478

Journal of Experimental Psychology:
Human Perception and Performance
1984, Vol. 10, No. 6, 812–832

Functionally Specific Articulatory Cooperation Following Jaw Perturbations During Speech: Evidence for Coordinative Structures

J. A. Scott Kelso
Betty Tuller

E. Vatikiotis-Bateson
Carol A. Fowler

ERRATUM

A typographical error occurred on p. 818, column 2, line 3. It should read (SD = 7 ms).

Journal of Experimental Psychology:
Human Perception and Performance
1984, Vol. 10, No. 6, 812–832

Functionally Specific Articulatory Cooperation Following Jaw Perturbations During Speech: Evidence for Coordinative Structures

J. A. Scott Kelso
Haskins Laboratories, New Haven, Connecticut,
and University of Connecticut

Betty Tuller
Cornell University Medical College and Haskins
Laboratories, New Haven, Connecticut

E. Vatikiotis-Bateson
Haskins Laboratories, New Haven, Connecticut,
and Indiana University

Carol A. Fowler
Dartmouth College and Haskins Laboratories,
New Haven, Connecticut

In three experiments we show that articulatory patterns in response to jaw perturbations are specific to the utterance produced. In Experiments 1 and 2, an unexpected constant force load (5.88 N) applied during upward jaw motion for final /b/ closure in the utterance /bæb/ revealed nearly immediate compensation in upper and lower lips, but not the tongue, on the first perturbation trial. The same perturbation applied during the utterance /bæz/ evoked rapid and increased tongue-muscle activity for /z/ frication, but no active lip compensation. Although jaw perturbation represented a threat to both utterances, no perceptible distortion of speech occurred. In Experiment 3, the phase of the jaw perturbation was varied during the production of bilabial consonants. Remote reactions in the upper lip were observed only when the jaw was perturbed during the closing phase of motion. These findings provide evidence for flexibly assembled coordinative structures in speech production.

The bewildering complexity of human speech is readily apparent when one attempts to track the spatiotemporal activities of the many anatomical structures involved. One needs little persuasion that talking constitutes an extraordinary feat of motor control, particularly if each degree of freedom were to be individually controlled. A notion that has gained some limited recognition in neuroscience (e.g., Evarts, 1982; Nashner, Wollacott, & Tuma, 1979; Soechting & Lacquaniti, 1981) and behavior research (e.g., Bernstein, 1967; Fowler, Rubin, Remez, & Turvey, 1980; Kelso, Southard, & Goodman, 1979; Turvey, 1977) is that the degrees of freedom of any articulator system (however one counts them) are not individually regulated during purposive activity. Rather, in many actions, ranging, for example, from locomotion to handwriting, ensembles of muscles and joints exhibit a unitary structuring—a preservation of inter-

---

This article is a more complete version of a paper entitled "The Functional Specificity of Articulatory Control and Coordination," presented at the 104th meeting of the Acoustical Society of America, Orlando, Florida, November 1982 (*Journal of the Acoustical Society of America,* 1982, *72,* S103 [Abstract]). Experiment 3 was presented at the 107th meeting of the Acoustical Society of America, Norfolk, Virginia, May 1984, under the title "Remote and Autogenic Articulatory Adaptation to Jaw Perturbations During Speech: More on Functional Synergies" (*Journal of the Acoustical Society of America,* 1984, *75,* S23–S24 [Abstract]).

The research was supported by National Institute of Neurological, Communicative Disorders, and Stroke Grant NS-13617, Biomedical Research Support Grant RR-05596, and Contract No. N0014-83-C-0083 from the U.S. Office of Naval Research. Betty Tuller was supported by National Institute of Neurological, Communicative Disorders, and Stroke Grant NS-17778.

We are very grateful to the following individuals: Milton Lazanski, former head of the Department of Orthodontics at Yale University, for his patience in helping us design and produce the first of the jaw prostheses used in this study; Gerald Alexander for constructing the second; Kiyoshi Honda for performing the electrode insertions; F. S. Cooper, J. W. Folkins, and four anonymous reviewers for helpful comments on an earlier version of this article. Thanks also to Nancy O'Brien for much editorial assistance and to Eric Muller and James Abbs for technical advice.

Requests for reprints should be sent to J. A. Scott Kelso, Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06511.

nal relations among muscles and kinematic components that is stable across scalar changes in such parameters as rate and force (see Grillner, 1982, and Kelso, 1981, for reviews). Thus, significant units of control and coordination appear to be functional groupings of muscles and joints (referred to as *functional synergies* or *coordinative structures*) that act as a unit to accomplish a task (Bernstein, 1967; Boylls, 1975; Gelfand, Gurfinkel, Tsetlin, & Shik, 1971; Greene, 1972, 1982; Turvey, 1977). Insights into the cooperative behavior among articulators during speech are therefore likely to lie in the identification and analysis of coordinative structures.

The behavior of complex systems possessing active, interacting components and large numbers of degrees of freedom can be studied by perturbing the system dynamically during an activity and examining how the free variables reconfigure themselves. Thus, a group of potentially independent muscles could be said to constitute a single functional unit if it were shown that a challenge experienced by one (or more) members of the group was responded to by other members of the group at a site remote from the challenge. For the concept of coordinative structure, the response of the neuromuscular ensemble would not be stereotypic; rather, it would be adapted quickly and precisely to accomplish the task. In the case of speech, the components of the articulatory apparatus would cooperate in such a way as to preserve the linguistic intent of the speaker.

Although the speech literature contains a number of observations that suggest a coordinative-structure mode of articulatory organization, few experiments have employed dynamic perturbation analysis. By and large, the perturbations introduced to the system have been of a static nature. Thus, patterns of cooperation have been observed in various articulators following immobilization of the jaw (as in bite-block experiments, e.g., Fowler & Turvey, 1980; Kelso & Tuller, 1983; Lindblom & Sundberg, 1971), restrictions on lip movements (e.g., Riordan, 1977; Tuller & Fitch, 1980), surgical removal of the alveolar plate or reconstruction of the mandible (e.g., Zimmermann, Kelso, & Lander, 1980), and the insertion of palatal prostheses (e.g., Hamlet & Stone, 1978). Generally, the ability of the speech system to compensate for these disturbances is quite remarkable. However, in many of these studies, various kinds of adjustments could have occurred before the test utterances were actually produced. Thus, a more illuminating method may be to perturb the articulators during the speech act and then observe consequent movement patterns, if any, and the speed with which they are achieved.

A pioneering experiment by Folkins and Abbs (1975) did precisely this by occasionally loading the jaw during the closure movement for the first /p/ in the utterance "a /hæ pæp/ again." Lip closure was attained in all cases, apparently by exaggerated displacements and velocities of the lip-closing gestures, particularly by the upper lip.[1] Similarly, Folkins and Zimmermann (1982) used electrical stimulation to produce unexpected depression of the lower lip prior to and during bilabial closure. It was observed that compensatory changes in jaw and upper-lip movements effected the bilabial gesture. Although these findings are consistent with the coordinative-structure concept, it is not clear from existing data whether the patterns of articulator coupling following jaw perturbations are in any sense standardized (as one might predict if they were completely preprogrammed or a result of fixed input–output loops) or whether they are "functional," that is, directed to the stable production of the intended utterance. If the former, the pattern of response to a given jaw perturbation should be the same regardless of utterance. If the latter, different patterns of articulator cooperation (coordinative structures) should occur, tailored to the particular phonetic requirements.[2]

---

[1] Initially, Folkins and Abbs (1975) interpreted their data as support for on-line feedback processing, that is, "a lip control system that is adjusted on the basis of feedback information about the relative position of the lips and jaw" (p. 218). A more recent interpretation, or perhaps a redescription by Abbs and Cole (1982), is that the data support "a feedforward, open-loop control process" in which "information is fed forward for making adjustments in motor commands to structures having parallel involvements" (p. 171). Suprabulbar pathways were hypothesized to play a mediating role.

[2] Anecdotal evidence for such tailoring is reported by Abbs and Gracco (1983), who note that upper-lip com-

In the first two experiments reported here, we examined the effects of jaw perturbation on production of two phonetic segments, /b/ and /z/. For /b/, the primary vocal-tract constriction is created normally by bilabial closure. For /z/, the main constriction is produced by positioning the tongue in close approximation to the palate or teeth. Note that from a low-vowel environment, (such as /a/) jaw and lips cooperate for production of /b/, whereas jaw and tongue cooperate in the raising gesture for /z/. Thus, if the jaw is perturbed during the transition into the final /b/ in /bæb/, then the primary response should occur in the lips, rather than, say, in the tongue. In contrast, if the same perturbation is applied during the raising of the jaw to produce the final /z/ in /bæz/, the primary response should occur in the tongue, not the lips. Experiment 1 presents an initial exploration of this idea. Experiment 2 provides more detailed electromyographic (EMG) and kinematic evidence for task-specific articulator cooperation. In Experiment 3, we attempted to converge on the interpretation of the first two experiments by examining remote reactions to jaw perturbation as a function of the phase of jaw motion at which loads are applied. For example, upper-lip responses should be observed only when the jaw is perturbed during the closing gestures for bilabial consonant production, that is, when the upper lip contributes to vocal-tract occlusion.

Experiment 1

Method

Subject, materials, and procedures. One adult male (one of the authors) participated in the first two experiments reported here.[3] The speech sample contained two utterance types, "a /bæb/ again" and "a /bæz/ again." In the first part of the experiment, 30 trials of each utterance were performed in a single block. On 20% of the trials (6 randomly selected trials out of 30 for each utterance), a load perturbation was applied to the jaw during the closing gesture for the second consonant, /b/ or /z/. The perturbation was triggered during /bæb/ and /bæz/ utterances when the jaw reached the same predetermined point approximately midway through its upward trajectory. The experiment was performed with a constant force load of 1.5-s duration. The same procedure was repeated in the second part of the experiment, but with a 50-ms load. It is important to note the subject did not know on which trials his jaw would be perturbed. Moreover, until the first perturbed trial, the subject was unaware of the specific locus of the perturbation during the raising trajectory and the magnitude of the applied load.

