

“COMPENSATORY ARTICULATION” UNDER CONDITIONS OF REDUCED AFFERENT INFORMATION: A DYNAMIC FORMULATION

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A well-established feature of speech production is that talkers, faced with either anticipated or unanticipated perturbations, can spontaneously adjust the movement patterns of articulators such that the acoustic output remains relatively undistorted. Less clear is the nature of the underlying processes involved. In this study we examined five subjects' productions of the point vowels /i, a, u/ in isolation and of the same vowels embedded in a dynamic speech context under normal conditions and under a combined condition, in which (a) the mandible was fixed by means of a bite block; (b) proprioceptive information was reduced through bilateral anesthetization of the temporomandibular joint; (c) tactile information from the oral mucosa was reduced by application of a topical anesthetic; and (d) auditory information was masked by white noise. Minimal distortion of the formant patterns was found in the combined condition. These findings are unfavorable for central (e.g., predictive simulation) or peripheral closed-loop models, both of which require reliable peripheral information; they are more in line with recent work suggesting that movement goals may be achieved by muscle collectives that behave in a way that is qualitatively similar to a nonlinear vibratory system.

The remarkable generativity of human movement is a mystery that continues to resist explanation. Within limits, people (and animals) can achieve the same “goal” through a variety of kinematic trajectories, with different muscle groups and in the face of ever-changing postural

and biomechanical requirements. This phenomenon, variously referred to as *motor equivalence* (Hebb, 1949) or *equifinality* (von Bertalanffy, 1973), has been demonstrated again quite recently by Raibert (1978), who showed writing patterns to be characteristic of the same

individual even when produced by structures (such as the foot or mouth) that had never previously been used for the act of writing.

Human language is generative in a qualitatively similar way. We seem to have a potentially infinite number of ways of constructing sentences. Nor is it trivial that language, even when stripped of its symbolic component, is a creative or generative activity. Articulatory maneuvers for producing speech sounds can be effected in spite of continuously varying initial conditions. Often the same phonetic segment in different environments can be achieved by very different movement trajectories to different positions.

One commonly used experimental paradigm for examining equifinality in speech takes the form of placing a bite block between the teeth, thus fixing the position of the mandible. Under such conditions, so-called "steady-state" vowels can be produced apparently without the need for on-line acoustic feedback. Formant patterns typical for the speaker are obtained under bite-block conditions even at the first glottal pulse (Gay, Lindblom, & Lubker, 1981; Lindblom, Lubker, & Gay, 1979; Lindblom & Sundberg, 1971). Moreover, speakers are capable of such "compensatory articulation" with little (if any) articulatory experimentation. Recent work on bite-block speech has shown that the response times required to produce vowels of the same acoustic quality under normal and bite-block conditions are nearly identical. In addition, the degree of "compensation" for the bite block (as indexed by deviations from normal formant frequencies) remained unchanged as a function of practice (Fowler & Turvey, 1980; Lubker, 1979). The evidence, then, favors an interpretation that articulatory adjustments to novel contextual conditions created by a bite block are essentially immediate.

What kind of control processes could account for the adaptive, generative nature of speech production? An open-loop control system in which commands for producing a given vowel prescribe in detail the activities of relevant muscles can be dismissed because, by definition, such systems are insensitive to changing contextual conditions. On the other hand, closed-loop control offers the advantage of adjustment to different initial conditions. In peripheral closed-loop feedback systems, a sensory goal in the form of a spatial (MacNeilage, 1970) or auditory (Ladefoged, DeClerk, Lindau, & Papcun, 1972; MacNeilage, 1980) target is paired with an appropriate set of commands for accomplishing the goal. Resulting sensory consequences are then compared with the sensory goal so that corrections can be made. A potential problem with peripheral closed-loop control is that the corrective process requires time (at least one cycle around the corrective loop). However, if the adjustment to novel conditions is indeed immediate (thus excluding the need for trial and error methods), then a closed-loop mechanism tied to the peripheral motor system fails to capture the phenomenon of interest.

