

Pattern Formation in Speech and Limb Movements Involving Many Degrees of Freedom*

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INTRODUCTION

There are over 792 muscles and 100 joints in the human body, while, according to my eldest son's biology textbooks, the elephant's trunk contains over 40000 muscles and tendons. Thus, any activity of the human body or the elephant's trunk involves the cooperative effort of very many degrees of freedom. But what form do principles of cooperation in multivariable movements take? For some years now, my colleagues and I have viewed this question as continuous with the general issue of understanding the emergence of order and regularity in complex systems (see, e.g., Yates 1979, for defining characteristics of complexity). The core idea that we have pursued is that the collective action among multiple neuromuscular components is fundamentally task-related, and that the significant units of control and coordination are *functional* groupings of muscles and joints which we call coordinative structures or functional synergies (e.g. Fowler et al. 1980; Kelso et al. 1979; Kelso and Tuller 1984a; Kugler et al. 1980; Saltzman and Kelso 1985b; Turvey 1977). The hallmark of a coordinative structure is the temporary marshalling of several articulators into a task-specific pattern.

This notion of functional units of action, or coordinative structures differs in significant ways from conventional treatments of movement control that are based on either the neurophysiological notion of a central pattern generator or the information processing notion of a motor program. First, unlike the notion of a hard "prewired" central pattern generator, the coordinative structure construct underscores the *soft* or *flexible* nature of action units that are functionally specific, not anatomically specific. One of the goals of this paper is to buttress this claim using examples from recent research on the motor control of speech and limb movements. Second, contrary to the motor program formulation that relies on symbol-string manipulation familiar to computer technology, the coordinative structure construct highlights the analytic tools of qualitative (nonlinear) dynamics (e.g. Kelso et al. 1981, 1985a; Saltzman and Kelso 1985b) and the physical principles of cooperative phenomena (e.g. Kelso and Tuller 1984a, b; Kugler et al. 1980, 1982). Thus, the problem of pattern formation for skilled actions is couched as a specific aspect of the more general topic of cooperative phenomena in nonlinear, open systems (see, e.g. Haken 1975, 1977, 1983). Such systems display ordered states that are not imposed by programs, but that actively evolve from the dynamic interplay

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of processes, in a so-called “self-organized” fashion. Although the present theoretical approach is in preliminary form as far as biological movements are concerned (see Kelso 1981a; Kelso and Tuller 1984a; Kugler et al. 1980, 1982), this paper attempts to convey the flavor of the approach, not only theoretically, but in terms of the kinds of experiments that it motivates. In the following sections I shall briefly address four questions drawing from our own and others’ experimental work on limb movements and speech articulators involving many degrees of freedom.

1. The cooperativity question. What kind of unitary organization is formed by an ensemble of neuromuscular components?
2. The control question. What kind of control structure underlies the generation of certain movement patterns? What are the essential control parameters and how are parameter values specified?
3. The stability question. What characterizes the stability of a movement pattern, and what is the informational basis for the stability? Colloquially speaking, what holds a pattern together?
4. The change question. What are the necessary and sufficient conditions that give rise to change in an articulatory pattern?

THE COOPERATIVITY QUESTION

The Concept of Coordinative Structure

Do relatively independent articulators (muscles, joints) function as a unitary ensemble, and, if so, what kind of ensemble is it? Consider the act of speaking. Even a simple speech gesture involves cooperation among very many degrees of freedom operating at respiratory, laryngeal, and supralaryngeal levels. Yet in spite of (or perhaps because of) such a large number of neuromuscular elements, speech emerges as a coherent and organized activity. An attractive hypothesis proposed by Bernstein (1928/1967) and developed by his colleagues (e.g., Gelfand et al. 1971) is that the central nervous system, rather than controlling each degree of freedom separately, organizes them into “collectives”, “linkages”, or “synergies” that then behave, from the perspective of control, as a single degree of freedom.

Of course, as emphasized earlier, our notion of synergy or coordinative structure is unlike that of Sherrington (1906) or Easton (1972) (see, Kelso and Tuller 1984a) in that the collective action among multiple muscles or kinematic components is not rigid or machine-like, but fundamentally task- or function-specific. In this, Darwinian-like hypothesis, function dictates the form of cooperativity observed in an aggregate of neuromuscular components, not anatomical connections. But how might this notion be tested, and what evidence exists in its favor for complex actions?