Apparatus and data recording. Figure 1 illustrates the experimental setup. The subject sat in a dental chair with his head fixed in a specially designed cephalostat (basically a plaster cast mold constructed for the subject's head and a clamp that fitted onto the bridge of the subject's nose—all enclosed in a wooden box; see Figure 1, Panels A and B). A custom-made titanium dental prosthesis was fitted onto the subject's lower teeth (Figure 1, Panel C). Two small rods of the prosthesis protruded from the sides of the mouth and were coupled by a thin wire to a Brushless DC torque motor that was situated perpendicular to the subject's chin. A load cell placed in series with the coupling wire monitored applied torque. This enabled us to control the torque motor under force feedback and made it possible to couple the motor to the jaw with a very small tracking load of approximately 30 g. Jaw movements were monitored by a rotary voltage displacement transducer placed at the axis of rotation of the sector arm (see Figure 1, Panel B). The existence of

---

pensation to a lower-lip perturbation occurs in the utterance /aba/ but not in /afa/. Similarly, Folkins and Zimmermann (1982) concluded their article on electrical stimulation of the lower lip with the suggestion that "it *may be* [italics added] that interactions between the lips and jaw *may be* [italics added] different for bilabial closing, bilabial opening, labiodental closing, and lip rounding gestures" (p. 1232). Again, a direct test of this hypothesis, which we conduct here, has not been made. In fact, all the dynamic perturbation studies conducted thus far have involved bilabial gestures.

[3] Some explanation is necessary about the small number of subjects and the chronological aspects of the research. Since these experiments started in late 1978 we tried to prepare four subjects for participation. For each subject, special dental casts were made of the upper and lower teeth, prior to constructing a titanium prosthesis for the lower jaw. Only with two subjects, however, was it possible to proceed according to plan for the following reasons. First, to seat the prosthesis in the mouth firmly so that it did not come out or reverberate when a load was applied, it was necessary that the subject have at least one (preferably several) of the rear molars missing (see Figure 1, Panel C). Second, and relatedly, it was crucial that there be sufficient clearance at the sides of the subject's mouth so that the protruding rods to the torque motor did not interfere in any way with the subject's speech. Two subjects met these criteria, although the second subject did not become available until early 1983. We tried to test him in the larger version of Experiment 1, but he was unable to withstand the insertion of fine wire electrodes into the tongue and hence could not be used to study fricative production. Because of these difficulties, we can report only our efforts to provide a within-subject replication of the experiment (Experiment 2). The second subject, however, participated in Experiment 3, which did not require invasive procedures. We did not have the subject in Experiments 1 and 2 participate in Experiment 3 because we were concerned that possible experiential factors might influence the results.

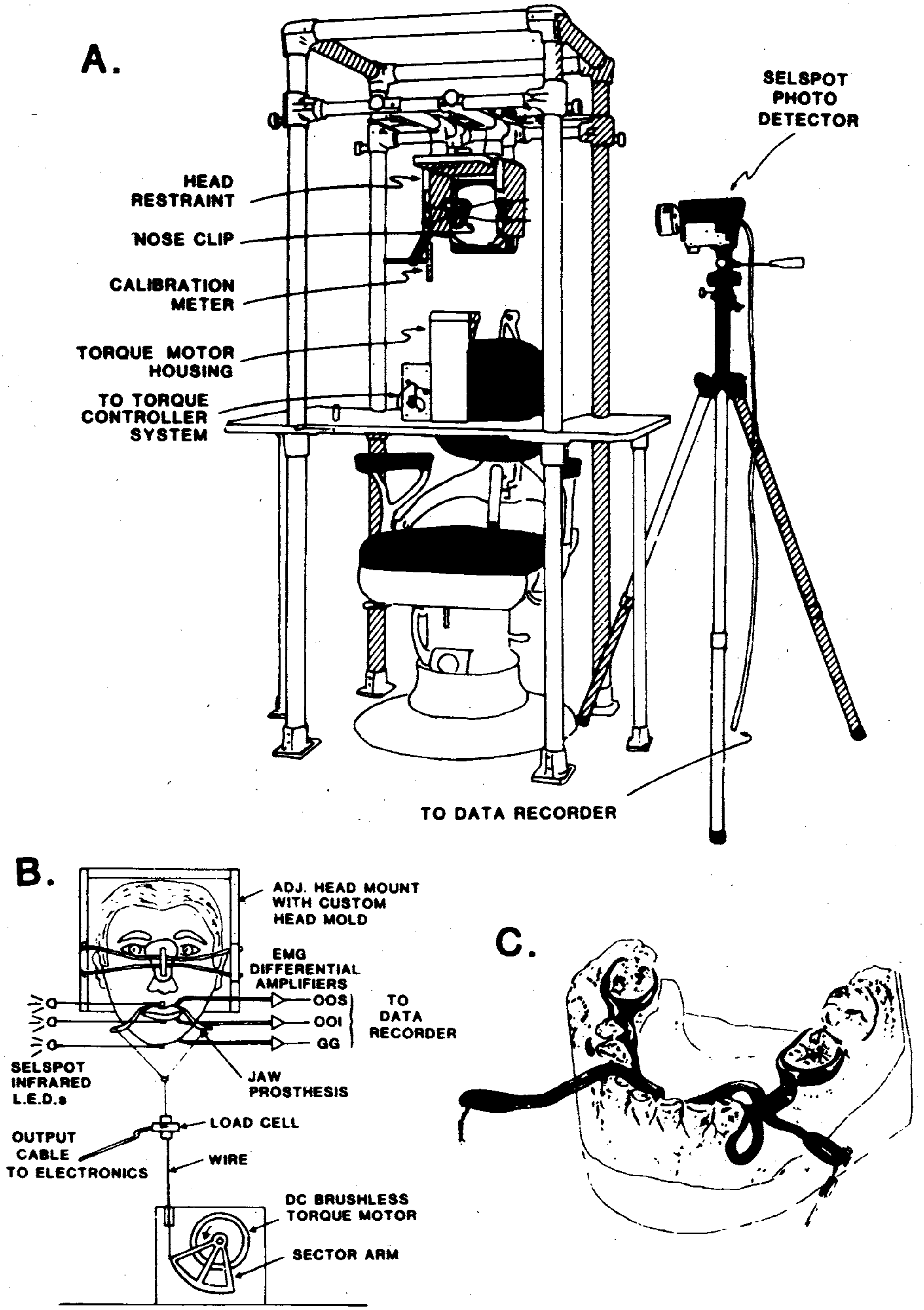

Figure 1. Panel A. The general experimental setup. Panel B. A schematic of the subject in the head apparatus, showing placement of light-emitting diodes for movement tracking and electrodes for monitoring EMG activity. (OOS and OOI are orbicularis oris superior and inferior, respectively. GG is the genioglossus, a major tongue muscle.) Panel C. A specially designed jaw prosthesis. (Note gaps for missing teeth that afford a unique capability for setting the prosthesis firmly in the mouth of the subject [see Footnote 3].)

Table 1
Mean Articulator Positions and Standard Deviations in mm for Control and Loaded Trials

	At onset of closure for /bæb/ utterances				At onset of frication for /bæz/ utterances			
	Control		Load		Control		Load	
Articulator	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
				1.5-s load				
Jaw	41.4	.41	35.4	.35**	42.3	.01	34.6	.01**
Lower lip	23.3	.01	23.0	.46	23.3	.01	22.8	.46*
Upper lip	2.3	.39	1.6	.47*	6.1	.24	5.8	.41
				50-ms load				
Jaw	41.2	.41	40.5	.81	42.2	.01	41.9	.42
Lower lip	23.1	.23	23.0	.23	23.3	.23	23.3	.01
Upper lip	2.6	.18	2.1	.36*	5.5	.44	5.6	.39

Note. Mean articulator position was measured from an arbitrary reference position. The lower the number for a given articulator, the lower is its spatial position.
* $p < .05$. ** $p < .001$.

the tracking force had no perceptible effects on the subject's speech, nor on observed movement and EMG activity. The experiments were completely controlled by a programmable microcomputer that specified on which trials the load was to be added and the magnitude of the load. In each experiment the load was the same (5.88 N), and the rise time to peak load was small, 2 ms–3 ms.

Infrared light-emitting diodes (LEDs) were attached at the vermilion border of the subject's upper and lower lips at the midline and were sensed by an optical tracking system (a modified SELSPOT system). The displacements of the articulators and the acoustic speech signal were stored on FM tape for computer analysis. A set of software routines was used to differentiate the movement signals and display the audio output along with movement information in a time-synchronized format. The acoustic recordings were inspected to determine the first evidence of bilabial closure for the final /b/ in /bæb/ trials (defined here as the point when the high-frequency components of the periodic wave disappear) and of frication onset for /z/ in the /bæz/ trials (defined as the onset of high-frequency, low-amplitude noise).

Results and Discussion

In this experiment, we evaluated the effect of the jaw perturbation on upper- and lower-lip movement and whether the effect was context sensitive. We first established that the 1.5-s load prevented the jaw from reaching its usual position, by measuring jaw height at the earliest acoustic evidence of lip closure or frication. The results are presented in Table 1, which shows the mean articulator positions for the jaw, lower lip (including the jaw contribution), and upper lip, obtained from an arbitrary reference point. For both phonetic contexts, the jaw was significantly lower during 1.5-s load trials than it was for the immediately preceding unloaded (control) trials, $t(10) = 26.99$, $p < .001$, and $t(10) = 3.18$, $p < .05$, for /bæb/ and /bæz/, respectively.

The coordinative-structure concept predicts one consequence of this difference in jaw height, namely, that when the jaw load is applied, upper-lip displacement downward should increase when the speaker produces /b/, but not when he produces /z/. The displacement of the upper lip downward in each trial was measured at the time of acoustic onset of final /b/ closure or final /z/ frication. As predicted, the position of the upper lip at final /b/ closure was lower for the perturbed trials than it was for the immediately preceding unperturbed trials, $t(10) = 2.64$, $p < .05$. In contrast, there was no difference in upper-lip position for the production of /z/ with and without a load, $t(10) = 1.44$, $p > .1$. In addition, the position of the lower lip in space at the point of closure for the production of /b/ was unaffected by the 1.5-s load, indicating a considerable adjustment for the lower jaw position, $t(10) = 1.65$, $p > .01$. Similarly, for the production of /z/, although the lower lip was lower in space, $t(10) = 2.68$, $p < .05$, the difference was small in comparison with the much lower jaw position. These lower-lip reactions are considered in more detail in Experiment 2.