An alternative account favored by Lindblom and colleagues (e.g., Lindblom et al., 1979) replaces the peripheral feedback loop with a central simulation process that

derives the expected sensory consequences from a *simulated* set of motor commands before the *actual* efferent signals are sent to the periphery. An internal comparison between the simulated and "target" sensory consequences yields an error signal based on which new (and correct) commands can be emitted. In this manner, adjustments to changes in context can be made in the internal simulation without incurring erroneous effects at the periphery.

Note that the models discussed thus far assume that reliable peripheral information about the articulators' initial conditions is available before motor commands (simulated or actual) are generated. In the peripheral closed-loop model, for example, sensory input must be compared to the internal referent before the output of command signals. In the central loop model, simulated motor commands are generated for the initial conditions that currently exist (Lindblom et al., 1979). It is not clear in the latter formulation what would happen if contextual conditions changed between the time that simulated and actual motor commands were generated. A more efficient system would be continuously sensitive to, and capable of modulation by, contextual conditions. For the sake of argument, however, let us assume with Lindblom et al. that one benefit of the internal loop is its speed of correction; possibly the loop is so fast that appropriate output can be generated before contextual conditions have changed.

In any case, for both closed-loop models, elimination or reduction of peripheral information about initial conditions should affect the system's ability to adjust to the novel situation created by a bite block. There are only limited data on this point. Gay and Turvey (1979) found that a single subject (a phonetician) made several attempts before producing a perceptually acceptable token (with appropriate formant frequencies) of the vowel /i/ under conditions in which a bite block was combined with topical anesthesia of the oral mucosa and a bilateral nerve block of the temporomandibular joint. Although this result has suggested to some (cf. Perkell, 1979) that joint and tactile information are used to establish an "orosensory frame of reference," we believe there are grounds for caution. One problem is that it is unclear how, given the probably considerable reduction of peripheral information, Gay and Turvey's subject was capable of adaptive adjustment at all. One possibility, which we consider here, is that auditory information may have played a potentiating role. Although auditory information does not appear to be a necessary condition for compensatory articulation (e.g., Lindblom et al., 1979), the Gay-Turvey experiment does not preclude an auditory contribution in "recalibrating" the speech system when information from motor structures is reduced or rendered unreliable.

The present experiment was designed to examine the role of auditory and somesthetic information in accounts of "immediate adjustment" by asking naive subjects to produce vowels under normal conditions and under bite-block conditions in which somatosensory information was reduced (if not eliminated) and audition was

masked by white noise. In addition we question whether the so-called "steady-state" paradigm for bite-block vowels reflects normal dynamic speech motor processes. As is shown, the availability of normal peripheral information from either auditory or peripheral motor structures does not appear to be crucial to immediate adjustment. We take this result as nonsupportive for extant models of the phenomenon. In their place, we offer a class of model, emerging in other areas of motor control (Bizzi, 1980; Fel'dman, 1966, 1980; Kelso, 1977; Kelso & Holt, 1980; Kelso, Holt, Kugler, & Turvey, 1980; Polit & Bizzi, 1978) as well as in the recent speech production literature (cf. Fowler, 1977; Fowler, Rubin, Remez, & Turvey, 1980), that identifies functional groupings of muscles as exhibiting properties qualitatively similar to a nonlinear oscillatory system. The bottom line of this model and of the present paper is that the equifinality characteristic of vowel production may not be prescribed by closed-loop servomechanisms of the peripheral or central kind. Rather, we argue that it may be a consequence of the parameterization of a dynamical system whose design is intrinsically self-equilibrating—that is, a design in which equilibrium points are a natural by-product of the stiffness and damping specifications for the vowel-producing system.

METHOD

Subjects

Four female adult volunteers were paid to participate in this experiment. All were naive to the purpose of the experiment. A fifth subject (male) was phonetically trained and had prior experience in a similar experiment (see Gay & Turvey, 1979). No subject had any known neurological impairment.