A window into the behavior of a complex system possessing large numbers of active, interacting components can be gained by perturbing it dynamically during an activity and examining how the system reconfigures itself (e.g., with respect to response latencies, magni-

tudes, etc.). Thus, a group of potentially independent articulators could be said to behave in a unitary fashion if it were shown that a disruption to one (or more) members of the group was responded to by other members of the group at a site remote from the challenge. According to the concept of coordinative structure, the response of the articulatory ensemble would not be stereotypic; rather, it would be adapted quickly and precisely to accomplish the task. In general, the components of the neuromuscular system would cooperate in such a way as to preserve the performer's intent. Some evidence of so-called "remote compensation" phenomena that support a motor system design based on coordinative structures exists in both the speech and limb movement behavior literatures. These data are considered below.

Coordinative Structures in Multidegree of Freedom Movements

Although the speech literature contains a number of observations that are consistent with a coordinative structure mode of articulator organization, few experiments have been designed to test the notion explicitly. In one experiment by Folkins and Abbs (1975) the jaw was occasionally loaded during the closure movement for the initial /p/ in the utterance "a /hae paep/ again." Lip closure was attained in all cases apparently by exaggerated displacement and velocities of the lip closing gestures, particularly by the upper lip. Similarly, Folkins and Zimmermann (1982) used electrical stimulation to produce an unexpected depression of the lower lip prior to, and during, bilabial closure. Compensatory changes in the jaw and upper lip were observed to effect the bilabial closure. Abbs and colleagues (see, Abbs et al. 1984, for review) report that both autogenic (i.e., lower lip) and remote (upper lip) effects occur when a 40-g load is applied to the lower lip unexpectedly 30 ms before the onset of the phasic EMG burst in orbicularis oris inferior. They interpret these remote effects, after Houk and Rymer (1981), as evidence for open-loop, feed-forward control which is "a precise, experience-based representation of the relationship between afferent signals from one movement (from which a potential error is detected) and the motor output of a parallel synergistic movement (where the adjustment is implemented)." Autogenic compensations made by the structure perturbed are slower and thought to be under closed-loop feedback control.

Although these findings are consistent with the coordinative structure concept it is not clear whether, in fact, the patterns of articulator coupling following 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 indeed "functionally organized," i.e., directed to the stable production of the intended utterance. If the former, the pattern of response to a given perturbation should be the same regardless of the utterance. If the latter, different patterns of articulator cooperation (coordinative structures) should occur, tailored to the particular phonetic requirements.

Direct evidence that speech articulators (lip, tongue, jaw) do make *functionally specific*, near-immediate compensations to unexpected perturbations at sites remote from the locus of perturbation comes from our recent work (Kelso et al. 1982, 1984). An unexpected constant force load (5.88 N) applied during upward motion for final /b/ closure in /baeb/ revealed near-immediate changes in upper and lower lip muscles and movements (15-30 ms), but no changes in tongue muscle activity. The same perturbation applied during the utterance /baez/ evoked rapid and increased tongue muscle activity (genioglossus) for /z/ friction, but no active lip

compensation. Although the jaw perturbation represented a threat to both utterances, no perceptible distortion of speech occurred. That a challenge to one member of a group of potentially independent articulators was met — on the very first perturbation experience — by remotely linked members of the group provides preliminary support for coordinative structures. Further anecdotal support for coordinative structures is mentioned in a review paper by Abbs and Gracco (1983). They report that for the utterance /aba/, upper and lower lips compensate when the lower lip is loaded in order to preserve bilabial closure. In contrast, for /afa/ which in theory does not require upper lip movement, only lower lip compensatory responses to a lower lip perturbation occur.

Analogous results emerge from recent studies of human posture (e.g. Cordo and Nashner 1982; Marsden et al. 1983). For example, in response to a perturbation applied to the thumb, which was performing a tracking task, Marsden et al. observed reactions in muscles remote from the prime mover (e.g., in pectoralis major of the same limb, in triceps of the opposite limb, in the opposite thumb when it served to stabilize motion, etc.). These distant reactions are much faster than typical reaction time responses; indeed they are sometimes faster (e.g., 40 ms in pectoralis) than the local, autogenetic reflex in the structure perturbed. But most interesting for the coordinative structure hypothesis is that postural responses occur only if they perform a useful function and they are flexibly tuned to that function. For example, postural responses in triceps disappear if the hand is not exerting a firm grip on an object. If, instead of holding a table top, the nontracking hand holds a cup of tea, the responses in triceps reverse, which is precisely what they have to do to prevent the tea from spilling. Marsden et al. (1983) conclude 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. Such remarks, however, reflect a strong Western bias. For example, Russian studies done in the 1960s reveal similar interactions between posture and voluntary movement (see Gelfand et al. 1971). Moreover, Bernstein (1967) refers to his published experimental work (in Russian) in the early 1920s that affords the conclusion that "movements react to changes in one single detail with a whole series of others which are sometimes very far removed from the former, both in space and in time" (p. 69).