When the applied load was of 50-ms duration, no effect of perturbation on jaw position was apparent by the time closure or frication was achieved, $t(10) = 2.02$ for /bæb/ utterances and $t(10) = 1.57$ for /bæz/ utterances, $ps > .05$. Lower-lip position also showed no effect of the 50-ms load, for /bæb/, $t(10) = 1.05$, and for /bæz/ $t(10) = .42$, $ps > .1$. Although the upper-lip position for /z/ production was similarly unaffected by the short-duration load, $t(10) = 0.26$, $p > .1$, the upper lip in the production of /b/ did increase its downward deflection in loaded trials relative to unloaded trials, $t(10) = 2.96$, $p < .05$. The change in upper-lip displacement, but not lower-lip displacement is probably a function of an increase in compression of the upper lip.[4]

To summarize, these preliminary observations suggest that a disruption in movement of one articulator (the jaw) is responded to by another, remote articulator (the upper lip) when the phonetic context is one for which that reaction is functionally appropriate. However, the experiment has three shortcomings. First, although we provided evidence of a coordinative structure during /b/ production, we did not provide direct evidence for its presence in /z/ production. Second, to understand the articulatory system's response to perturbation, both detailed kinematic and electromyographic (EMG) information are desirable. Third, and relatedly, to evaluate the reliability of the effects described in Experiment 1, a greater number of trials is warranted. For example, in Experiment 1 it may be that the 50-ms load had a slight effect on articulatory movements (as suggested by the increase in upper-lip displacement for /b/ production), but six loaded trials do not constitute a sensitive enough test. For these reasons, we performed a second experiment, similar in many respects to Experiment 1. In Experiment 2, the total number of trials was increased and, in addition to monitoring jaw and lip movements, we obtained EMG potentials from tongue and lip muscles. We were especially interested in evaluating tongue-muscle activity during /z/ production.

Experiment 2

Method

Subject, materials, and procedures. The same subject who participated in Experiment 1 took part in Experiment 2. The speech sample contained the same two utterances as those in Experiment 1, "a /bæb/ again" and "a /bæz/ again." In each part of the experiment, 40 trials of each utterance were performed in two 20-trial blocks. At least 5 s separated individual trials. On 25% of the trials (10 randomly selected trials out of 40 for each utterance), a load (5.88 N) was applied to the jaw during the closing gesture for production of the second consonant, /b/ or /z/. The load was triggered during /bæb/ and /bæz/ when the jaw reached the same predetermined point approximately midway through its upward trajectory. Once again, the subject knew that some of the trials would be perturbed but not which ones. The subject did not experience any form of loading (except the tracking load) until the experiment proper. The first part of the experiment was performed with a constant force load of 1.5-s duration, the second part with a 50-ms load. The utterance order was counterbalanced across loading conditions.

Apparatus and data recording. The jaw loading device and the methods of tracking movements of the jaw, upper lip, and lower lip were identical to those used in Experiment 1. Paint-on electrodes were used to obtain EMG potentials from a muscle in the upper lip (orbicularis oris superior, OOS) and a muscle in the lower lip (orbicularis oris inferior, OOI). Bipolar hooked-wire electrodes, inserted by a laryngologist, Dr. Kiyoshi Honda, were used to obtain EMG potentials from a tongue muscle (the posterior portion of genioglossus, GG). The genioglossus recordings were used as an index of tongue activity during /z/ production. The displacements of the articulators, the EMG signals from tongue and lip muscles, and the acoustic speech signal were stored on FM tape for later computer analysis. Software routines were used to differentiate the movement signals, ensemble average the rectified EMG signals, and display the audio output synchronized with movement and EMG information.

Results and Discussion

The results of Experiment 2 established once more that the upward jaw trajectory differed in loaded and unloaded trials. The position of the jaw in each trial was measured at the earliest acoustic evidence of final /b/ closure or /z/ frication. The position of the jaw in loaded trials was then compared with that in normal conditions and was found to be significantly lower for both /bæb/, $t(18) = 10.20$, $p < .001$, and /bæz/, $t(18) = 22.45$,

---

[4] Peak lip displacement can occur after closure is attained because of the elastic nature of the lips. Once the upper and lower lips touch, achieving closure, they can and usually do compress further as closure proceeds.

$p < .001$. In Figure 2, a sample of the jaw velocities is shown for the first eight perturbed trials of both /bæb/ and /bæz/ utterances. The effect of the load perturbation was to alter the direction of jaw movement almost immediately in a very consistent manner. That is, the jaw velocity became sharply negative just after torque onset. Loaded trials showed very small trial-to-trial variability in the jaw-velocity profiles for both utterances.

The displacements and velocities of the upper lip, the lower lip (with the contribution of jaw subtracted), and the jaw itself are shown for perturbed and unperturbed (control) trials in Figures 3 and 4. Each trace represents the average of 10 tokens; the dotted trace indicates the control utterances and the solid trace, the perturbed utterances. The vertical line in each window of the figures marks the onset of torque to the jaw. Even though the torque prevented normal upward jaw motion, lip closure for /b/ production and frication for /z/ production were attained on all trials. In /bæb/, for example, peak lower-lip displacement and upper-lip displacement occurred, on the average, 5 ms before and 5 ms after acoustic closure (see Footnote 4), respectively, on control trials, and 11 ms and 7 ms, respectively, after acoustic closure on perturbed trials. Thus, the differences in timing among articulators between perturbed and unperturbed utterances were small, and we were not able to hear any obvious differences between perturbed and control conditions.

Examination of the kinematics in Figures 3 and 4 and corresponding rectified and averaged EMG activity in Figure 5 reveals interesting adjustments in response to jaw perturbation. Figure 3, Panel A shows that in the perturbed trials, the downward displacement of the upper lip in /bæb/ is greater than it is in the control trials. Measured at the acoustic onset of /b/ closure for final /b/ production, this difference is highly significant, $t(18) = 3.19$, $p < .01$, two-tailed. In contrast, for /bæz/ (Figure 3, Panel B) the upper lip shows no differences in displacement for perturbed and control conditions, $t(18) = .001$, $p > .1$, when measured at the onset of /z/ frication.

One anomalous result is that OOS (Figure 5, top) shows an active increase in EMG activity with an average latency of 20 ms in response to the added load for both /bæb/ and /bæz/ utterances ($SD = 18$ ms). Thus, even though there are differential movement effects for /bæb/ and /bæz/ as a function of perturbation, the EMG response, at least in terms of its timing, is similar in both utterances. Although this result is puzzling, several, perhaps related, interpretations are possible. One is that although in /bæz/ utterances there was little vertical upper-lip displacement,

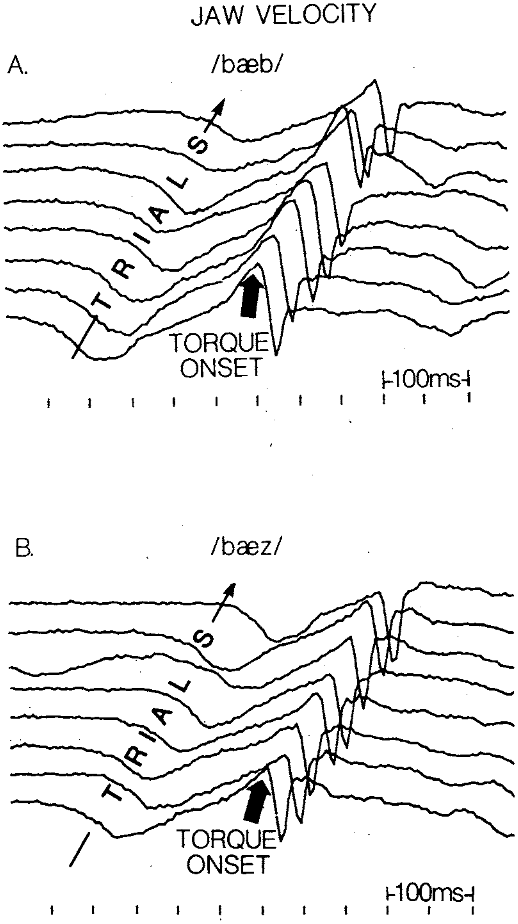

Figure 2. The consistent reaction of the jaw to a constant force load (5.88 N, 1.5 s) applied during closing for the final consonant in /bæb/ and /bæz/ utterances. (Velocity changes direction abruptly in response to torque. The traces are raw data and represent the first 8 of a set of 10 perturbation trials presented randomly in a sequence of 40 trials. The remaining two traces were very similar but are not shown because of a graphics display limitation.)

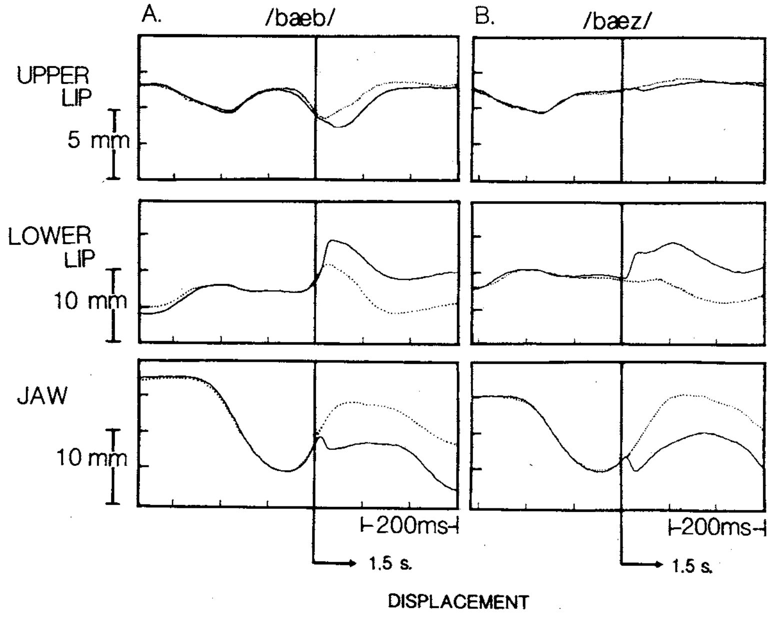

Figure 3. Upper lip, lower lip (with jaw movement contribution subtracted), and jaw displacement for the utterances /bæb/ and /bæz/. (Each trace represents the average of 10 tokens for perturbed [solid line] and control [dotted line] conditions. The vertical line in each window marks the onset of torque to the jaw. For illustration purposes, the two conditions have been overlaid by temporally sliding the control condition, which does not have a torque line-up point, relative to the perturbed condition, which does, taking the jaw as a reference point.)

