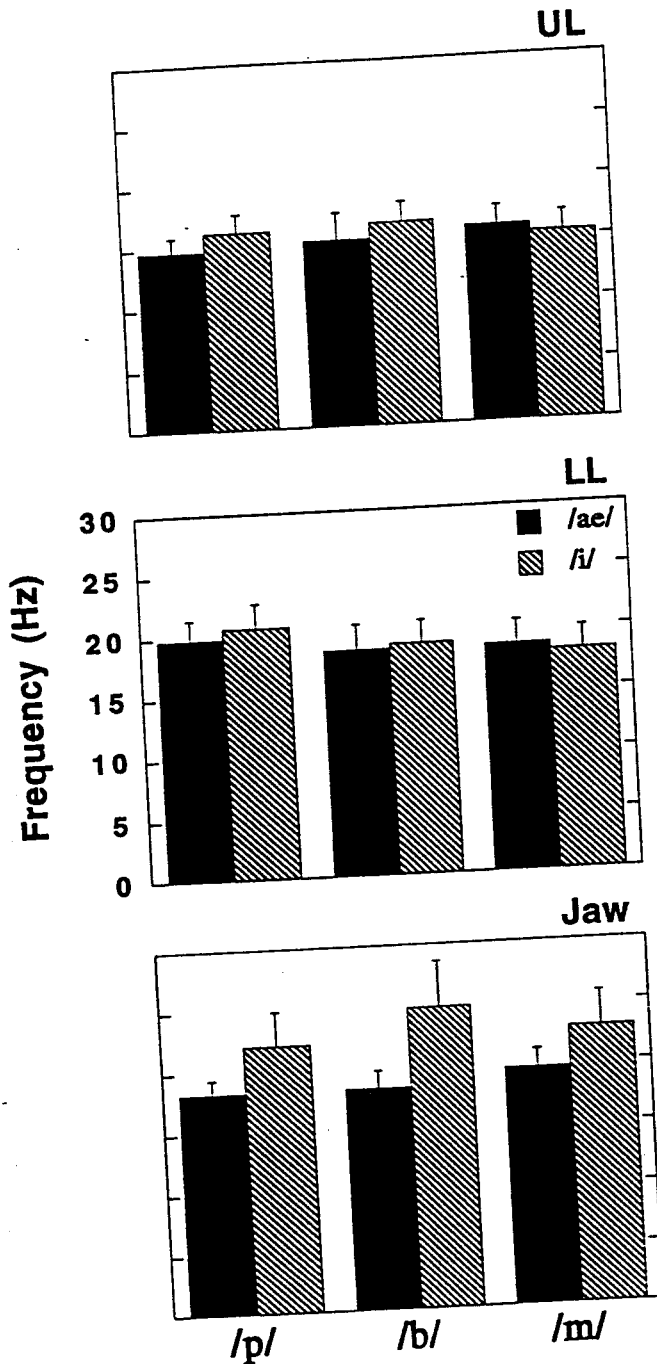


FIGURE 8. Average mass-normalized stiffness for the upper lip (UL), lower lip (LL) and jaw (J) oral closing for the different vowel-consonant combinations for the group. Mass normalized stiffness was derived by dividing the peak velocity, in mm/sec, by the peak closing displacement, in mm, resulting in units of frequency (1/sec). Vertical bars indicate one standard deviation for the group.

Hixon, & Hardy, 1967; Black, 1950), empirical evidence suggests that higher lip closing velocity does not directly translate into greater lip contact force. Using a miniature pressure sensor, Lubker and Paris (1970) were unable to find reliable differences in lip contact pressure for /p/ and /b/. An

additional consideration is the higher lower lip opening velocity for /m/. If oral pressure and lip velocity covary, then the lowest oral pressure sounds, like /m/, should consistently have the lower closing and opening velocity. However, in the same vowel context, lower lip opening velocity following /m/ closure was higher than /p/. It seems premature at best to conclude that lip closing velocity is modulated according to oral pressure characteristics, especially when a direct measure of lip contact does not support such an interpretation.

Similarly, mass-normalized stiffness, defined as the ratio of the peak closing velocity and peak displacement, was not found to consistently differentiate the different vowel and consonant combinations. Although the LL stiffness estimates for the closing movements were found to be consistently higher for /p/ than /b/ or /m/, the upper lip and jaw estimates were not. For the upper lip, estimates of mass-normalized stiffness often varied reciprocally with the LL values whereas the jaw values showed no consistent patterns. It is hard to reconcile a differential modulation of stiffness for three articulators contributing to the same movement or phonetic goal. Although stiffness may be a convenient means of describing the motion or rate of an articulator, it is not clear that it qualifies as a controlled variable. Rather than a single physical control variable, it appears that speech movements are more likely organized according to principles that take into account the function of the action related to the overall goal of communication (Gracco, 1990, 1991).

A potential explanation for voice/voiceless differences can be presented from examining the relative timing of the opening and closing actions. The relative timing or phasing of articulatory motion was found to be a consistent variable differentiating the voiced and voiceless consonants. For the voiceless /p/, the closing action was initiated earlier than for /b/ or /m/ whereas for oral opening, /p/ was initiated later than either /b/ or /m/. These two timing results are consistent with previous acoustic results related to durational differences for voiced and voiceless consonants. In many languages, two related durational phenomena have been reported for voiced and voiceless sounds. Vowel length is shorter and duration of the consonant closure, defined acoustically, is longer for voiceless than for voiced consonants. In the present phonetic context, the interval between jaw opening velocity for /ae/ and oral closing velocity is essentially identical to the duration of the vowel (McClellan, Kroll, & Loftus, 1990). As such, the earlier onset of the closing action for the /p/ is a kinematic manifestation of the differential vowel length effect (Denes, 1955; House & Fairbanks, 1953). Similarly, the longer opening movement duration following /p/ closure is consistent with longer acoustic closure duration reported for voiceless sounds. It seems, from the acoustic durational effects reported previously and the kinematic effects reported here and elsewhere, that voiced and voiceless consonants differ primarily in their timing with other kinematic variations, such as velocity differences, secondary or consequential. The movement velocity changes may be considered a natural consequence of the timing requirements for the different consonants.