The microscopic workings of a coordinative structure can be further explored by varying the phase of the jaw perturbation during bilabial consonant production. For example, recent work has asked: Does perturbing the jaw during the opening phase of the utterances /baeb/ and /baep/ induce a remote reaction in the upper lip? If the cooperativity between oral structures is functionally based, remote effects are predicted only when a jaw perturbation occurs in the closing phase (i.e., during the transition out of the vowel into the final consonant), when the upper lip is actively involved in producing consonantal closure. On the other hand, if the form of interarticulator coupling is in any sense rigid, remote reactions should be seen regardless of when the jaw is perturbed. In fact, the data support the former hypothesis. Remote reactions in the upper lip were observed only when the jaw (Vatikiotis-Bateson and Kelso 1984; Kelso et al. 1984) or lower lip (Munhall and Kelso 1985) was perturbed during the closing phase of motion, that is, when the reactions were necessary to preserve the identity of the spoken utterance.

The phase-specific patterning in speech shares a likeness to recent work in other motor systems. For examples, in cat locomotion (cf. Forssberg 1982, for review), when light touch or weak electrical shock is applied to a cat's paw during the flexion phase of the locomotor 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 (Forssberg et al. 1975). This "stumble corrective reaction" is present in intact and spinal animals and, like speech compensation, 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 the foregoing data on articulatory reactions to perturbation appear specific to the spoken utterance, so also do the data on cat locomotion reveal reactions that are nonstereotypic and functionally suited to the phase-dependent requirements of locomotion.

In summary, the evidence presented in this section in support of task-specific action units poses a challenge not only to the neuroscientist, but to anyone who seeks to understand the relation between an organism's structure and its function. The adaptive reactions discussed here could certainly be *described* as reflexive because of their speed. Their mutability, on the other hand, speaks against any hypothesis about fixed reflex connections or rigidly constructed servomechanisms. Similarly, it is not parsimonious to assume that the computation is pre-programmed in such a way that the articulatory ensemble produces precisely those movements that accomplish the task. The problem is exacerbated when unexpected environmental challenges are introduced whose dimensions (e.g., magnitude, duration, locus) are potentially manifold. The main message that emerges is that the multiple components of the motor system are "softly" assembled and flexible in function, not machinelike and rigid — in either the hard-wired language of central pattern generators or the hard-algorithmed language of computers, which are the source of the motor program idea.

THE CONTROL QUESTION

What are the essential control structures that govern the patterning of articulator motion in space and time? Though this question is of much interest to many in the field of motor control in general, here the movements of speech articulators will be the primary focus. However, the kinematic relationships that we shall identify and focus upon are not unique to speech at all, a fact that is quite appealing in that it suggests a common vocabulary might exist to describe the underlying control structure of speech and other actions.

Obviously there are many surface features of a movement that one might propose as significant candidates for controlled variables. What then, fashions the constraints on the choices one makes? Is the selection among controlled variables really like a multiple choice exam (cf. Stein 1982)? Or, might a "deep structure" for motor control exist, that can be recognized in the face of much surface variability? And, if so, on what principle(s) is it based? In the following, the idea is developed that a *dynamic* control regime governs movement patterns.

After Maxwell (1877), dynamics can be viewed as the simplest and most abstract description of the motion of a system. The relations among, and the values of, dynamic parameters (e.g., mass, stiffness, damping) can produce a wide variety of kinematic consequences (e.g., position, velocity). Thus, kinematics provides a surface description of the movements of a system which are generated from a given type of dynamical organization. Note that the dynamics referred to here is not to be interpreted as local and concrete, or to be equated with pure biomechanics. Rather the branch of dynamics emphasized here, nonlinear dynamics, is concerned with the underlying, abstract basis of *forms of motion* or pattern formation in complex, multidegree of freedom systems (e.g., Abraham and Shaw 1982; Haken 1983). These forms of motion are specified, roughly, by the qualitative shapes observed in phase portraits of a system's behavior (see below). For example, the muscles, joints, and neuronal structures that cooperate to produce a walking pattern involve literally thousands of degrees of freedom, but the pattern itself represents a low dimensional form — a cyclical motion of the limbs — which can be operated by low dimensional control (see Garfinkel 1983). In fact, changes in gait in the decerebrate cat can be manipulated experimentally by a single parameter — the intensity of electrical stimulation delivered to the midbrain (Shik et al. 1966).