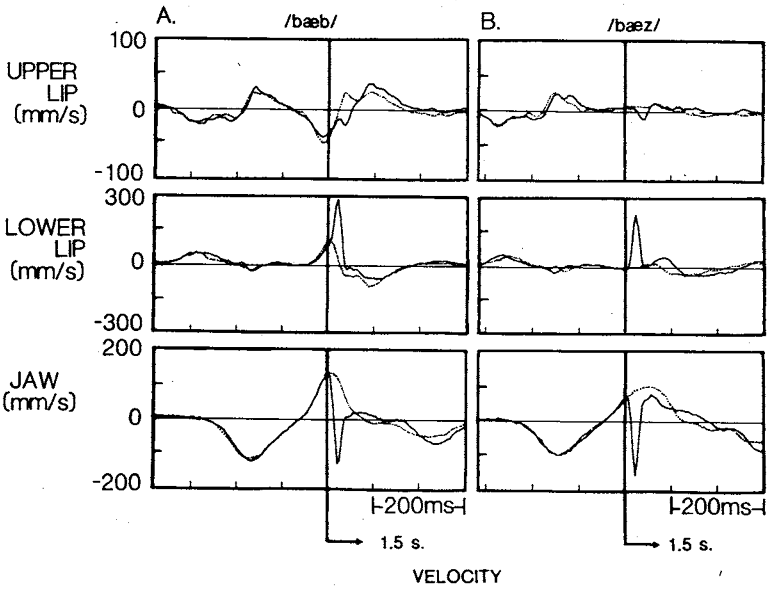

Figure 4. The articulatory velocity profiles for the same data shown in Figure 3 with the same plotting conventions.

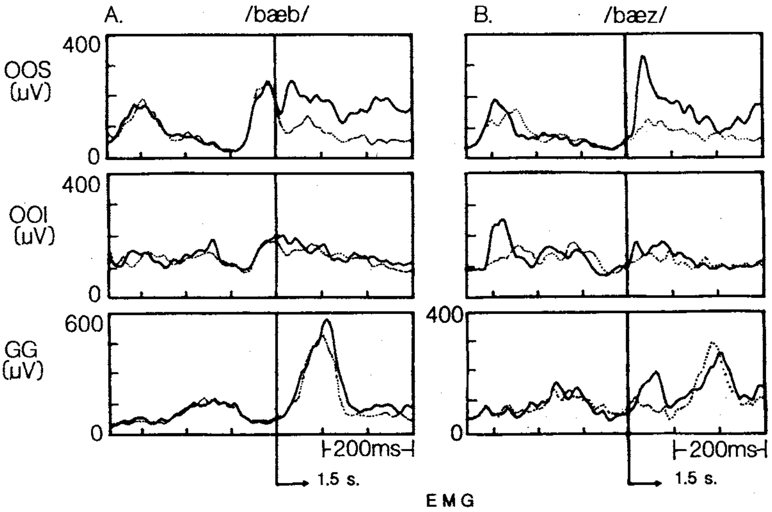

Figure 5. Average rectified electromyographic (EMG) activity of upper lip (OOS), lower lip (OOI), and tongue (GG) muscles for perturbed (solid trace) and control (dotted line) conditions.

we observed that the subject protruded the lips slightly, a maneuver that could be revealed by measuring horizontal displacement. The present study, however, does not allow us to evaluate this possibility. Relatedly, the data shown in Figures 4 and 5 suggest that the jaw and upper lip may be functionally coupled in /bæz/ as well as in /bæb/. The increase in EMG activity that is time locked to jaw perturbation, combined with a small increase in upper-lip downward velocity (Figure 4, Panel B), renders this interpretation viable. Alternatively, the EMG response to perturbation in both /bæb/ and /bæz/ may only reflect a general stiffening in the upper lip rather than active trajectory control. Further research is needed to evaluate these possibilities.

In contrast to the upper-lip kinematics, the lower lip exhibits compensatory movement behavior in both /bæb/ and /bæz/ utterances (Figures 3 and 4). Examination of displacement and velocity profiles reveals a rapid increase in lip kinematic values when the jaw is perturbed. The nearly immediate and highly consistent response of the lower lip to perturbation is shown for individual tokens in Figure 6. The onset delay of the increase in lower-lip velocity—seen as an inflection point in the closing gesture for /bæb/ and as a sharp velocity spike in /bæz/—is on the order of 5 ms to 10 ms. As an interesting aside, the difference between the trajectory of the lower lip in /bæb/ and that in /bæz/ before perturbation suggests that the lower lip is not ordinarily involved in producing /z/ but is involved in /b/ production (see also averaged data in Figures 3 and 4).

The almost immediate response of the lower lip to jaw loading and the finding that there were no significant increases in OOI activity (Figure 5, middle row) for either utterance indicate that the lower-lip perturbation response is a passive mechanical effect that arises when jaw motion is abruptly halted. In addition, the highly stereotypic lower-lip reaction to jaw perturbation contrasts with the findings of other perturbation studies in speech that show considerable trial-to-trial variability in articulator movements. For example, Abbs and Gracco (1983; in press) found that in response to a brief perturbation applied to the lower lip, there were reciprocal trade-offs in amplitude between upper- and lower-lip movements as well as in associated muscle activity. In "active compensation," different (but systematic) magnitudes of movement and EMG activity in coupled articulators are apparent (see also Hughes & Abbs, 1976). The stereotypy evident in the present data on lower-lip movements, however, is more indicative of a passive shearing of the lower lip from the jaw, arising as a consequence of the momentum created by halting jaw motion.

One important feature of the lip closure response to perturbation should not be overlooked, namely, that the lips do not meet at the same point in space as they do in control conditions. In Figure 3, Panel A, for example, the amplified response of the lower lip alone (solid line) does not mean that the lower lip is more elevated in perturbed conditions than it is in control conditions. In fact, the opposite is true because the increase in lower-lip displacement is smaller than the decrease in jaw height created by loading. Thus, not only is the upper lip lower in space in perturbed conditions relative to control conditions, but the lower lip is also, $t(18) = 3.20$, $p < .01$. What seems important here is that closure, not some spatial target, is achieved (cf. MacNeilage, 1970, 1980, for a discussion of the status of target theories in speech).

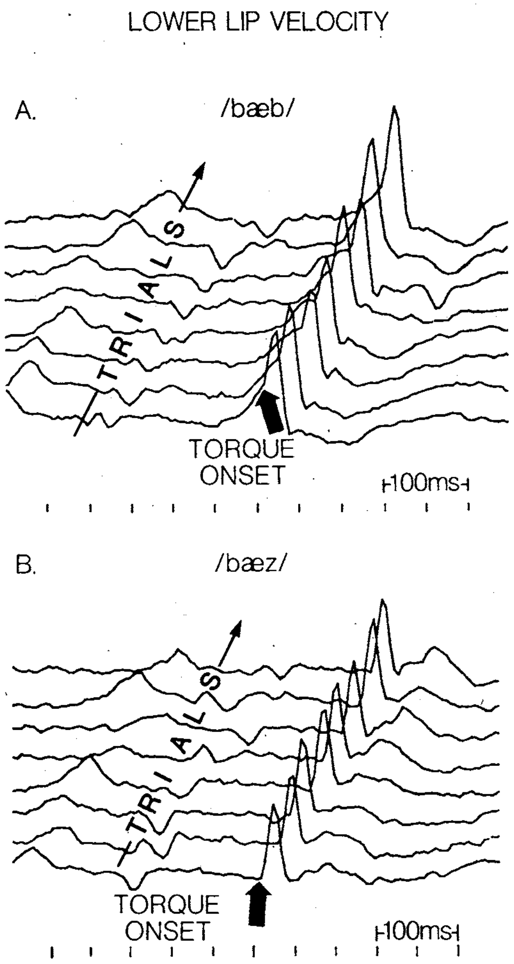

Figure 6. The very rapid and consistent lower lip reaction, seen as an inflection in the velocity trace, to perturbations of the jaw for /bæb/ and /bæz/ utterances. (The plotting convention is identical to that shown in Figure 2.)

The passive reaction of the lower lip contrasts with the active compensation to jaw loading evident in tongue-muscle activity for /bæz/. When EMG responses from genioglossus are aligned and averaged with respect to the onset of /z/ frication, the increased amplitude in perturbed trials relative to control trials is highly significant, $t(18) = 7.76$, $p < .001$. Again, as it is for the lips in /bæb/, the EMG response in /bæz/ is time locked to the application of torque (see Figure 5, Panel B) and occurs remarkably quickly (range: 20 ms–30 ms). No such differences in tongue-muscle activity occur for /bæb/, $t(18) = .88$, $p > .10$.[5]

The pattern of reactions to perturbations of the same magnitude but of much shorter duration (50 ms) was similar in some respects to those discussed earlier but with some marked differences. Figures 7 and 8 present the kinematic variables of displacement and velocity for each articulator, and Figure 9 shows corresponding EMG data. One difference that is immediately apparent is that the articulators for both /bæb/ and /bæz/ utterances quickly return to their normal trajectories following the offset of the perturbation (compare Figures 3 and 4 with Figures 7 and 8). In fact, by the time closure is achieved, there are no significant differences between perturbed and control conditions in displacement of the upper lip for /bæb/, $t(18) = 0.1$, $p > .1$. Differences in the amplitude of muscle activity in the tongue for /bæz/ come close to, but miss, significance, $t(18) = 1.84$, $p > .05$.

---

[5] The large burst of genioglossus activity evident in /bæb/ utterances and the second peak in /bæz/ utterances are related to production of the /g/ in the carrier phrase "again." Examination of the acoustics revealed that the torque occurred closer to the onset of /b/ closure than to the onset of /z/ frication. This is reflected in the proximity of genioglossus activity to torque onset in /bæb/ utterances relative to /bæz/ utterances.

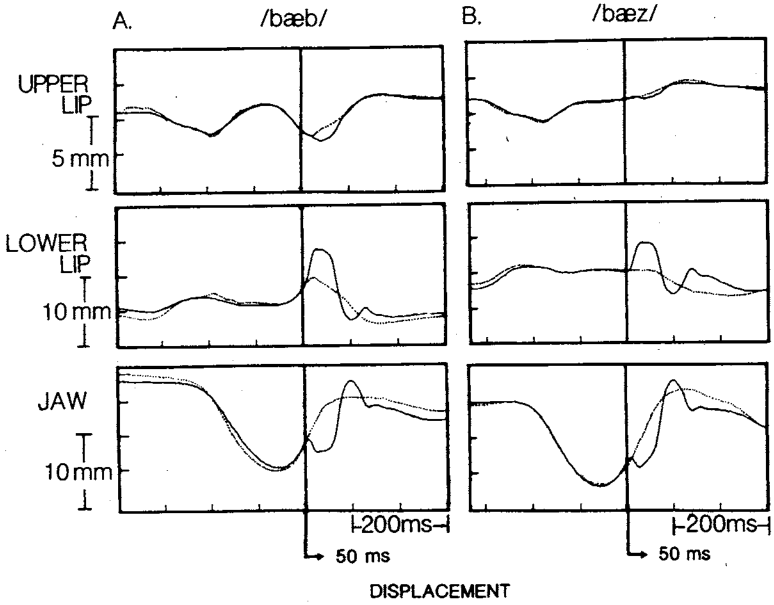

Figure 7. Upper lip, lower lip (with jaw movement contribution subtracted), and jaw displacement for the utterances /bæb/ and /bæz/. (Each trace represents the average of 10 tokens for perturbed [solid line] and control [dotted line] conditions. The vertical line in each window marks the onset of torque to the jaw. In this case a torque of 5.88 N is applied for only 50 ms.)