However, an explanation of articulatory timing as a means to differentiate sounds within a class leaves open the question as to why articulatory timing differs. Recently it has been

TABLE 4. Derived stiffness values, defined as the ratio of peak velocity to peak displacement for the first oral closing movement for the upper lip (UL), lower lip (LL), and jaw (J) for the 4 subjects. Results are presented according to vowel and consonant context for the first movement sequence. A single asterisk indicates a significant /p/ /b/ or /m/ difference at $p < .01$; double asterisks indicate that /p/ was significantly different than both /b/ and /m/. All comparisons were within vowel.

	/aep/	/aeb/	/aem/	/lp/	/lb/	/lm/
Subject 1						
UL	13.4 (.24)**	14.8 (.25)	15.5 (.25)	15.1 (.16)	15.1 (.20)	15.2 (.18)
LL	18.2 (.28)	18.3 (.22)	18.7 (.19)	18.5 (.20)	18.6 (.22)	18.1 (.22)
J	17.7 (.20)*	19.0 (.28)	20.2 (.26)	20.8 (.28)	22.2 (.34)	20.7 (.36)
Subject 2						
UL	12.7 (.20)**	15.1 (.32)	15.0 (.17)	12.6 (.27)*	14.7 (.21)	12.4 (.18)
LL	21.0 (.27)*	19.4 (.34)	19.0 (.24)	19.8 (.22)**	18.3 (.21)	17.1 (.25)
J	18.9 (.19)	17.7 (.15)	18.4 (.17)	21.8 (.42)**	29.4 (.79)	24.2 (.46)
Subject 3						
UL	17.0 (.32)	16.6 (.63)	18.7 (.37)	20.4 (.31)	20.3 (.36)	19.0 (.45)
LL	20.1 (.21)**	17.9 (.28)	17.6 (.42)	23.2 (.49)**	20.3 (.42)	19.5 (.42)
J	19.6 (.14)	20.3 (.20)	21.3 (.24)	28.0 (.85)	27.8 (.82)	27.1 (.63)
Subject 4						
UL	15.6 (.22)	14.6 (.24)	14.9 (.21)	16.9 (.24)*	16.3 (.27)	14.7 (.25)
LL	20.0 (.28)	18.7 (.48)	19.2 (.35)	21.5 (.34)*	18.4 (.34)	17.5 (.30)
J	16.8 (.20)	16.2 (.27)	18.3 (.26)	17.8 (.23)*	19.9 (.43)	19.2 (.40)

suggested that /p/ - /b/ differences in vowel duration reflect a perceptually salient feature of speech production that enhances the acoustic differences between voiced and voiceless consonant sounds (Kluender, Diehl, & Wright, 1988). That is, voiced and voiceless consonants differ in their timing because of the perceptual enhancement the durational differences provide to the listener. A recent investigation by Fowler (1992), however, suggests that there is no auditory-perceptual enhancement to be obtained from the shorter vowel durations and longer consonant closure durations for /p/ versus /b/. A simpler and less speculative explanation is that timing differences among the bilabial consonants reflect modifications to accommodate concomitant articulatory actions. In the case of /p/, the longer closure duration compared to /b/ is to accommodate the laryngeal adjustment associated with devoicing. As such, from a functional perspective /p/ is an inherently longer sound than /b/. The shortening of the vowel reflects an intrusion of the phonetic gesture for /p/, including the laryngeal devoicing, on the vowel. The closing must be faster to integrate the lip and the larynx actions whereas the opening is slower to provide the appropriate voice onset time. It is suggested that all voiced and voiceless sound pairs (cognates) are fundamentally differentiated by their relative timing or phasing, which is a direct consequence of the supralaryngeal-laryngeal interaction and consistent with aerodynamic requirements (Harris et al., 1965; Lisker & Abramson, 1964; Lubker & Parris, 1970).

Speech Movement Coordination

Another robust finding of the present investigation was the consistency of the upper lip-lower lip timing relations associated with the different bilabial consonants. For all subjects, the temporal relations of the velocity peaks for the upper and lower lips were essentially constant across

phonetic contexts, indicating a constraint on their coordination. Although the UL-LL timing was relatively consistent, the sequence of events (UL-LL-J) did not remain constant as had been observed in more limited phonetic contexts (Caruso et al., 1988; Gracco, 1988; Gracco & Abbs, 1986; McClean et al., 1990). However, based on a number of investigations that have reported different sequences, it is not clear that the actual pattern or sequence of articulatory events is of importance (DeNil & Abbs, 1991). Rather, it is the general trend for covariation that is indicative of an underlying invariant control parameter (Gracco, 1990, 1991). That is, while the sequence of events may change with rate, stress, or phonetic context, such variation does not indicate a lack of invariance as suggested recently by DeNil and Abbs (1991). As pointed out by von Neumann (1958), the nervous system is not a digital device in which extremely precise manipulations are possible but an analog device in which precision is subordinate to reliability. Establishing the presence of invariance on fixed stereotypic patterns, similar to those observed in a mechanical system, is inconsistent with principles of biological systems. Rather, constraints on coordination are most likely specified stochastically with specific limits on variation contingent on the overall goal of the action (see also Lindblom, 1987, for arguments for the adaptive nature of variability). As suggested by the quantal nature of speech (Stevens, 1972, 1989), there are vocal tract actions that may require relatively more precise control than others because of the potential acoustic consequences. However, it is doubtful that the timing of bilabial closure is a context in which absolute precision is required (see also Weismer, 1991).