Stimuli

The vowels /i, a, u/ were said in isolation and in a /p/-vowel-/p/ context. The /pVp/ syllables were spoken in the carrier phrase, "A _____ again." Utterances were produced in three groups of three tokens of a particular vowel or phrase for each condition. The subjects were instructed to produce all tokens of a given utterance in exactly the same fashion, with a clear pause after each token. They were also told not to talk between experimental conditions or to practice the production task.

Conditions

The bite blocks were small acrylic cylinders with wedges carved out of each end so that they could fit snugly between the teeth. A 5-mm cylinder was used to restrict the normally low jaw position for production of /a/ and /pap/. Either a 17-mm or a 23-mm cylinder was used (depending on the individual subject's oral dimen-

sions) for production of /i, u, pip, pup/, which normally involve a high jaw position.

All anesthetic procedures were performed by Dr. Robert Gross, a specialist in oral and maxillofacial surgery who collaborated with us in earlier work (Tuller, Harris, & Gross, 1981). Tactile information from the oral mucosa was reduced by spraying the surface of the tongue and oral cavity with a 2% Xylocaine solution. The effectiveness of the topical anesthetic agent was tested by pricking the surfaces with a needle. Spraying and pricking were continued until the subject no longer reported sensation. A few catch trials also were included in an attempt to ensure honest reporting from the subject. Information from mechanoreceptors in the jaw was reduced by injecting percutaneously a 2% Xylocaine solution directly into left and right temporomandibular joint capsules to achieve auriculotemporal nerve blockage. This procedure has been shown to impair perception of joint position and movement (Thilander, 1961). This condition is referred to as the *TMJ block*.

In order to restrict the availability of auditory information, white noise was presented to the subject over headphones at approximately 90 dB SPL. The subject was prevented from increasing vocal intensity in the following manner. First, we determined how far the needle on a VU meter was deflected during conversational speech without the masking noise. The subject then was instructed to monitor the VU meter and restrict the excursion of the needle to the same level or below when speaking with the masking noise.

All subjects spoke with and without the bite block prior to the application of anesthesia and under all subsequent experimental conditions. Two of the four naive subjects received the TMJ block before the topical anesthesia, and the other two subjects underwent topical anesthesia first. In each of these pairs, one subject spoke under conditions of auditory masking and the other subject was allowed normal auditory information. The phonetically trained subject received topical anesthesia before the TMJ block and spoke with masking noise in combination with these two procedures.

Measurement Procedure

Individual utterances were input through a Ubiquitous Spectrum Analyzer to a Honeywell DDP-224 computer, using a 12.8-msec window and a 40-Hz frequency resolution. The first and second formants of each utterance were measured from a spectral section display. As in previous experiments (e.g., Fowler & Turvey, 1980; Lindblom et al., 1979), acoustic measures of the isolated vowels were made at the first glottal pulse. For many English speakers the isolated vowels may not be truly static; that is, they may show some articulatory movement and thus some shifting of formant frequencies. Nevertheless, the procedure which was adopted was to measure formant frequencies at the first glottal pulse. For the /p/-vowel-/p/ syllables, *F1* and *F2* values were taken from the point within the vowel at which *F2* was

most extreme. This point was chosen as the closest approximation to the "target" vowel formants.

RESULTS

The main interest of the present experiment rests on a comparison of speech under normal conditions and under conditions of reduced peripheral information. Because of the lack of any consistent acoustic change, we have restricted our discussion to normal or auditorily masked speech compared with the most extreme condition of sensory deprivation, omitting the intermediate conditions. Figure 1 shows the mean values for F_1 and F_2 for each subject. The top half shows the mean formant values for the isolated vowels and the bottom half, the mean formant values for the /p/-vowel-/p/ syllables.