This homeorhetic property of the articulatory trajectories (i.e., a tendency to return to a "preferred" trajectory) has been observed before in studies of human finger movements (e.g., Kelso & Holt, 1980) and monkey arm movements (cf. Bizzi, Chapple, & Hogan,

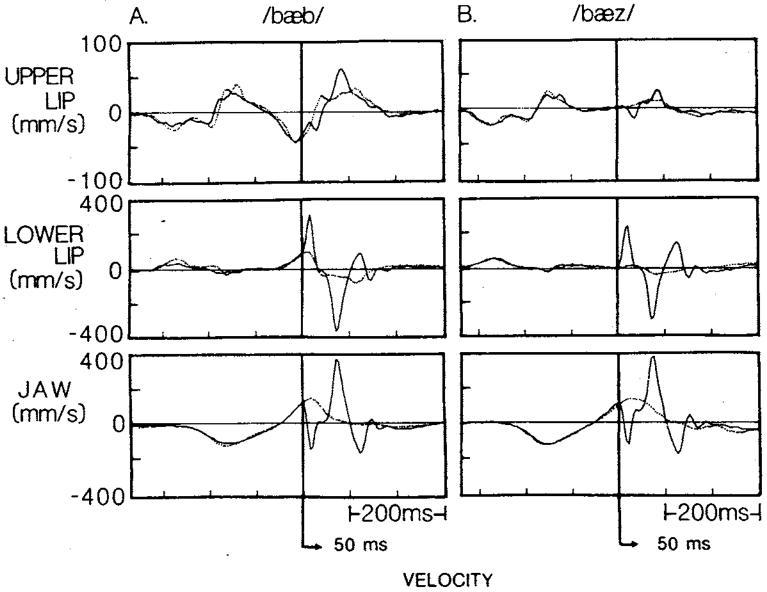

Figure 8. Corresponding articulatory velocity profiles for the displacement data shown in Figure 7.

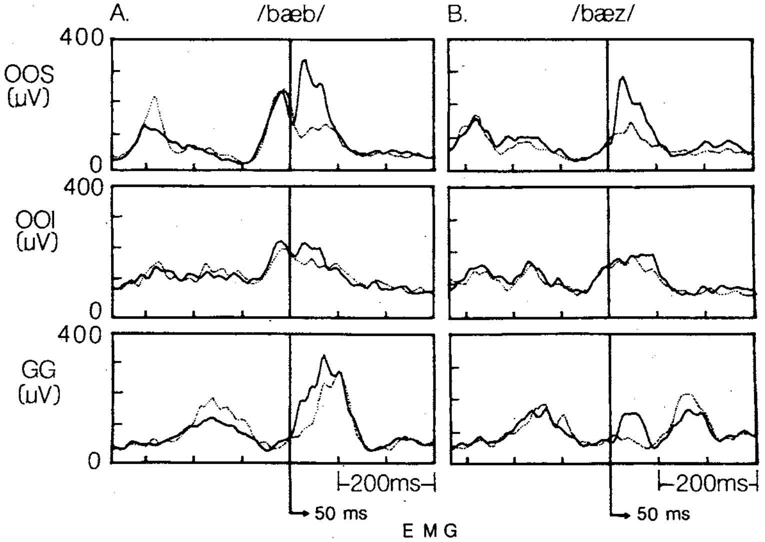

Figure 9. Electromyographic (EMG) profiles corresponding to kinematic data for briefly perturbed (solid lines) and control (dotted lines) trials. (Each trace is the average of 10 tokens.)

1982) and has led to the proposal that trajectory is an actively controlled variable (Bizzi et al., 1982). However, the present data display lightly damped springlike behavior; the return to a normal jaw trajectory, for example, is preceded by an overshoot response. Thus, homeorhesis may arise as a consequence of the behavior of a dynamic system and need not require the assumption of active trajectory control.

In summary, although the present findings are preliminary, they are consistent with coordinative-structure theory, particularly when recent work on speech and other motor activities is also considered. For example, the highly flexible character of the EMG and kinematic patterns observed in Experiments 1 and 2 is similar to the adaptive reactions found in recent studies of cat locomotion (cf. Forssberg, 1982, for review). When light touch or a weak electrical shock is applied to a cat's paw during the flexion phase of the step cycle, an abrupt withdrawal response occurs as if the cat were trying to lift its leg over an obstacle. When the same stimulus is applied during the stance phase of the cycle, the flexion response (which would make the animal fall over) is inhibited, and the cat responds with added extension (cf. Forssberg, Grillner, & Rossignol, 1975). The "stumble corrective reaction" is present in intact and spinal animals and, like the forms of interarticulator cooperation we observed, occurs remarkably quickly. The earliest flexor burst in response to a tactile stimulus applied during the swing phase, for example, occurs with a latency of 10 ms. Just as these reactions are not stereotypic and are functionally suited to the requirements of locomotion, so the patterns obtained in our experiments appear to be flexibly tailored to meet phonetic requirements.

In Experiment 3 we attempted to converge on the task-specific nature of coordinative structures by determining, in a manner akin to that used in the research discussed earlier, whether the cooperative behavior among articulators is sensitive to the phase of motion during which an unexpected perturbation is applied. For example, does perturbing the jaw during the opening phase of the utterance /bæb/ induce a remote reaction in the upper lip? Since the upper lip is minimally (if at all) involved in the opening, vowel-producing phase, we would not expect to see a remote response in that phase unless the system were rigidly coupled. However, in the closing phase (i.e., the transition out of the vowel into the final consonant), in which the upper lip is actively involved in the closing gesture, the upper lip should respond to a sudden lowering of the jaw and lower lip. In addition to examining remote reactions, we evaluated possible phase-dependent responses in the structures local to the perturbation, namely, the lower lip and the jaw itself.

Experiment 3

Method

Subject, materials, and procedures. One subject, an adult male who was not one of the authors and who had never participated in a perturbation study, took part in this experiment (see Footnote 3). The speech sample contained two utterances, "/bæb/ again" and "/bæp/ again." Eighty trials of each utterance were performed in a single block, for a total of 160 trials. In each block, 12.5% of the trials were perturbed during the opening phase of jaw motion, and 12.5% were perturbed during the closing phase. The jaw was perturbed at the same predetermined position in both phases of the motion. As in Experiments 1 and 2, a constant force load of 5.88 N of 1.5-s duration was delivered to the jaw via a torque motor attached to a custom-made dental prosthesis. Between perturbations, the motor exerted a 30-g tracking force that did not perceptibly impede or alter normal articulation.

As in Experiments 1 and 2, jaw and upper- and lower-lip movements were optically tracked by a modified SELSPOT system. In addition, EMG potentials from OOS and OOI were obtained from noninvasive surface (paint-on) electrodes. It is important to note that the subject knew neither which trials would be perturbed nor the phase of jaw motion that would be loaded. Therefore, an additional level of uncertainty was present in this experiment. Movement and EMG data and the audio signal were recorded for later off-line processing.

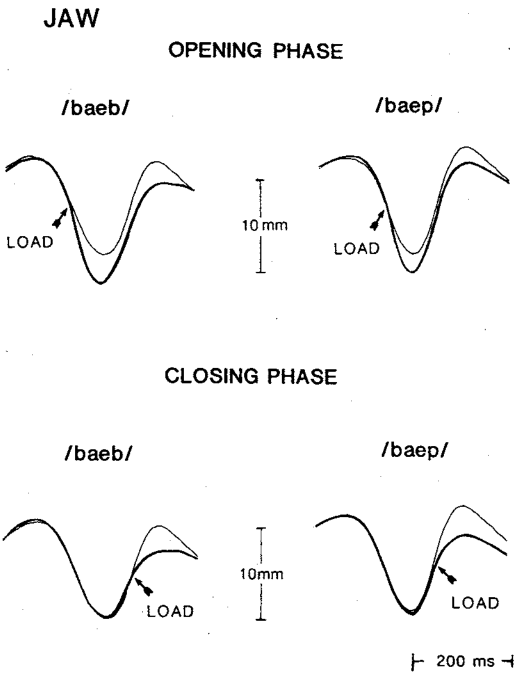

Figure 10. Four pairs of jaw-movement trajectories corresponding to the four experimental conditions examined. (The thin lines are the average unperturbed, control trials. Thick lines represent the mean perturbed trajectories.)

Results and Discussion

The following analysis of the movement trajectories is based largely on differences between perturbed and control trials in peak articulator positions for opening and closing phases of the respective gestures. Once again, the load systematically influenced jaw motion as intended. Figure 10 shows four pairs of jaw-movement trajectories, corresponding to the four conditions examined. Each pair represents the averaged trajectories for all the perturbed and control trials in that loading phase and for that phonetic context. During the opening phase of jaw movement, the perturbed trajectories (denoted by the heavier line in Figure 10) rapidly diverge downward after load onset. At the point of maximum opening for the vowel, they are much lower, for /bæb/ utterances, $t(14) = 4.63$, and for /bæp/ utterances, $t(17) = 4.59$, $ps < .001$.[6] Note also that the jaw trajectories are still lower at the point of peak raising for production of the final consonant; for /bæb/ utterances, $t(14) = 5.21$, and for /bæp/ utterances, $t(17) = 4.26$, $ps < .01$. This is perhaps not surprising, because the load remains on for 1.5 s. When the load is applied during the closing phase of motion, the jaw trajectories, as expected, are not different at peak jaw

---

[6] In the following analyses, there are always 10 control trials to compare with the perturbed trajectories. However, because of technical difficulties (e.g., the subject's making nonspeech jaw movements that triggered the perturbation), there are not always 10 perturbed trials. Therefore, we present the pooled degrees of freedom (N-2) for statistical tests, although we have performed all the tests using the adjusted degrees of freedom as well. Pooled and adjusted results are very similar; however, where they diverge, we report both.