More importantly, in the present study as in previous investigations of speech movement timing, the consistent relative timing relations among the UL-LL-J indicate that the timing of these articulators is not controlled independently. Rather, timing adjustments covary across functionally re-

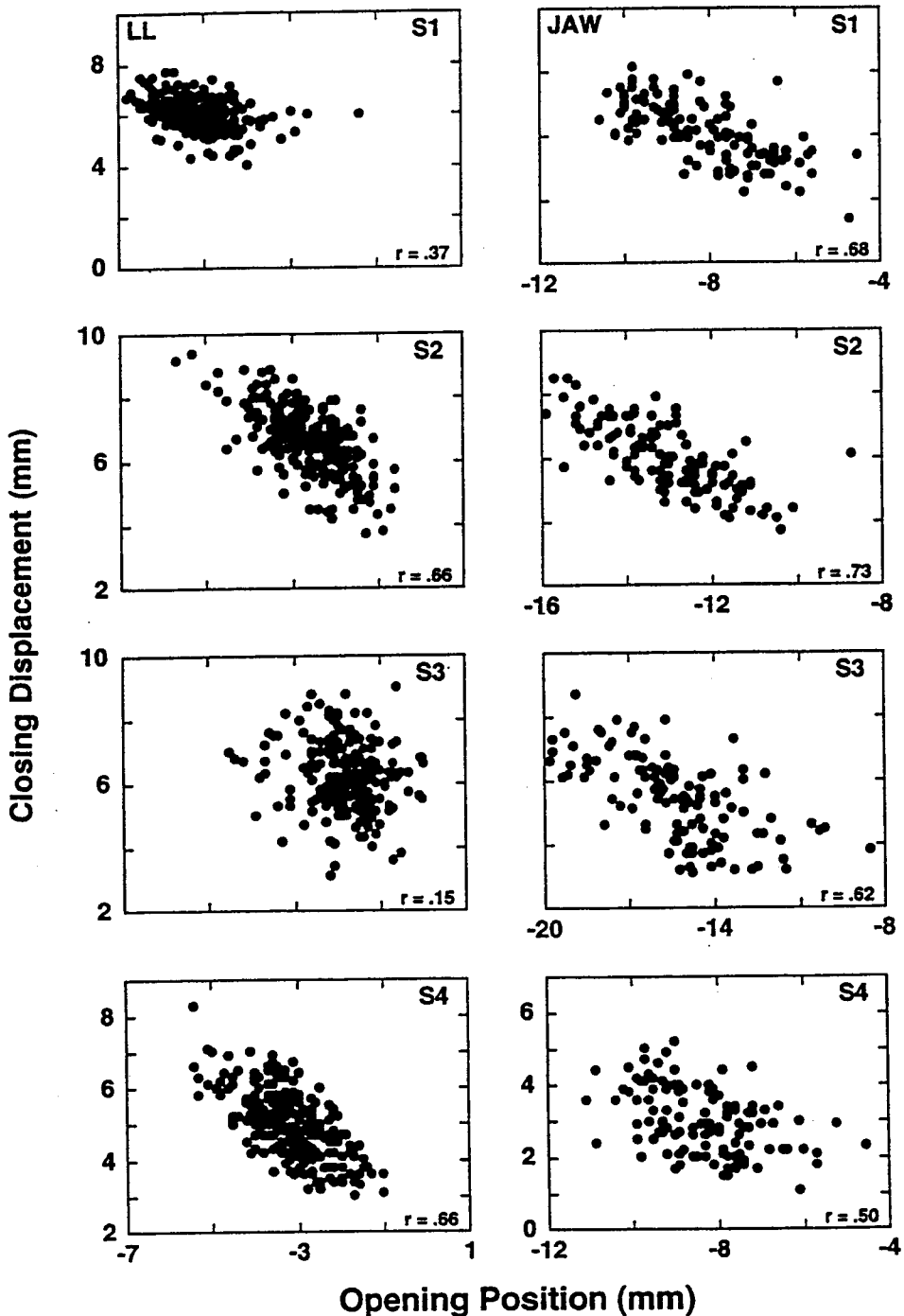


FIGURE 9. Scatter plots of the lower lip (LL, left side) and jaw (Jaw, right side) closing displacements as a function of the relative positions of the respective articulators for the preceding vowel. Product-moment correlation coefficients (r) are presented at the bottom right corner of each plot. Only the jaw opening positions/jaw closing displacements are presented for /ae/ (see text for explanation).

lated actions and contributing articulators are effectively constrained to minimize the degrees of freedom to control (Gracco, 1988). While performance variables such as phonetic context, speaking rate, and the production of emphasis will change the surface kinematics, the underlying

principles governing their coordination remain unchanged. Moreover, the articulator interactions such as the lip adjustments to changes in jaw position and the opening and closing velocity covariation are additional manifestations of the interdependency of speech movement coordination.