Such low dimensional forms are called *attractors* and represent the asymptotic stable behavior of a whole family of trajectories. As a simple example, a damped mass spring system can have many trajectories depending on its initial conditions and its parameter values (mass, stiffness, damping). Such a system is called a *point attractor*, a generic dynamical category that reflects the fact that all trajectories converge to an asymptotic, static equilibrium state. Importantly, however, a *multidegree* of freedom system whose trajectories likewise converge to a single rest position can also be described as a point attractor. Thus, a point attractor is a low dimensional description of a potentially high dimensional state space and exhibits the property of *equifinality* — the tendency to achieve an equilibrium position regardless of initial conditions. Though the language and the concepts of nonlinear dynamics may be unfamiliar (but see Kelso and Kay 1986, for a tutorial), the intent here is to show that one can apply this framework (combined with a quantitative treatment of articulator trajectories) to the analysis of speech production and other biological activities.

The advantages of a dynamical approach to control are several (see Kelso and Kay 1986, for details; also Saltzman, this volume). Among these, hinted at above are: (a) Generativity, an invariant dynamic structure can give rise to much surface kinematic variability; (b) no explicit representation or pointwise control of the system's planned trajectory need exist in a dynamical system; (c) different dynamic regimes (e.g., point attractor, periodic attractor) can serve to categorize different tasks (see Kelso and Tuller 1984b; Saltzman, this volume; Saltzman and Kelso 1986). For example, recent work in the motor control field — especially on voluntary limb and finger movements — indicates that discrete and rhythmic movements can be modeled as a damped mass-spring, point attractor (e.g., Bizzi et al. 1976; Cooke 1980; Fel'dman 1966; Houk 1978; Kelso 1977; Kelso and Holt 1980; Schmidt and McGown 1980) or limit cycle, periodic attractor system, respectively (Fel'dman 1980; Kelso et al. 1981). These control structures are characterized by sets of invariant dynamic parameters (e.g., damping, stiffness, and equilibrium length), and kinematic variations (e.g., position, velocity, acceleration over time) can be viewed as *consequences* of these underlying patterns of dynamic control parameters. A final, related advantage is that the abstract task level of description and the description of muscle-joint properties are entirely commensurate. That is, a dynamical

description applies at all levels. The problem becomes one of relating dynamics that operate on different time scales.

In complex movements like speech, however, we seldom make direct measurements of the dynamic parameters themselves, e.g., the mass, damping, and stiffness values for an organization of neuromuscular elements. In our ongoing work, we measure and compute articulatory kinematics during the production of simple syllables and use the relations among these kinematic variables to infer the underlying functionally defined dynamic control regimes. One main paradigm involves reiterant speech, in which subjects are required to substitute a simple syllable (e.g., /ba/ or /ma/) for the real syllable in an utterance, yet still maintain the utterance's normal prosodic structure. The benefit of the reiterant technique for production studies is that the removal of segmental factors (i.e., the different consonants and vowels of real speech), besides having minimal effects on the timing/metrical pattern, allows one to measure movements of those supralaryngeal articulators that are consistently active over the entire utterance, in this case the lips and jaw involved in /ba/ or /ma/.

Kelso et al. (1985a) employed a phase plane analysis (a continuous plot of articulator position vs velocity) of lip and jaw movement trajectories followed by a quantitative kinematic analysis of opening and closing gestures. Several interesting kinematic results were obtained (see Fig. 1). First, largely unimodal velocity patterns of jaw and lips occurred for opening and closing gestures at both slow and fast speaking rates (Fig. 1A); second, a given gesture's peak velocity (V_p) covaried with its displacement (d). Regression analysis of the data showed not only a strong relation between V_p and d , but also that the slope of the relation changed depending on the reiterant syllable's stress and rate. As shown in Fig. 1, shorter amplitude motions corresponding to unstressed gestures and faster speaking rates had steeper slopes than stressed gestures spoken at a normal rate.