Each subject's nine normal productions of a given utterance were compared using t tests with his or her productions under the most extreme condition of sensory deprivation. Four of the five subjects showed no differences in formant frequency values between the normal and the extremely deprived conditions. This was the case regardless of whether the vowels were spoken in isolation or in a consonantal frame; $t(8)$ values ranged from .05 to 1.79, $ps > .1$. For Subject 1, a significant mean difference occurred between masking only and the most deprived condition for F_1 and F_2 of the vowel /u/. It is difficult to account for this anomaly. The presence of a bite block might be expected to raise all formant frequencies for productions of /u/ because of possible structural limitations on lip protrusion and constriction or because of increased pharyngeal constriction with the

jaw lowered. In contrast, however, this subject's productions of /u/ with a bite block showed frequencies which were 95 Hz lower F_1 and 363 Hz lower F_2 than when there was no bite block. Neither can the effect be attributed only to masking, which might implicate higher formant frequencies, because the formant values for combined sensory deprivation conditions are very similar with and without masking. It is also worth remarking that Subject 5 in Figure 1 is the phonetically trained subject. His results conform to the general pattern shown by naive subjects.

Before concluding that these results reflect immediate adjustment in the deprived condition, it is necessary to exclude the possibility that systematic changes in formant values occurred over trials. We examined this statistically for all subjects by performing linear regression analyses across trials of each subject's productions under normal and deprived conditions. To determine whether the slopes of the regression lines differed from zero, t tests were performed. Of the 60 analyses performed (5 subjects \times 6 utterance types \times 2 formants), only two showed a nonzero slope; nonsignificant $t(7)$ values ranged from .00 to .84, $ps > .1$. One of the two regression lines with nonzero slope occurred in the control condition for Subject 1's productions of /pip/; $t(7) = 2.92$, $p < .05$. The other regression line with positive slope is illustrated in Figure 2, which shows the F_1 and F_2 values for individual tokens, in order, for the vowel /i/ produced by Subject 5 under the most extreme conditions (i.e., topical anesthesia, TMJ block, a 23-mm bite block, and masking noise). Also shown are the mean F_1 and F_2 values for this combined condition and for the normal condition. The slope of the regression line for F_2