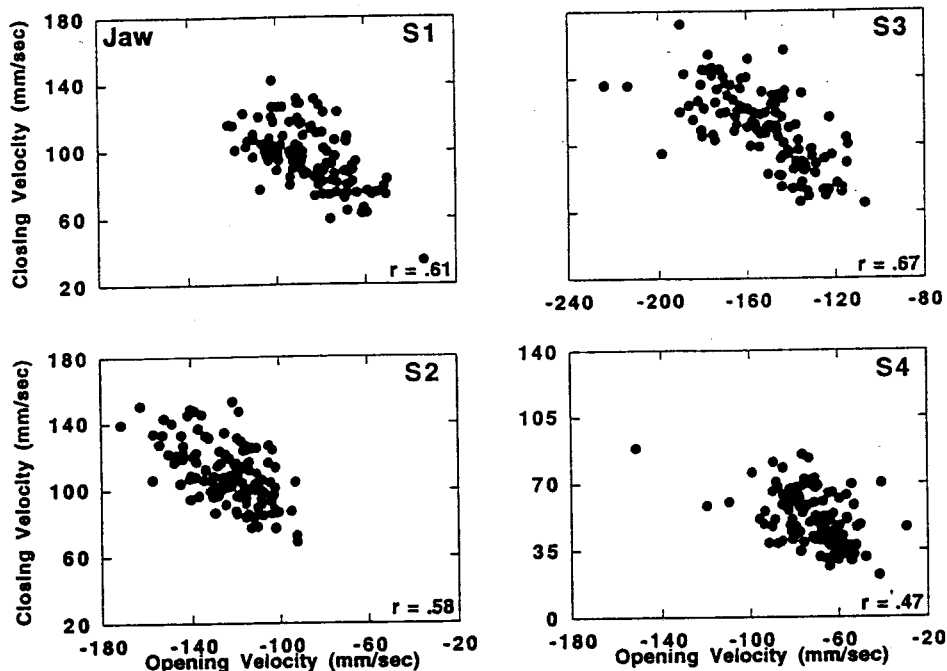


FIGURE 10. Jaw opening peak velocity for /ae/ and the corresponding jaw closing peak velocity for the three consonants. Product-moment correlation coefficients (r) are presented at the bottom right corner of each plot. As shown, as the jaw opens faster there is a tendency for the jaw to close faster as well.

Opening/Closing Differences

The present results also suggest that opening and closing movements are fundamentally different actions operating under different constraints (Gracco, 1988). Oral opening was found to be the locus of the most significant consonant- and vowel-related articulatory adjustments. Oral closing adjustments, on the other hand, varied primarily as a function of oral opening. Only the LL peak closing velocity for the different consonants demonstrated any consistent change across subjects. In con-

trast to the tightly coupled lip and jaw timing during closing, oral opening coordination was found to be more variable. The different spatiotemporal patterns observed suggest that opening and closing phases of sequential speech motor actions are differentially modifiable for context. Oral closing is generally faster, involving relatively abrupt constrictions or occlusions in various portions of the vocal tract. Oral opening is generally slower, involving resonance-producing events associated with vowel sounds. Hence these two classes of movements reflect fundamentally different speech actions with distinct functional

TABLE 5. Stepwise regression of the upper lip (ul), lower lip (ll), and jaw (j) oral closing displacement (disp) for the first opening/closing sequence. The displacement of each individual articulator was regressed on the relative position of each of the three articulators for the preceding vowel.

Subject	Displacement	R	adj. R-squared
Upper Lip			
S1	UL disp = $3.45 + .56(\text{ul}) + .15(\text{j}) + .27(\text{ll})$	.66	.42
S2	UL disp = $3.06 + .38(\text{ul}) + .08(\text{j})$	.37	.12
S3	UL disp = $1.45 + .64(\text{ul}) + .13(\text{j}) + .09(\text{ll})$	.67	.43
S4	UL disp = $2.02 + .84(\text{ul}) + .21(\text{j}) + .2(\text{ll})$	.67	.44
Lower Lip			
S1	LL disp = $2.63 + .37(\text{ll}) + .26(\text{j}) + .26(\text{ul})$	.67	.44
S2	LL disp = $2.66 + .71(\text{ll}) + .18(\text{j})$	.72	.50
S3	LL disp = $3.99 + .32(\text{ll}) + .14(\text{j})$	.36	.11
S4	LL disp = $.1 + .6(\text{ll}) + .28(\text{j}) + .46(\text{ul})$	.78	.60
Jaw			
S1	J disp = $.85 + .58(\text{j}) + .66(\text{ul})$	.74	.53
S2	J disp = $3.1 + .61(\text{j}) + .32(\text{ul}) + .22(\text{ll})$	.76	.57
S3	J disp = $.07 + .37(\text{j}) - .49(\text{ul})$	.64	.40
S4	J disp = $.01 + .48(\text{j})$	.50	.24