The impressive scaling relation between V_p and d is not unique to speech where it has been reported before, often as an incidental result (e.g., Kent and Moll 1975; Sussman et al. 1973). An inventory of other activities, ranging from natural reaching movements to tongue movements (see Kelso and Kay 1986, for review; and Viviani, this volume) to infant kicking (Thelen et al. 1985) shows the same relationship. *Thus, this lawful regularity is observed not only in different material structures, but in activities involving multiple degrees of freedom.*

What kind of dynamic control structure could give rise to such kinematic relations? Consider the relationship "ut tensio sic vis; that is the power of any spring is in the same proportion with the tension thereof" (Hooke 1678, cited in Timoschenko 1953). By spring, Hooke meant any "springy body" and by "tension", what we would now call "extension" or more generally, strain. This linear relationship is called Hooke's law ($F = -kx$), where F is the restoring force, k is a proportionality constant representing spring stiffness, and x is displacement. The elementary equation of motion can be derived from Newton's second law, $F = m\ddot{x}$. That is, $F = -kx = m\ddot{x}$; therefore, $m\ddot{x} + kx = 0$, where m is mass and \ddot{x} is acceleration.

This last equation describes the motion of a simple harmonic oscillator with a given mass and stiffness and no damping. On the phase portrait, all concentric trajectories of the oscillator have the same shape with the same periodicity for a given set of dynamic parameters. Note that any changes in initial conditions (x, \dot{x}) are precisely accommodated by changes in peak

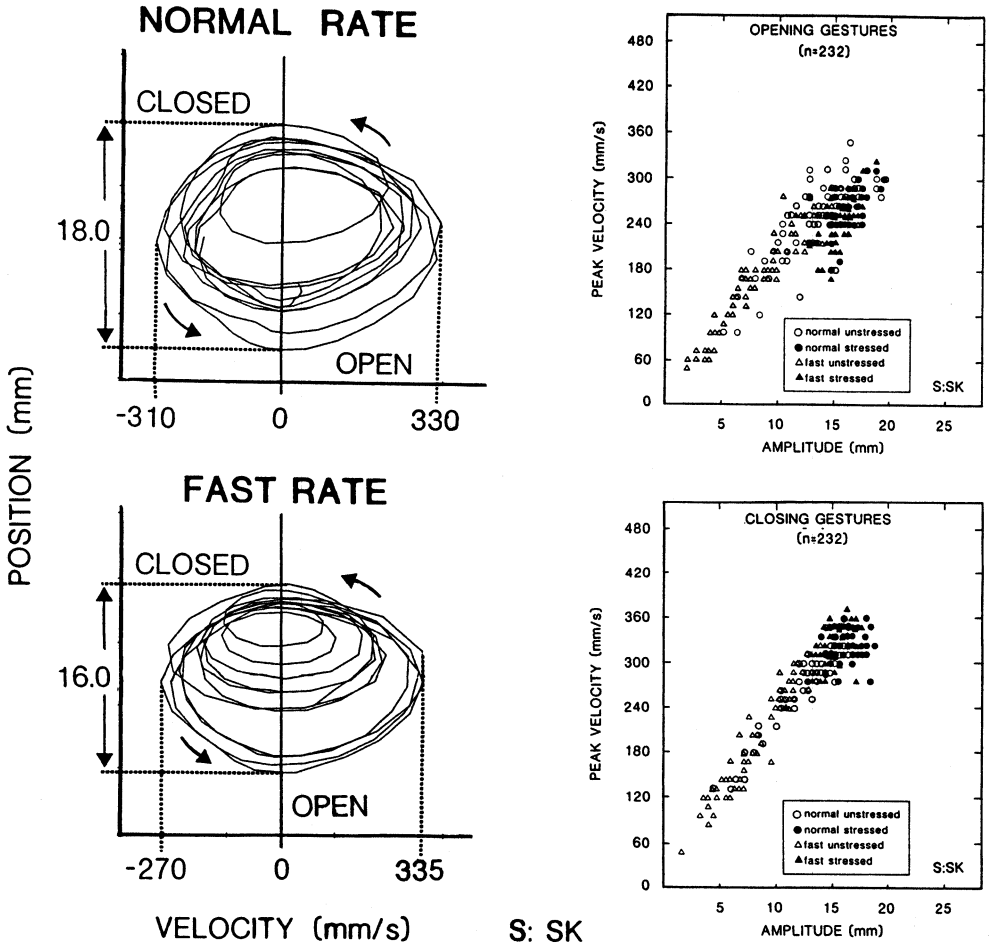


Fig. 1. Left: Phase plane trajectories of lower lip plus jaw (i.e., from a sensor placed on the lower lip) for reiterant speech spoken at a normal (top) and fast (bottom) rate with /ba/ as the reiterant syllable. Right: Scatter plot of peak velocity vs displacement (lower lip plus jaw) of a subject's opening gestures associated with the consonant–vowel portion of the syllable (top) and closing gestures associated with the vowel–consonant portion of the syllable. The legend specifies conditions (from Kelso et al. 1985a)