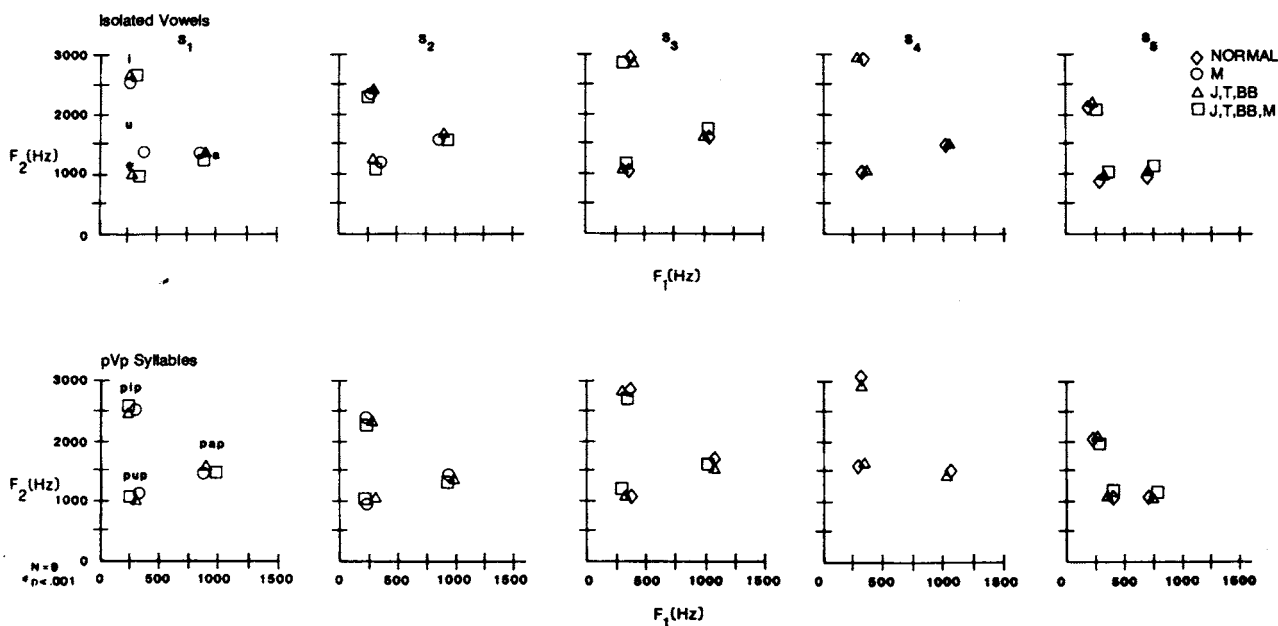


FIGURE 1. Mean values of F_1 (x axis) and F_2 (y axis) for nine repetitions of the indicated utterances. Data for the five subjects are presented separately. Top: Isolated vowels. Bottom: /pVp/ syllables. M = masking noise, J = TMJ block, T = topical anesthesia, BB = bite block.

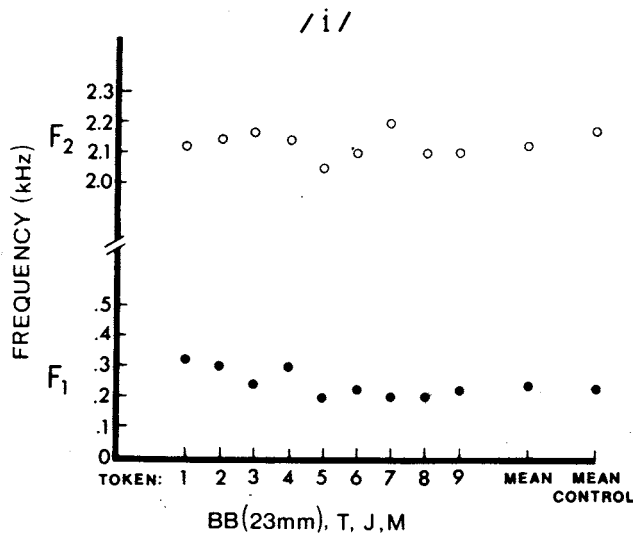


FIGURE 2. F_1 and F_2 values for individual tokens, in order, of the vowel /i/ produced by Subject 5 under the most extreme experimental condition.

over trials is not significantly different from zero. Although the slope of the line formed by F_1 across tokens does differ from zero [$t(7) = 3.7, p < .01$], it does not differ significantly from the line formed in the (non-bite block) control condition. In general, there was little or no evidence for any systematic learning effect occurring over trials in either the deprived or control conditions.

DISCUSSION

The present data are not easily explained by the conventional models of movement control that have been proposed to account for the remarkable context sensitivity of the speech production system. Closed-loop models, involving either central or peripheral comparisons, entail the availability of reliable sensory information about the initial conditions of the articulators. However, our experiment shows that acoustically normal vowels can be produced not only when the normal relationships among the articulators are changed by a bite block, but also when sensory information from auditory, joint, and tactile sources is reduced as well. Furthermore, and as other recent work also suggests (cf. Fowler & Turvey, 1980), articulatory compensation appears to be achieved immediately and with little or no practice. None of our naive subjects' data provided any evidence of short-term adaptation. In support of the latter claim, the data displayed in Figure 2 are actually from the same subject who appeared to display motor learning effects in an earlier study (Gay & Turvey, 1979).¹

¹Indeed, it was after observing the bite-block performance of our naive subjects under reduced information conditions that this person offered to participate in the present experiment. This was a magnanimous gesture for which we express our gratitude.

Before offering an alternative interpretation of our data in terms other than closed-loop models, two caveats may be in order. The first is that our results do not necessarily refute closed-loop control when the system is in its normal mode, that is, when all sources of information are available. The second is that our paradigm in all likelihood does not completely eliminate peripheral information; hence, a closed-loop simulation model cannot be ruled out entirely. Nevertheless, given the reduction or distortion of propriospecific information that was induced in our experiment, we (and surely the proponents of closed-loop models) might have expected much more severe distortion of the acoustics than was observed here.