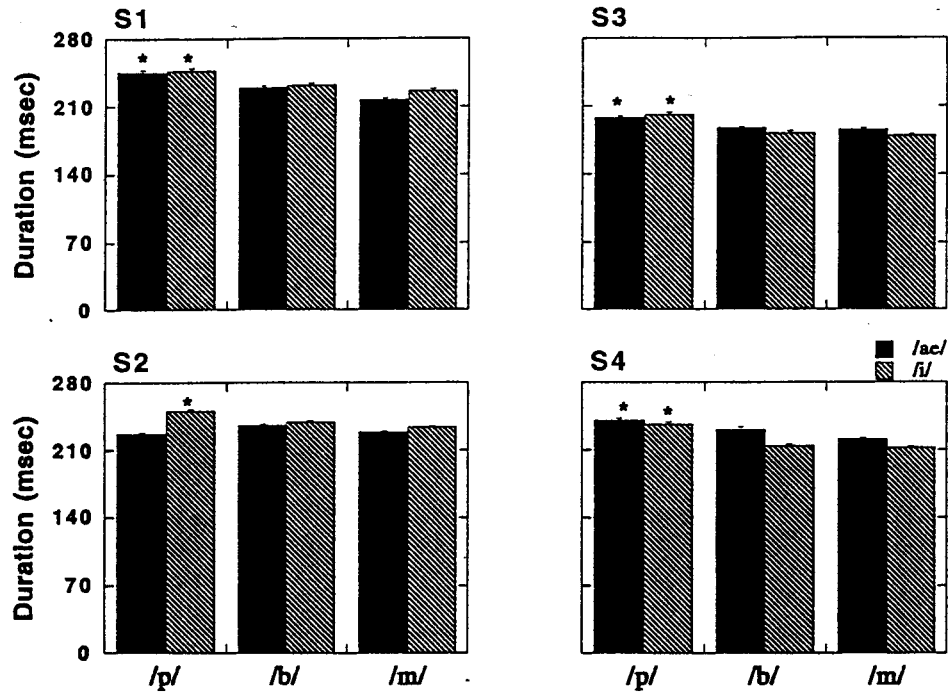


FIGURE 11. Duration (In milliseconds) of the second movement cycle (S-2) for the oral opening for /ae/ and subsequent closing for /p/ following the different vowel-consonant combinations in the first cycle (S-1) for each of the 4 subjects. Vertical bars indicate one standard error; asterisks indicate significant /p/ - /b/ or /m/ difference ($p < .01$).

(aerodynamic and acoustic) consequences (see also Fowler, 1983; Perkell, 1969).

Why this might be so may, in part, reflect the different biomechanical influences on the closing and opening actions. Oral opening involves temporarily moving the lips and jaw from some rest or neutral position to a position that requires stretching the associated tissues (skin, muscle, ligament). For closing, the lip and jaw motion is assisted by the elastic recoil from the opening stretch. A consequence of the different biomechanical influences on opening and closing would be that opening movements could be controlled directly by agonistic muscle actions. That is, changes in lip and jaw opening may result from direct modification of jaw and lip opening muscle activity. In contrast, to counteract the elastic recoil of the lip and jaw tissue, oral closing adjustments would require some combination of reduction in agonistic activation and/or agonist-antagonist co-contraction. It is suggested that the opening action would be an easier task to control than the closing action and that the biomechanical influences would differentially affect the two actions. The closing action would be more rapid due to the contribution of tissue elasticity and less variable. Such influences are possible factors affecting the patterns observed in the present investigation reflecting biomechanical optimizations and may account for certain aspects of the ontogeny of the phonological system.

Articulator Differences—Consonants and Vowels

In addition to the different functions of the opening and closing actions, it can also be suggested that the lips and jaw

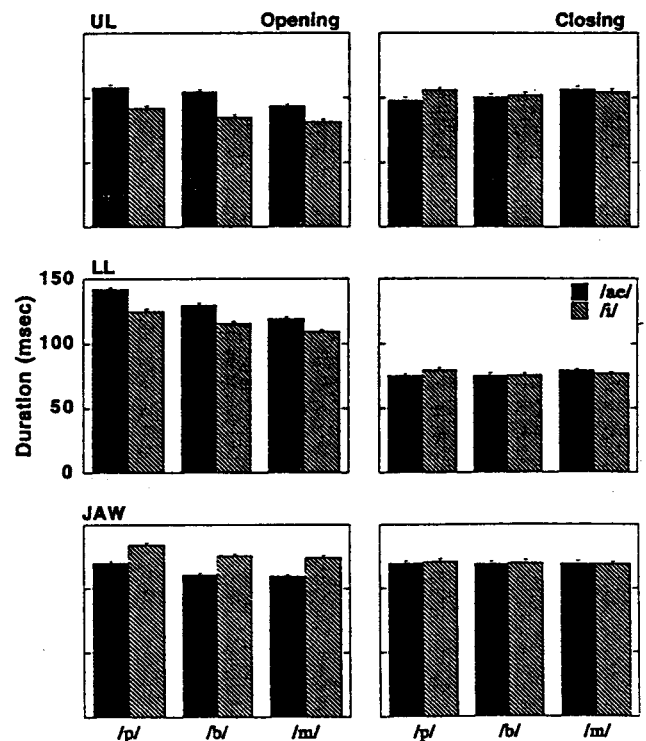


FIGURE 12. Group means of the duration of opening (Op₂) and closing (Cl₂) movements for the second sequence for the upper lip (UL), lower lip (LL), and jaw. The opening movement durations for the UL and LL were reliably longer for /p/ compared to /b/ and /m/. Vertical bars indicate one standard error.