velocity. Thus, the V_p/d scaling relationship is *specified* by this particular dynamical system, since $\omega_0 A$ is the peak velocity of simple harmonic motion, and the slope of $\omega_0 A$ vs A is ω_0 (where A is cycle amplitude and $\omega_0 [= (k/m)^{1/2}]$ is the angular frequency of motion). Assuming constant mass, the slope of the V_p/d relationship is proportional to $k^{1/2}$. Changing stiffness changes the eccentricity of the phase plane trajectories – which is what Kelso et al. (1985) observed – and increases the slope of the peak velocity–displacement relation (see also Cooke 1980; Ostry and Munhall 1985). Time or duration per se plays no explicit role here as

a controlled variable. Rather, a spatiotemporal pattern arises as a consequence of a dynamic regime in which, at worst, only two system parameters, stiffness and rest length, are specified according to task requirements. Movement certainly *evolves* in time, but time is not directly controlled or metered out by a central executive or timekeeper in this scenario (cf. Schmidt 1980, 1982).

This simple model strongly suggests that the stiffness or elasticity of the system is an important control parameter for skilled actions. In concluding this section, the potential (and more generalized) theoretical significance of this claim is addressed. To do this, we need to develop briefly a perspective based on elasticity theory (see Landau and Lifshitz 1981; Love 1927; Timoschenko 1953).

The most general form of Hooke's law, i.e., beyond a simple force-displacement description, is that over a wide range of applied stresses, the measured strain increases in the same proportion. The proportionality linking stresses to strains is the elastic constant, k . Thus, Hooke's law is fundamentally a description of *elastic deformation processes*. This generalization, though entirely consistent with recent work demonstrating stiffness or impedance control (e.g., Hogan 1985) offers a very different image for movement control. It characterizes movement fundamentally as *form*: solid bodies (limbs, jaws, tongues) can be made to change their size and shape, that is, their *configuration*, by the application of suitable forces (stresses). In this view, any new configuration is expressed by the specification of strains. Note that displacement is only a *measure*, often on a single plane of motion, of strain or deformation. Strains themselves are changes in the *relative* positions (or configuration) of a body. They usually, require a tensorial description (e.g., Love 1927). In Kelso et al. (1985a), changes in movement duration and displacement that occurred when speaking rate and stress changed, were characterized as consequences of the dynamic parameters of stiffness and equilibrium position. This formulation can now be recast into an equivalent, but more conceptually meaningful form, one that affords insights into the regulation of *multiple* muscles during action, not simply an agonist-antagonist pair (e.g., Bizzi et al. 1982; Cooke 1980).

When an effector system, say the jaw-lip complex, moves from one configuration to another, the system in general does some work. A way to envisage the system specification of equilibrium position and stiffness is to express the work done as a potential strain or energy function. The latter specifies the macroscopic relation between stresses and strains. In Fig. 2A, a linear force-displacement relation is mapped onto a strain-energy surface in which the potential energy is a quadratic function of the strain components (in this case simply displacement). The corresponding phase portrait is also shown. For comparison purposes, the case in which stiffness changes nonlinearly as a function of displacement, the so-called "soft" spring (cf. Jordan and Smith 1977; Kelso et al. 1983) is illustrated in Fig. 2B.

It is apparent from Fig. 2 that the amount of potential energy is proportional to displacement (or more generally, configuration) and that the slope of the force-displacement function specifies stiffness. In this view, the system's "endpoints" or "targets" correspond to minima of potential energy functions whose gradients define spring force. As Kugler et al. (1980) emphasize, to produce a movement is to effect a change in the underlying geometry of the dynamics, captured as a potential field. Some years ago this language was not common in the field of motor control. However, it is interesting to quote Greene and Boylls's (1984) assessment of trends in the field -