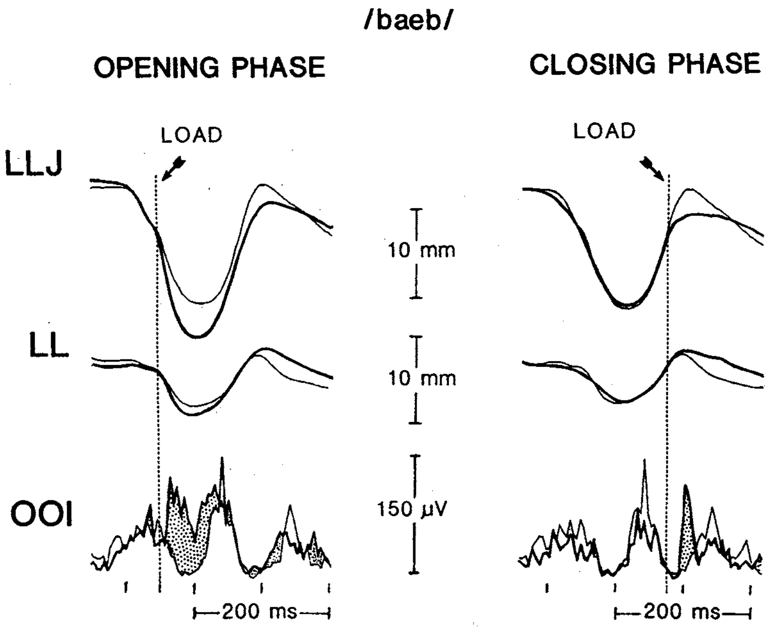

Figure 11. Average lower lip plus jaw (LLJ) and lower lip alone (LL) trajectories for the utterance /bæb/ under perturbed (thick line) and control (thin line) conditions. (OOI is the rectified and averaged, but unsmoothed electromyographic response of a lower lip raising muscle, orbicularis oris inferior.)

lowering for either /bæb/, $t(12) = -.20$, or /bæp/, $t(18) = -1.73$, $ps > .10$. Following load onset, however, the trajectories again diverge, and the loaded jaw remains much lower at stop closure in both phonetic contexts, for /bæb/, $t(12) = 8.69$, $p < .01$, and for /bæp/, $t(18) = 5.23$, $p < .01$. It is clear, therefore, that load application in both phases of the motion had the intended effect on the jaw trajectories.

In Figures 11 and 12, we show the extent to which "local" reactions occur in the lower lip in response to jaw perturbation for the utterances /bæb/ (Figure 11) and /bæp/ (Figure 12). In the figures, the lower-lip position is shown in absolute space as it rides the jaw (the LLJ traces) and without the jaw motion contribution (the LL traces). The traces along the bottom of the figures are averaged, but unsmoothed, signals for a lower-lip muscle (OOI), which is active for bilabial closure. Stippled portions in the figures denote increased muscle activity in perturbed trials (the thicker line) relative to control trials.

As the jaw does, the lower-lip–jaw complex shows a reaction to the jaw load during the opening phase of motion. Measured at maximum lowering, LLJ is perturbed downward in both /bæb/, $t(14) = 6.03$, and /bæp/, $t(17) = 5.96$, $ps < .01$. Again, because the load remains on, the lower-lip–jaw complex remains lower at the point of peak closure on perturbed trials, for /bæb/, $t(14) = 3.71$, $p < .01$, and for /bæp/, $t(17) = 4.75$, $p < .01$. When the jaw is loaded during the closing phase of motion, there is a difference between perturbed and control LLJ traces only at the point of peak closure, for /bæb/, $t(12) = 6.08$, $p < .01$, and for /bæp/, $t(18) = 5.38$, $p < .01$. As expected, the trajectories are not significantly different at peak lowering, that is, before the load is applied, for /bæb/ utterances, $t(12) = -.47$, and for /bæp/ utterances, $t(18) = -1.55$, $ps > .10$.

Figures 11 and 12 also show the responses of the lower lip alone (LL) to perturbation in the opening phase. Independently of jaw lowering, the lip traces diverge rapidly after load onset and are reliably lower at peak opening for the vowel after jaw loading in both /bæb/ utterances, $t(14) = 5.55$, and /bæp/ utterances, $t(17) = 6.00$, $ps < .01$. A marked increase in

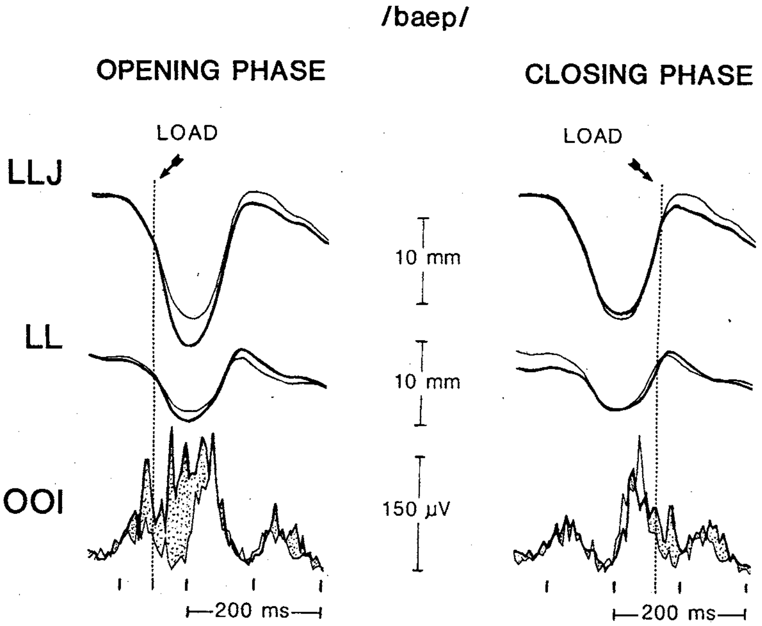

Figure 12. Average lower lip plus jaw (LLJ) and lower lip alone (LL) trajectories for the utterance /bæp/ under perturbed (thick line) and control (thin line) conditions. (OOI is the rectified and averaged, but unsmoothed electromyographic response of a lower lip raising muscle, orbicularis oris inferior.)

OOI activity accompanies the lower-lip response. A conservative estimate of the mean latency in OOI is 20 ms, with a range of 15 ms–35 ms. Although the mean lower-lip position is not as high at closure in conditions when the jaw is loaded during the opening phase as it is in control conditions, the effect is highly variable and nonsignificant, for /bæb/, $t(14) = -1.06$, $p > .10$, and for /bæp/, $t(17) = -1.31$, $p > .10$.

The right side of Figures 11 and 12 shows the average lower-lip response to perturbations applied during the closing phase of jaw motion. The peak closure displacements of perturbed trials are not different from those of control trials for either /bæb/, $t(12) = -1.24$, $p > .10$, or /bæp/, $t(17) = .53$, $p > .10$, which suggests that the lower lip has completely compensated for the lower jaw position. Again, there is a noticeable OOI reaction some 30 ms on the average after load onset, although this may in part reflect overall stiffening of the lower lip (note the generally elevated posture of the lower lip after peak closure has occurred). As expected, the lip trajectories are not different prior to load onset, that is, at peak lower-lip depression, $t(12) = -.79$, $p > .10$ for /bæb/ and $t(18) = .86$, $p > .10$ for /bæp/.

Local movement and EMG reactions occur in response to jaw perturbations that are introduced in both opening and closing phases of the gestures. The very pronounced OOI acitivity when the load occurs during the opening phase of jaw motion may be indicative of the upcoming requirement of lip closure. Because the mean lower-lip position (independent of jaw movement) is lower as a result of the perturbation, it must move further and more rapidly to contribute to bilabial closure. Hence, an increase in muscle activity is not surprising. The active changes in lower-lip muscle activity in this subject contrast with the passive "shearing" effects exhibited by a different subject in Experiment 2 (and possibly in Experiment 1 as well). Note that the form of the jaw trajectories in the same phonetic context (/bæb/) is also dramatically different for the two subjects. For the first subject, the jaw was essentially halted by a load applied during the raising trajectory (see Figure 3). For the subject in this experiment,

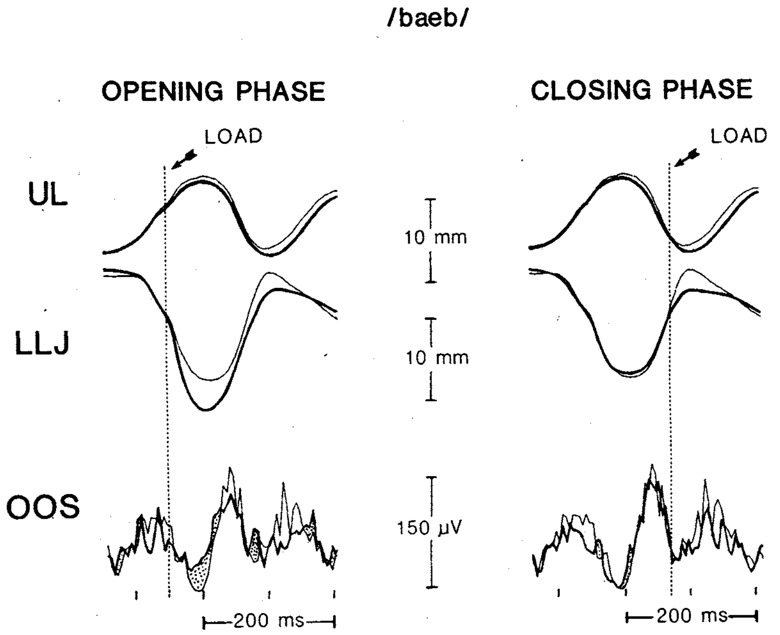

Figure 13. Average upper lip (UL) and lower lip plus jaw (LLJ) trajectories for the utterance /bæb/ under perturbed (thick line) and control (thin line) conditions. (OOS is the rectified and averaged, but unsmoothed, electromyographic response of an upper lip lowering muscle, orbicularis oris superior.)

the load did not have such an effect on the jaw trajectory. These between-subject differences in jaw trajectory in reaction to a load may influence the extent to which a structure linked to the jaw (the lower lip) actively participates. A sudden halting of the jaw may cause a shearing response in the lower lip, whereas a reduction in the magnitude of the load or a stronger jaw reaction to the load may be associated with a more active neuromuscular response in locally linked articulators. A systematic manipulation of load magnitude could help resolve this question.