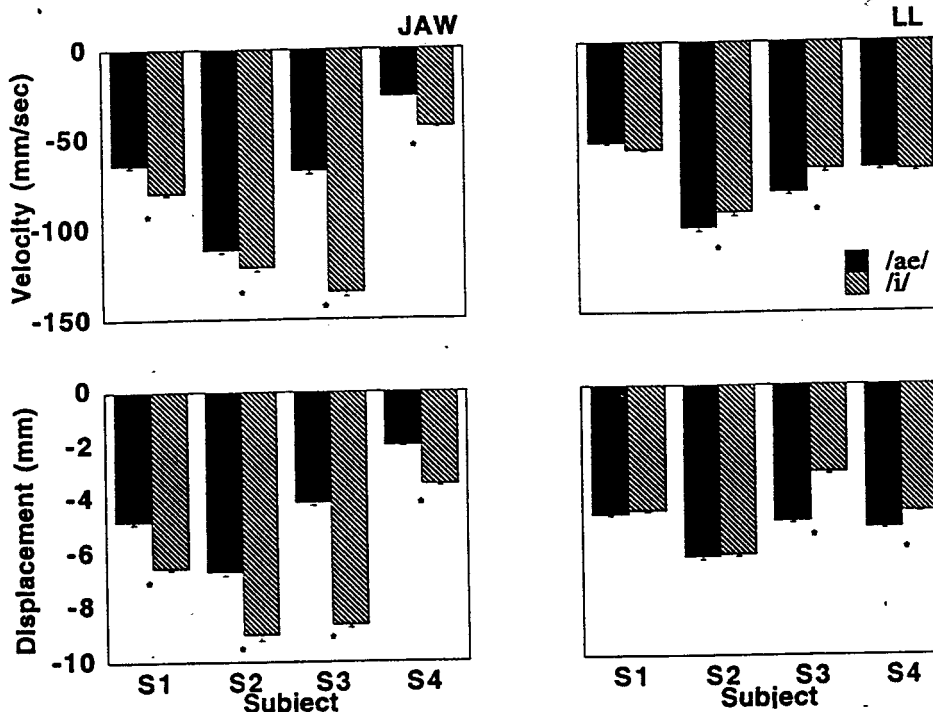


FIGURE 13. Peak opening velocity and displacement for jaw (Jaw) and lower lip (LL) for the second movement sequence for the 4 subjects. Vertical bars indicate one standard error; asterisks indicate significant vowel differences ($p < .01$). As shown, the jaw opening is faster and farther when the preceding vowel is /i/ compared to /ae/. The same trend is not seen in the lower lip.

contribute to sound production in different ways. Examination of the lip and jaw movement characteristics suggest that although all three articulators contribute to the general opening and closing, their roles are not identical. The lower lip closing and opening velocity varied as a function of the different consonant sounds. The upper lip, in contrast, did not. In addition, the lower lip and jaw closing displacements were significantly and systematically related to the opening position for the preceding vowel; the upper lip closing movement displacement was only weakly related. It is plausible that the upper lip contributes in a more stereotypic manner to consonant actions whereas the lower lip and jaw provide

more of the details related to phonetic manipulations. Each lip contributes in an interdependent but not redundant manner to the achievement of oral closing.

From the lip and jaw differences noted in the present investigation it can be suggested that consonant and vowel adjustments are articulator-specific. The jaw, while assisting in the oral closing, was more significantly involved in the production of the vowels than was either of the lips. This was noted not only for the first syllable in which the vowel varied between a phonetically high /i/ and low /ae/, but in the second syllable in which jaw motion for the same syllable varied dependent on the identity of the preceding vowel. The same

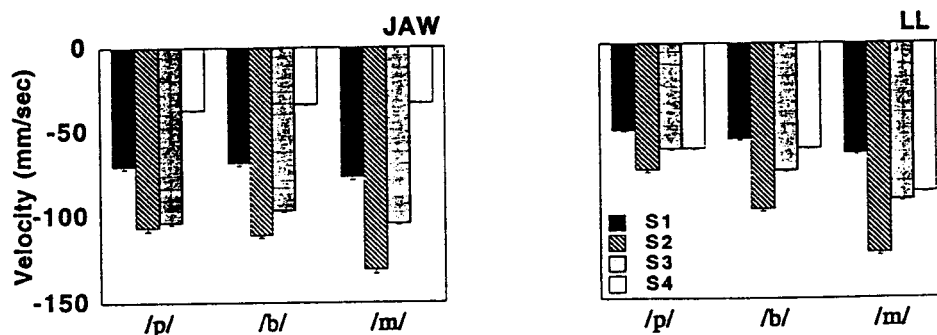


FIGURE 14. Jaw and lower lip opening velocity for the second movement sequence as a function of preceding consonant identity for the 4 subjects. For all subjects, the LL opening velocity was highest for /m/ compared to /p/ or /b/; the same trend was not found for the Jaw. Vertical bars indicate one standard error.

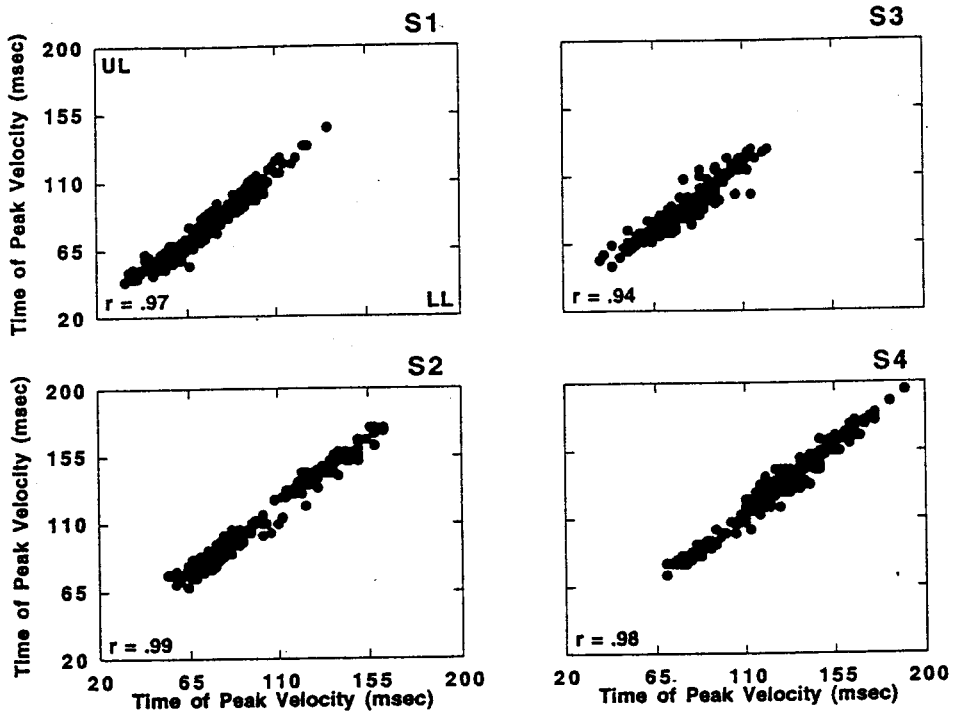


FIGURE 15. Scatter plots of the relative timing of the upper lip (UL) and lower lip (LL) peak closing velocity (Cl₁) for the different vowel-consonant contexts for the 4 subjects. Time of peak velocity was referenced to the time of the jaw opening peak velocity for the first vowel (Op₁). Product-moment correlation coefficients (*r*) are presented at the bottom right corner of each plot.