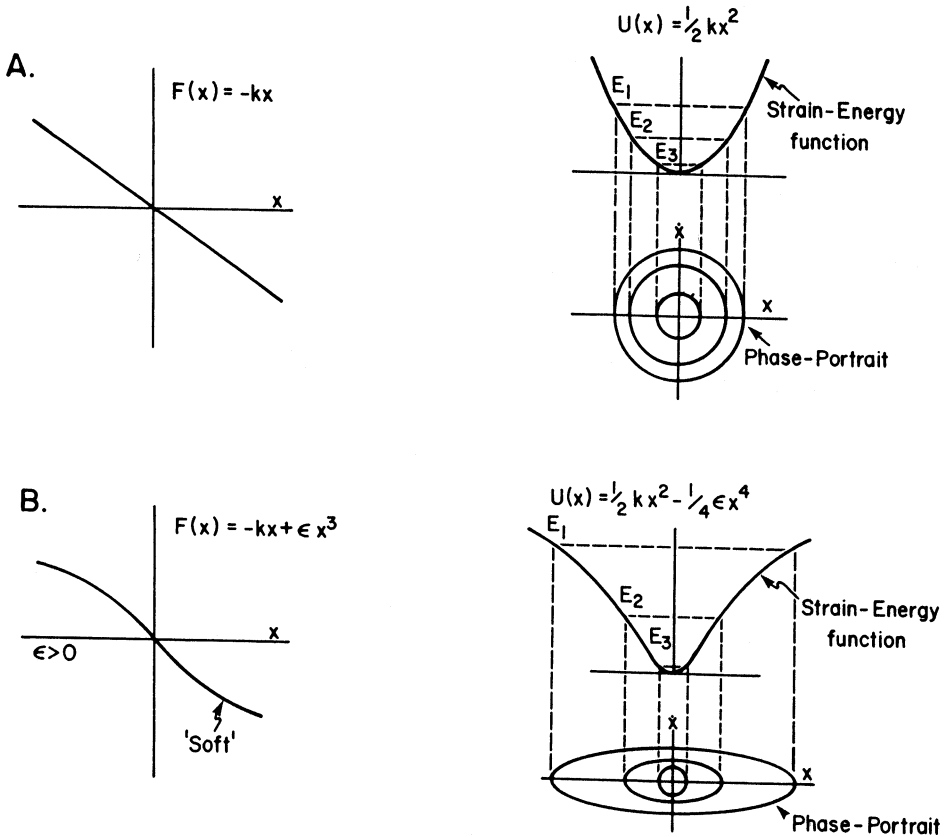


Fig. 2. A. Left: A graph illustrating Hooke's law. The deviation of the force (F) from linearity is symmetrical about the equilibrium position ($x = 0$). Right: The potential (or strain-) energy function corresponding to the linear force-displacement relation and its associated phase diagram in x, \dot{x} coordinates. Three phase paths are drawn, corresponding to the three values of total energy, E , indicated by dotted lines in the potential function. B. The form of the above relationships when the force is less than the linear term alone and the system is said to possess a "soft" nonlinearity

post-Bernstein — "that bear watching. ... [It] seems likely that the theory of impedance or end-point control will soon be recast in terms of potential functions (with endpoints as extrema of such functions to be 'sought', gradient fashion, by the state of the skeletomuscular system)" (p. xxiii). See Kugler et al. (1980, pp. 34–40) and Hogan (1981) for applications to robotic motion. Recently, Hogan (1984) has elaborated this framework for the trajectories of multijoint movements. Successive target locations are specified by means of a time-varying potential field with stable equilibria at the "target" locations.

There are two main points that arise from the perspective advanced here. First, because we are dealing with potential energy functions, only scalar quantities are involved. Several advantages for control accrue immediately. Since energy is a scalar quantity, unlike force (which is a

vector), energy is invariant under coordinate transformations. Thus, the coordinate system can be chosen to simplify the problem (see Marion 1970). Also, it is often impossible to define exactly what the forces are (e.g., in a multimuscule system), whereas it is often possible to express the kinetic and potential energies. The latter are intrinsic to the system under study, whereas the standard force description places its emphasis on an outside agency acting on a body. Relatedly, because scalar potentials may be superimposed, the overall effect of multiple muscle activity can be obtained by addition of the potential functions (Marion 1970). This characterization may offer considerable advantages for a compact description of control in multidegree of freedom movements.

But the second main feature of the present perspective is that the potential or strain-energy function (Love 1927) can be properly conceived as an *elastic field*. (As an aside, Asada (1982) has recently demonstrated how elastic fields can be used for planning stable grasp in a robot manipulator.) The notion that movement involves deformation of an elastic field may ground one of Bernstein's most interesting intuitions, namely that movement is a morphological object. The ubiquity of the peak velocity-displacement relation, then, may offer a window into processes that form and deform the configuration of the body. If correct, an ancient theme for "static" forms — that a few simple rules can fashion come very intricate products (e.g., Gould 1980; Stevens 1974) — may apply equally well to the forms of patterned motion that interest us here.