Although we did not expect the patterns of cooperation among articulators to be identical among subjects, we did predict (provided anatomical limitations have not been violated) that the integrity of the phonetic act would be preserved. What then of phase-dependent remote effects? In Figures 13 and 14 we display the upper-lip movement and EMG traces for perturbed and control trials of /bæb/ utterances (Figure 13) and /bæp/ utterances (Figure 14). To aid comparison, the trajectories for the lower lip plus jaw are also shown. When the perturbation was applied during the opening phase, the upper-lip trajectories were variable and no different from those for control trials when measured at the peak raising point, for /bæb/, $t(14) = 1.45$, $p > .10$, and for /bæp/, $t(17) = 1.70$, $p > 1.0$. However, in opening-phase perturbation trials, the upper lip did lower further on perturbed trials that it did on control trials when lip position was measured at peak *closure,* for /bæb/, $t(14) = 3.65$, $p < .01$, and for /bæp/, $t(17) = 3.51$, $p < .01$. Presumably this lowering occurs to accommodate the reduction in lower lip–jaw height.

When the load was applied during closure, there was again a significant lowering of the upper lip for both /bæb/ utterances, $t(12) = 2.77$, $p < .01$, and /bæp/ utterances, $t(18) = 2.68$, $p < .02$, but no differences earlier in the trajectory at the point of the peak raising movement, for /bæb/, $t(12) = 1.22$ and $t(18) = -1.32$ for /bæp/, $ps > .10$.

In general, although the upper-lip muscle recordings are good, clear differences between perturbed and control trials in either timing

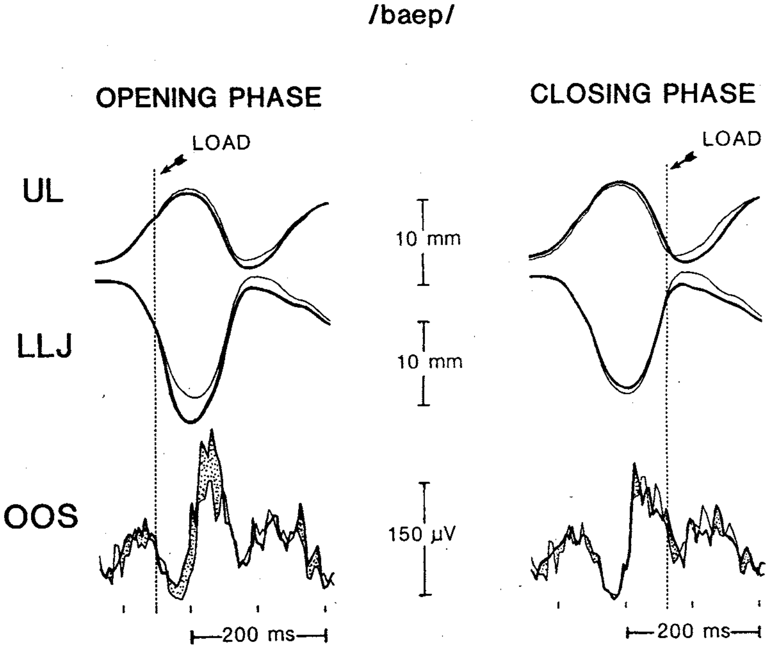

Figure 14. Average upper lip (UL) and lower lip plus jaw (LLJ) trajectories for the utterance /bæp/ under perturbed (thick line) and control (thin line) conditions. (OOS is the rectified and averaged, but unsmoothed, electromyographic response of an upper lip lowering muscle, orbicularis oris superior.)

or magnitude were not readily discernible. For this subject, at least, OOS muscle activation may be sufficient to generate upper-lip motion until a collision with the lower lip occurs. In short, there may be no necessary requirement for a finely modulated EMG response in the upper lip because bilabial consonants are characterized by fixed boundary conditions.

General Discussion

Even simple speech gestures involve cooperation among many degrees of freedom operating at respiratory, laryngeal, and supralaryngeal levels. Bernstein (1967) hypothesized that rather than controlling each degree of freedom separately, the central nervous system collects multiple degrees of freedom together into functional synergies or coordinative structures that then behave, from the perspective of control, as a single unit. The present research addresses Bernstein's hypothesis in an effort to identify and analyze coordinative structures in speech. In this regard, it contrasts with much other work on motor control whose focus is restricted to actions of a single joint (see Stein, 1982, for many examples).

The hallmark of a coordinative structure as we define it (see also Boylls, 1975; Fowler, 1977; Kelso & Holt, 1980; Kelso & Saltzman, 1982; Kelso et al., 1979; Kugler, Kelso, & Turvey, 1980; Nashner et al., 1979; Turvey, 1977) is the temporary marshaling of many degrees of freedom into a task-specific, functional unit. This definition should not be confused with the traditional, reflex-based use of the term *synergy* elaborated, for example, by Easton (1972). As Szentagothai and Arbib (1974) have pointed out, such use of the term "is too restrictive to capture the concepts" (p. 165). Partly in response to these authors' request for "a redefinition of synergies to revitalize motor systems research" (Szentagothai & Arbib, 1974, p. 165), we have provided a recent elaboration of coordinative structures in terms of their neurophysiological and behavioral manifestations (Kelso & Tuller, 1983/1984; Kelso, Tuller, & Harris, 1981/1983).

The task specificity hypothesized by coordinative structure theory is supported by the findings in the present experiments. For the production of both /b/ and /z/, rapid and highly distinctive patterns of the upper lip, lower lip, and tongue occurred in response to unexpected jaw loadings so that the desired sound was produced. In all cases, the adjustments, though varied, were such as to preserve the integrity of the phonetic act. For example, for /z/ frication in Experiments 1 and 2, there was no detectable upper-lip movement. However, because the jaw was much lower than usual, highly amplified tongue-muscle activity, necessary to obtain an appropriate alveolar position for fricative production, was observed. As the lips did in /bæb/, the tongue in /bæz/ responded remarkably quickly on the first perturbation trial and again with no slurring or distortion perceptible to a listener. As in recent studies of bite-block speech (akin to speaking with a pipe in one's mouth), in which sensory information was drastically reduced by anesthetization of oral structures combined with auditory masking, we found no evidence of any short-term "learning" (cf. Kelso & Tuller, 1983). Articulatory "compensation" was achieved, therefore, with little or no practice.

The coordinative-structure account applies equally well to disruptions that are static and anticipated (like the bite-block experiments) and those that are time varying and unanticipated. Adjustment to either type of perturbation is a predictable outcome of an ensemble whose constituent muscles function cooperatively as a single unit. If the operation of certain variables is fixed, as it is in bite-block speech, or unexpectedly disturbed as a result of on-line perturbation, functionally linked variables will preserve the synergistic constraint. As we have emphasized before (Kelso & Tuller, 1983; see also Abbs & Gracco, 1983), "compensation" is characteristic of the speech system's normal mode of operation. For example, in a study of respiratory function during speech, Hixon, Mead, and Goldman (1976) found that the relative contributions of thorax and abdomen movements adjust in order to preserve subglottal pressure level across large postural changes (e.g., lying versus standing). Similarly, Sussman, MacNeilage, and Hanson (1973), in a study of lip and jaw movements in a variety of vowel-consonant-vowel triads, observed that jaw elevation at consonant closure was directly proportional to the height of the following vowel. Thus, to occlude the vocal tract for /p/ production in /æpæ/ versus /æpi/, the lips must "compensate" differentially to accommodate different jaw positions. Both of these studies suggest task-specific cooperation in naturally occurring situations.

One account of multimovement adjustments to unanticipated disruptions posits a closed-loop peripheral feedback mechanism (cf. Abbs, 1979; Folkins & Abbs, 1975). As we have pointed out, however (Fowler & Turvey, 1978, 1980; Kelso, 1981; Kelso & Tuller, 1983), a closed-loop system, though capable in theory of detecting and correcting "errors" in the perturbed structure, has no mechanism for producing adaptive movements in remote and nonbiomechanically linked articulators. Because of this limitation, Abbs and Gracco (1983) have recently proposed an "open-loop adjustment process" to account for upper-lip changes that occur as a result of lower-lip perturbations "based upon a pre-established sensorimotor translation between lower-lip afferent signals and upper lip motor actions" (p. 393). This notion is similar to the predictive, feedforward processes hypothesized by Ito (1975) for vestibular–ocular interactions during eye–head movement and elaborated more recently by Houk and Rymer (1981). Viable though feedforward may be, it is nevertheless difficult to envisage how—without the concept of coordinative structure—all the computation could be preestablished in such a way that the lips, jaw, and tongue (not to mention other possible articulators not observed in these experiments) perform precisely those movements that meet the speaker's objective. The problem is exacerbated when unexpected challenges are introduced whose dimensions (e.g., magnitude, duration, site) are potentially manifold. However, although the particular neural processes involved await clarification, a central conclusion of Abbs (in press), that the "nervous system prioritizes acoustically and aerodynamically significant multiaction gestures over individual movements and muscle actions" and that "these sensorimotor capabilities relieve the nervous system of having to prespecify the motor details" has much in common with the concept of coordinative structure.

The results of Experiment 3 provide further evidence for task-specific, coordinative-structures in speech production. Remote responses in upper lip were found to be phase dependent; that is, they occurred only when they were functionally appropriate. Similar functionally-based forms of neuromuscular cooperation have been observed in recent studies of posture in humans (e.g., Cordo & Nashner, 1982; Marsden, Merton, & Morton, 1981, 1983). For example, Marsden et al. (1983) applied a small perturbation to the thumb of a standing subject as he was performing a thumb tracking task, and observed reactions in muscles remote from the prime mover (e.g., in pectoralis major, in the triceps of the opposite limb when it gripped a table top, and in the opposite thumb when it served to stabilize motion). These distant reactions were very rapid (e.g., 40 ms in pectoralis), sometimes faster than the local autogenetic response in the structure perturbed. Although exquisitely sensitive, these reactions are not caused by length changes in the postural muscles themselves. Perturbations of only 7.5 g to the thumb or wrist, often not even detected by the subject, were associated with brisk, distant reactions.

As predicted by coordinative structure theory, distant reactions occur only when they perform a useful function and they are flexibly tuned to that function. Marsden et al. (1983) found that postural responses in triceps disappeared if the hand was not exerting a firm grip on the object. If, instead of holding a table top, the nontracking hand held a cup of tea, the responses in triceps reversed, which is exactly what they have to do to prevent the tea from spilling. Marsden et al. (1983) concluded that these rapid, remote effects "constitute a distinct and apparently new, class of motor reaction" (p. 645) that has led them to abandon an account based on stretch reflexes.