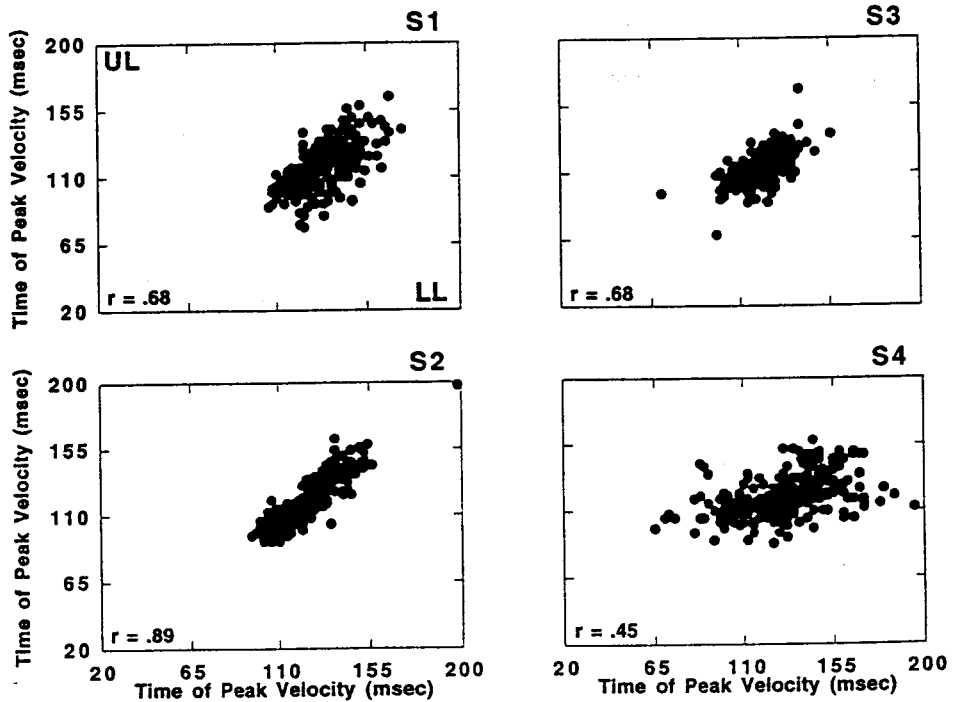


FIGURE 16. Scatter plots of the relative timing of the upper lip (UL) and lower lip (LL) peak velocity for the second oral opening (Op₂) for the 4 subjects. Time of peak velocity was referenced to the time of the upper lip peak velocity for the oral closing (Cl₁). Product-moment correlation coefficients (*r*) are presented at the bottom right corner of each plot.

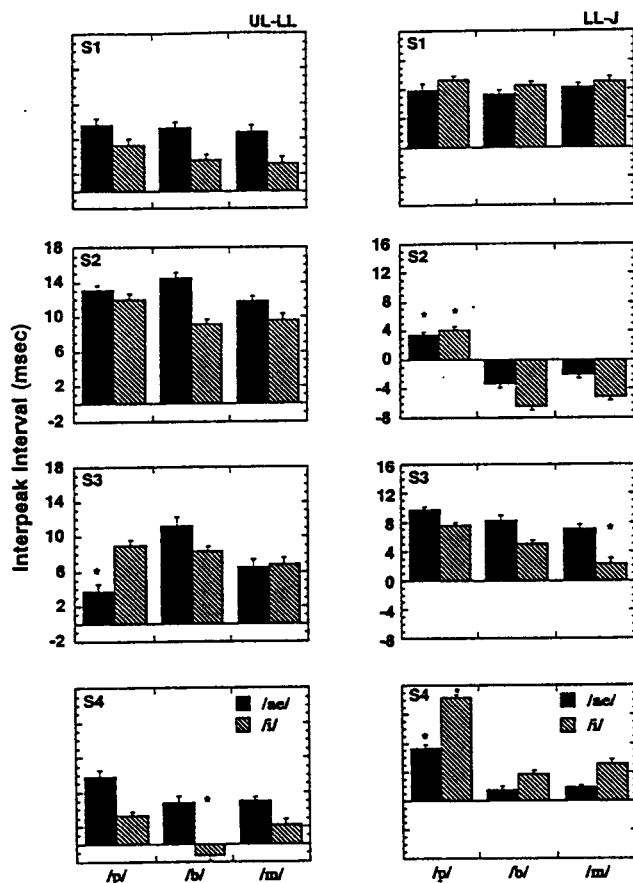


FIGURE 17. Upper lip-lower lip (UL-LL, left side) and lower lip-jaw (LL-J, right side) closing (C1) velocity interpeak intervals for the 4 subjects. The interpeak interval was defined as the time, in milliseconds, between the occurrence of the peak velocities for the different articulator pairs. A single asterisk centered over either /p/ bar indicates a single significant within-vowel consonant comparison; a double asterisk indicates that both comparisons (/p/ - /b/ and /p/ - /m/) reached significance ($p < .01$). An asterisk centered over any consonant pair indicates a significant within-consonant vowel comparison ($p < .01$).

pattern was not observed for the LL motion. In contrast, consonant-dependent opening movement differences were noted for the LL but were not found for the J. These results suggest that boundaries between phonetic segments and/or phonemic classes such as consonants and vowels may be identified by differential articulatory actions that overlap in time. The speech mechanism can be thought of as a special-purpose device in which individual components contribute in unique and complementary ways to the overall aerodynamic/acoustic events.