In spite of these caveats, we believe that a more parsimonious account of the phenomenon can be forwarded. This account does not depend on whether sensory input about the initial positions of articulators is available or not. Thus, there is no requirement for one model when sensory afference is available and another quite different model when it is absent.

The view that we express for the present data has been laid out in some detail elsewhere (Fowler et al., 1980; Kelso, Holt, Kugler, & Turvey, 1980). In brief, it argues that functional groupings of muscles, sometimes called synergies (cf. Gelfand, Gurfinkel, Tsetlin, & Shik, 1971) or coordinative structures (cf. Turvey, Shaw, & Mace, 1978), exhibit behavior qualitatively similar to a (non-linear) mass-spring system. Such systems are intrinsically self-equilibrating in the sense that the end-point of the system, or its "target," is achieved regardless of initial conditions. Thus, in normal and deafferented animals (Bizzi, Dev, Morasso, & Polit, 1978), it can be shown that desired limb positions are attainable without starting position information, even when the limb is perturbed on its path to the target. Similarly, the localization ability of functionally deafferented humans (Kelso, 1977; Kelso & Holt, 1980) and of individuals with the metacarpophalangeal joint capsule surgically removed (Kelso, Holt, & Flatt, 1980) is not affected by altered initial conditions or unexpected perturbations. These data have led to the view that the target of the system is not achieved by means of conventional closed-loop control; rather, its achievement is a consequence of the system's dynamic parameters (mass, stiffness, damping). In such a model, the only parameters that need to be specified for voluntary movement are stiffness and resting length. Kinematic variations in displacement, velocity, and acceleration are consequences of the parameters specified, rather than controlled variables, and sensory "feedback," at least in the conventional computational sense, is not required (cf. Fitch & Turvey, 1978; Kelso, Holt, & Flatt, 1980; Kelso, Holt, Kugler, & Turvey, 1980).

We do not wish to be interpreted as saying that peripheral information is unimportant; the question really is how it is used in the regulation and control of movement. As we have elaborated elsewhere (Kelso, Holt, & Flatt, 1980), standard views of peripheral mechanoreceptors are that they provide feedback about variables such as position, rate, and acceleration. Such feedback is ref-

erential to a structural entity, typically a setpoint that the system is trying to attain. Regulation and control are then affected by means of error detection and correction processes. There are good reasons to believe that this view has been greatly overvalued for biological systems (e.g., Yates, 1979; see also Kelso, 1981). While it might provide an accurate description of a system possessing a simple input-output function, it fails to capture the complexity involved in the control of a dynamical system composed of many muscles.

Multiple factors probably need to be considered in the analysis of muscle ensembles, among which are the geometrical properties of the different cooperating muscles and their nonlinear and nonisotropic characteristics (Titze, Note 1). We believe that a conception of information is required which is unique and specific to the state of the system's dynamics (Kelso, Holt, Kugler, & Turvey, 1980; Kugler, Kelso, & Turvey, 1980). This may not be given in terms of dimension-specific receptor codes but rather geometrically in the form of gradients and equilibrium points in a potential energy function (e.g., Hogan, 1980; Kugler et al., 1980). Recently Fel'dman and Latash (1982b) have presented a model emphasizing the intrinsic relationship between afferent and efferent signals in postural control which they feel "is in good correspondence with ideas [expressed here and elsewhere] about the dynamic nature of motor control and with the general concept that information in the nervous system reflects different forms of dynamic state and intrinsic metrics of control" (p. 188; see also Fel'dman & Latash, 1982a). This view of information as topologically specified in the system's dynamic qualities is obviously novel (but see Thom, 1972) and has yet to be fully explored, but it offers an alternative to simplistic coding schemes in which receptor signals on a single dimension are fed back to a setpoint or a system comprised of multiple setpoints. Interestingly, the appropriateness of the concept of setpoint in biological processes is currently being questioned.²

With respect to the present experiment, the dynamic view argues that the removal or reduction of any one afferent source or even of all of them may not necessarily disrupt the ability of a collective of muscles to achieve a specified equilibrium state. Certainly the evidence presented here bears this out. However, it is likely that the stability of transition processes (as might be reflected in the trajectory of tongue movement) could be affected, as Fel'dman (1974) has pointed out in the case of deafferented limbs. In the absence of information about trajectories, this remains an issue for further investigation.