In the present experiments, although the adaptive reactions could be described as reflexive because of their speed, their mutability speaks against any fixed reflex connections or rigidly constructed servomechanisms. Similarly, it is extremely doubtful that the articulatory patterns we observed in response to jaw loading at different phases of motion and in different phonetic contexts are completely preprogrammed. Rather, the system we are dealing with appears to be "softly" assembled and flexible in function, not machinelike and rigid (Iberall, 1978). The present data, preliminary though they are, suggest that the mode of operation of the speech system is intrinsically task oriented and that both rapid local and remote articulatory contributions are involved in the implementation of cooperative action. Most important, however, the adjustments appear to reflect a synergistic organization among articulators that is tailored to the requirements of the spoken act.

References

Abbs, J. H. (1979). Speech motor equivalence: The need for a multi-level control model. *Proceedings of the Ninth International Congress of Phonetic Sciences, 2,* 318–324.

Abbs, J. H. (in press). Invariance and variability in speech production: A distinction between linguistic intent and its neuromotor implementation. In J. S. Perkell & D. H. Klatt (Eds.), *Invariance and variability in speech processes.* Hillsdale, NJ: Erlbaum.

Abbs, J. H., & Cole, K. J. (1982). Consideration of bulbar and suprabulbar afferent influences upon speech motor coordination and programming. In S. Grillner, B. Lindblom, J. Lubker, & A. Persson (Eds.), *Speech motor control* (pp 159–186). Oxford: Pergamon Press.

Abbs, J. H., & Gracco, V. L. (1983). Sensorimotor actions in the control of multimovement speech gestures. *Trends in Neuroscience, 6,* 391–395.

Abbs, J. H., & Gracco, V. L. (in press). Control of complex motor gestures and orofacial muscle responses to load perturbations of the lips during speech. *Journal of Neurophysiology.*

Bernstein, N. A. (1967). *The coordination and regulation of movements.* London: Pergamon Press.

Bizzi, E., Chapple, W., & Hogan, N. (1982). Mechanical properties of muscles: Implications for motor control. *Trends in Neuroscience, 5,* 395–398.

Boylls, C. C. (1975). *A theory of cerebellar function with applications to locomotion: II. The relation of anterior lobe climbing fiber function to locomotor behavior in the cat* (COINS Technical Report 76-1). Amherst, MA: University of Massachusetts, Department of Computer and Information Science.

Cordo, P. J., & Nashner, L. M. (1982). Properties of postural adjustments associated with rapid arm movements. *Journal of Neurophysiology, 47,* 287–302.

Easton, T. A. (1972). On the normal use of reflexes. *American Scientist, 60,* 591–599.

Evarts, E. V. (1982). Analogies between central motor programs for speech and for limb movements. In S. Grillner, B. Lindblom, J. Lubker, & A. Persson (Eds.), *Speech motor control* (pp. 19–41). Oxford: Pergamon Press.

Folkins, J. W., & Abbs, J. H. (1975). Lip and jaw motor control during speech: Responses to resistive loading of the jaw. *Journal of Speech and Hearing Research, 18,* 207–220.

Folkins, J. W., & Zimmermann, G. N. (1982). Lip and jaw interaction during speech: Responses to perturbation of lower-lip movement during bilabial closure. *Journal of the Acoustical Society of America, 71,* 1225–1233.

Forssberg, H. (1982). Spinal locomotion function and descending control. In B. Sjolund & A. Bjorkland (Eds.), *Brainstem control of spinal mechanisms.* New York: Ferström Foundation Series.

Forssberg, H., Grillner, S., & Rossignol, S. (1975). Phase dependent reflex reversal during walking in chronic spinal cats. *Brain Research, 55,* 247–304.

Fowler, C. A. (1977). *Timing control in speech production.* Bloomington, IN: Indiana Linguistics Club.

Fowler, C. A., Rubin, P., Remez, R. E., & Turvey, M. T. (1980). Implications for speech production of a general theory of action. In B. Butterworth (Ed.), *Language production* (pp. 373–420). New York: Academic Press.

Fowler, C. A., & Turvey, M. T. (1978). Skill acquisition: An event approach with special reference to searching for the optimum of a function of several variables. In G. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 1–40). New York: Academic Press.

Fowler, C. A., & Turvey, M. T. (1980). Immediate compensation in bite-block speech. *Phonetica, 37,* 306–326.

Gelfand, I. M., Gurfinkel, V. S., Tsetlin, M. L., & Shik, M. L. (1971). Some problems in the analysis of movements. In I. M. Gelfand, V. S. Gurfinkel, S. V. Fomin, & M. Tsetlin (Eds.), *Models of the structural-functional organization of certain biological systems* (pp. 329–345). Cambridge, MA: MIT Press.

Greene, P. H. (1972). Problems of organization of motor systems. In R. Rosen & F. Snell (Eds.), *Progress in theoretical biology* (pp. 303–338). New York: Academic Press.

Greene, P. H. (1982). Why is it easy to control your arms? *Journal of Motor Behavior, 14,* 260–286.

Grillner, S. (1982). Possible analogies in the control of innate motor acts and the production of sound in speech. In S. Grillner, B. Lindblom, J. Lubker, & A. Persson (Eds.), *Speech motor control* (pp. 217–229). Oxford: Pergamon Press.

Hamlet, S. L., & Stone, M. (1978). Compensatory alveolar consonant production induced by wearing a dental prosthesis. *Journal of Phonetics, 6,* 227–248.

Hixon, T. J., Mead, J., & Goldman, M. D. (1976). Dynamics of chest wall during speech production: Function of the thorax, ribcage, diaphragm and abdomen. *Journal of Speech and Hearing Research, 19,* 297–356.

Houk, J. C., & Rymer, W. (1981). Neural control of muscle length and tension. In V. B. Brooks (Ed.), *Handbook of physiology: Sec. 1. Vol. II. Motor control, Part 1* (pp. 257–323). Bethesda, MD: American Physiological Society.

Hughes, O. M., & Abbs, J. H. (1976). Labial mandibular coordination in the production of speech: Implications for the operation of motor equivalence. *Phonetica, 33,* 199–221.

Iberall, A. S. (1978). Cybernetics offers a (hydrodynamic) thermodynamic view of brain activities. An alternative to reflexology. In F. Brambilla, P. K. Bridges, E. Endroczi, & C. Heusep (Eds.), *Perspectives in endocrine psychobiology* (pp. 529–564). New York: Wiley.

Ito, M. (1975). The control mechanisms of cerebellar motor systems. In E. V. Evarts (Ed.), *Central processing of sensory input leading to motor output* (pp. 293–304). Cambridge, MA: MIT Press.

Kelso, J. A. S. (1981). Contrasting perspectives on order and regulation in movement. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 437–457). Hillsdale, NJ: Erlbaum.

Kelso, J. A. S., & Holt, K. G. (1980). Exploring a vibratory systems analysis of human movement production. *Journal of Neurophysiology, 43,* 1183–1196.

Kelso, J. A. S., & Saltzman, E. L. (1982). Motor control: Which themes do we orchestrate? *The Behavioral and Brain Sciences, 5,* 554–557.

Kelso, J. A. S., Southard, D. L., & Goodman, D. (1979). On the nature of human interlimb coordination. *Science, 203,* 789–1031.

Kelso, J. A. S., & Tuller, B. (1983). "Compensatory articulation" under conditions of reduced afferent information: A dynamic formulation. *Journal of Speech and Hearing Research, 26,* 217–224.

Kelso, J. A. S., & Tuller, B. (1984). A dynamical basis for action systems. In M. S. Gazzaniga (Ed.), *Handbook of cognitive neuroscience* (pp. 321–356). New York: Plenum Press. (Reprinted from *Haskins Laboratories Status Report on Speech Research,* 1983, *SR-73,* 177–216)

Kelso, J. A. S., Tuller, B. H., & Harris, K. S. (1983). A "dynamic pattern" perspective on the control and coordination of movement. In P. F. MacNeilage (Ed.), *The production of speech* (pp. 137–173). New York: Springer-Verlag. (Reprinted from *Haskins Laboratories Status Report on Speech Research,* 1981, *SR-65,* 157–196)

Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 1–47). Amsterdam: North-Holland.

Lindblom, B., & Sundberg, J. (1971). Acoustical consequences of lip, tongue, jaw, and larynx movement. *Journal of the Acoustical Society of America, 50,* 1166–1179.

MacNeilage, P. F. (1970). Motor control of serial ordering of speech. *Psychological Review, 77,* 182–196.

MacNeilage, P. F. (1980). Distinctive properties of speech motor control. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 607–621). Amsterdam: North-Holland.

Marsden, C. D., Merton, P. A., & Morton, H. B. (1981). Anticipatory postural response in the human subject. *Journal of Physiology* (London) *275,* 47P–48P.

Marsden, C. D., Merton, P. A., & Morton, H. B. (1983). Rapid postural reactions to mechanical displacement of the hand in man. In J. E. Desmedt (Ed.), *Motor control mechanisms in health and disease* (pp. 645–659). New York: Raven Press.

Nashner, L. M., Woolacott, M., & Tuma, G. (1979). Organization of rapid response to postural and locomotor-like perturbations of standing man. *Experimental Brain Research, 36,* 463–476.

Riordan, C. J. (1977). Control of vocal-tract length in speech. *Journal of the Acoustical Society of America, 62,* 998–1002.

Soechting, J. E., & Lacquaniti, F. (1981). Invariant characteristics of a pointing movement in man. *Journal of Neuroscience, 1,* 710–720.

Stein, R. B. (1982). What muscle variables does the central nervous system control? *The Behavioral and Brain Sciences, 5,* 535–577.

Sussman, H. M., MacNeilage, P. F., & Hanson, R. J. (1973). Labial and mandibular dynamics during the production of bilabial consonants: Preliminary observations. *Journal of Speech and Hearing Research, 16,* 397–420.

Szentagothai, J., & Arbib, M. A. (Eds.). (1974). Conceptual models of neural organization. *Neurosciences Research Program Bulletin, 12*(3).

Tuller, B., & Fitch, H. (1980). Preservation of vocal tract length in speech: A negative finding. *Journal of the Acoustical Society of America, 6,* 1068–1071.

Turvey, M. T. (1977). Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting and knowing: Toward an ecological psychology* (pp. 211–265). Hillsdale, NJ: Erlbaum.

Zimmermann, G., Kelso, J. A. S., & Lander, L. (1980). Articulatory behavior pre and post full-mouth tooth extraction and alveoloplasty: A cinefluorographic study. *Journal of Speech and Hearing Research, 23,* 630–645.

Received November 17, 1983
Revision received May 25, 1984 ■