Speech Motor Programming/Serial Timing

Based on the opening/closing interactions outlined above, it is not unreasonable to suggest that speech movements are organized minimally across movement phases with movement extent and speed specified for units larger than individual opening and closing actions. The size of the organiza-

tional unit is at least on the order of a syllable and perhaps larger encompassing something on the order of a stress group (Fowler, 1983; Sternberg et al., 1988). It can further be suggested that modulation of the relative timing of movement phases is an organizational principle used to differentiate many sounds of the language. As such, serial timing and the associated mechanism is an important concept in speech production but one that has not received much empirical attention. It has been suggested previously that the serial order for speech is a consequence of an underlying rhythm-generating mechanism (Kozhevnikov & Chistovich, 1965; Lashley, 1951; Kelso & Tuller, 1984; Gracco, 1988, 1990). For Lashley (1951), the simplest of timing mechanisms are those that control rhythmic activity, and he drew parallels between the rhythmic movements of respiration, fish swimming, musical rhythms, and speech (see also Stetson, 1951). For speech, however, the mechanism cannot be simple or stereotypic since, as shown in this investigation, the different sounds in the language have different temporal requirements. Moreover, such a rhythmic mechanism most likely reflects a network property (Martin, 1972) as opposed to a property of a localized group of neurons, since dysprosody results from damage to many different regions of the nervous system (e.g., Kent & Rosenbeck, 1982). More likely, any centrally generated rhythmic mechanism for speech and any other flexible behavior must be modifiable by internal and external inputs (cf. Getting, 1989; Glass & Mackey, 1988; Harris-Warrick, 1988; Rossignol, Lund, & Drew, 1988).

Recent investigations on the discrete effects of mechanical perturbation on sequential speech movements are beginning to identify aspects of the underlying serial timing mechanism. Mechanical perturbations to the lower lip during sequential movement result in an increase or decrease in the movement cycle frequency depending on the phase of the movement the load is applied. (Gracco & Abbs, 1988, 1989; Saltzman, Kay, Rubin, & K-Shaw, 1991). One interpretation of these results is that a rhythmic mechanism is the foundation for the serial timing of speech movements and that this mechanism is modifiable, not stereotypic (Gracco, 1990, 1991). The present results demonstrating changes in opening and closing phasing with phonetic context reflect another aspect of the serial timing for speech. The consonants acted to differentially modify the ongoing speech rhythm. As such, consonants can be considered to act as perturbations on an underlying vowel-dependent rhythm. Consistent with this speculation is evidence from two apparently contradictory results obtained by Ohala (1975) and Kelso et al. (1985). Searching for the underlying preferred speech movement frequency, Ohala (1975) was unable to find an isochronous frequency associated with jaw movements during oral reading. In contrast, Kelso et al., (1985) provided evidence suggesting that jaw movements during reiterant speaking were produced with very little variation around a characteristic frequency. The difference in these two investigations is in the phonetic content used by the different investigators. The reiterant speech contained the syllable "ba" produced with different stress levels, whereas Ohala used unconstrained oral reading passages. Sounds of the language may have an inherent frequency (intrinsic timing; Fowler, 1980) which interacts with a central rhythm resulting in a modal

frequency with significant dispersion. Similarly, the degree to which a characteristic rhythm or frequency is modulated during speaking is no doubt a result of an interaction of a number of functional considerations such as the articulatory adjustments for the specific phoneme and other suprasegmental considerations such as stress and rate (Gracco, 1990, 1991). While speculative, further investigations of the serial timing characteristics or rhythm generation for speech (Gracco & Abbs, 1989; Saltzman et al., 1991) combined with computational models to evaluate the potential oscillatory network or serial dynamics (Laboissiere et al., 1991; Saltzman & Munhall, 1989) associated with the temporal patterning for speech are important areas of future research.

Speech Production: A Functional Neuromotor Perspective

The observations above suggest that the neuromotor representation for speech is more complicated than can be captured by a single control variable or sensorimotor mechanism. Rather, speech production is organized according to principles that incorporate the sequential nature of the process, the functional character of the production units, and the articulatory details that shape the acoustic output. It appears that speech motor control is organized at a functional level according to sound-producing vocal tract actions (Gracco, 1990, 1991; Kent, Carney, & Severeid, 1974). These functional groupings are stored in memory and map categorically onto the sounds of the language. The apparent constraint on coordinating functionally related articulators observed in this and other investigations (Gracco, 1988, 1990; Gracco & Löfqvist, 1989; in preparation) suggests that the temporal patterning among articulators is a component of the neuromotor representation. Observable speech movements (or vocal tract area functions) reflect a combination of stored representations with flexible sensorimotor processes interacting to form complex vocal tract patterns from relative simple operations (Gracco & Abbs, 1987; Gracco, 1990, 1991). Stored neuromotor representations and sensorimotor interactions simplify the overall motor control process by minimizing much of the computational load. Important areas of future research are to determine the precise role and contribution of biomechanical properties to the observable patterns, to evaluate the relative strength of articulator interactions, and to identify how articulator movements are modified by linguistic and cognitive considerations. The major contributions to understanding speech motor control and underlying nervous system organization will come from a better understanding of the neural, physical, and cognitive factors that govern this uniquely human behavior.

Acknowledgments

This research was supported by grants DC-00121 and DC-00594 from the National Institute on Deafness and Other Communication Disorders. The author thanks Carol Fowler, Anders Löfqvist, Ignatius Mattingly, and Rudolph Sock for comments on earlier versions of this manuscript. The author also thanks John Folkins for a thorough and constructively critical review of this manuscript.

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Received September 15, 1992

Accepted August 5, 1993

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