It is worth noting that the view expressed above is equally applicable to disruptions that are static and anticipated (as in the present bite-block experiment) and to

those that are time varying and unanticipated. For example, recent studies of the latter kind have shown that "compensatory responses" of short latency are observed in perturbed articulators as well as in others that contribute to the same "vocal tract goal" (cf. Abbs, 1979, for review). Current theorizing, however, offers two distinct mechanisms to explain the system's reaction to perturbation: (a) a predictive simulation mechanism for anticipated disruptions (Lindblom et al., 1979) and (b) a closed-loop peripheral feedback mechanism for unanticipated disruptions (Abbs, 1979).³

The analysis offered here views such a distinction as redundant. Immediate adjustment to either type of perturbation is a predictable outcome of a dynamical system in which muscles function cooperatively as a single unit. If the operation of certain variables is fixed, as in the bite block, or unexpectedly altered, as in on-line perturbation, linked variables will automatically assume values appropriate to the constraint relation, as long as biomechanical limitations are not violated. In short, dynamical systems—of which speech is an instance—always operate in a mode that one can describe as "compensatory."

Although we cannot offer a detailed description of the vocal tract muscles in terms of the style of control outlined above, we believe there are some grounds for optimism. Fujimura and Kakita (1979), for example, have performed a three-dimensional simulation of the tongue that uses quantitative control of contractile forces of the muscles actually involved. By treating the tongue muscles (in this case, the posterior and anterior portions of genioglossus) as a cooperative unit and maintaining the relative magnitude of contractile inputs to each muscle, it can be shown that the acoustic pattern for the vowel /i/ is obtainable with a wide variety of absolute force values. Thus, as long as the contractile balance among linked muscles is preserved, the exact magnitude of muscle contraction (beyond a critical value) does not matter (see also Kakita & Fujimura, 1977). The generality of this model is limited, at this time, to a single point vowel. Nevertheless, the nonlinear relationship between muscle forces and acoustic pattern allows, or rather provides for, a context-conditioned production system. As in recent accounts of limb localization, invariant targets can be attained with different stiffness specifications as long as the balance in stiffness among relevant muscles is preserved.

As a final point, the analysis offered here suggests a commonality in function between the system capable of

²Although recognizing that setpoints can play a useful role in certain engineering applications, Cecchini, Melbin, and Noordergraaf (1981) stated with reference to biological control that "there is no basis to conclude the existence of separate structural entities . . . that define setpoints" and that setpoints are better considered "an arbitrary convenience" (p. 393). (See also Kelso, 1981; Kugler, Kelso, & Turvey, 1982; Yates, 1979.)

³There are, however, recent data that also raise questions about the requirements for distinctive mechanisms. Folkins and Zimmermann (1981) found that the timing of EMG activity in a jaw raiser (medial pterygoid) was similar in normal and jaw-fixed conditions for the syllable /pæ/. If the closed-loop system enables reorganization of articulators when initial conditions are changed, why, Folkins and Zimmermann asked, is there extra activity in a muscle no longer involved in the movement? One answer consonant with the analysis offered here is that medial pterygoid is a part of a constrained relationship among a group of muscles and so performs in a roughly similar way for the syllable /pæ/, whether the jaw is fixed or not.

producing vowels and that involved in the attainment and maintenance of limb postures. Both systems are materially distinct from each other but may share behaviors qualitatively like a nonlinear mass spring. The strategy of identifying functional organizations common to structurally very different systems was central to Rashevsky's (1954) early attempts at formulating the field of relational biology and remains at the core of dynamical systems theory (e.g., Rosen, 1970). The non-trivial claim, then, is that speech and limb movements are dynamically alike in sharing a common solution to the equifinality problem.

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