THE STABILITY QUESTION

It is now well established that as an articulator ensemble performs its task at different speeds and forces, the relative timing of muscle contractions and/or articulator motions is preserved invariantly (e.g., Boylls 1975; Kelso et al. 1979; Kugler et al. 1980; Schmidt 1982; Shapiro 1978; Shapiro et al. 1981, for reviews). Such results rest on the assumption that the central program determines when pulses of muscular force are applied to the limbs and their durations and relative sizes. Thus, according to Schmidt (1980) the determination of *time* (emphasis his) of contractions and relaxations appears to be directly controlled. Many view an identified invariant as indicating a relevant control parameter. Our position has been exactly the opposite (e.g., Fowler and Turvey 1978; Kelso et al. 1979) — namely, that invariance represents a system constraint, a "freezing" of degrees of freedom, that is, an invariance tells the investigator what does *not* have to be directly controlled.

In the previous sections, it was argued that though muscles contract and relax and though movements flow in time, a movement's temporal structure may be a consequence of the system's dynamic parameterization. Here I want to show how stable *relative timing* among gestures may be understood without recourse to an extrinsically imposed timing program (see Kelso and Tuller 1985a, 1985b). But if timing is not controlled extrinsically in such a fashion, what processes might underlie the observed temporal stability? How in a complex system of articulators, does a given gesture/articulator "know" when it should be activated in relation to other gestures/articulators? With respect to our relative timing data in speech, for example, what information is needed for the upper lip (a remote, nonmechanically linked articulator associated with a consonantal gesture) to move in appropriate temporal relation to the vocalic movement cycle of the jaw? As we shall see, different views of relative timing emerge when the articulator motions are examined in different coordinative spaces.

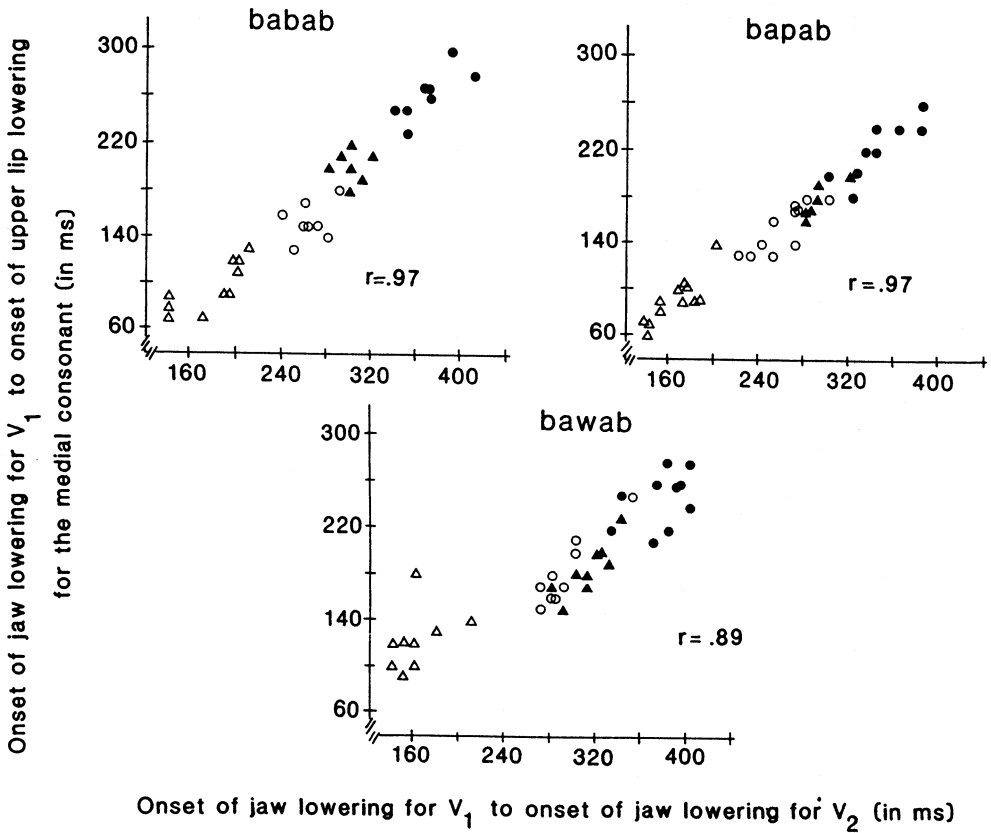


Fig. 3. Timing of upper lip lowering for medial consonant articulation as a function of vowel-to-vowel period for one subject's production of the indicated utterances. Each point represents a single token of the utterance: (●), primary stress on the first syllable spoken at a conversational rate; (○), primary stress on the second syllable (conversational rate); (filled triangle) and (open triangle), primary stress on the first and second syllables, respectively, spoken at a faster rate (from Tuller and Kelso 1984)

Consider first a very simple, but paradigmatic case in which the delay (in ms) of onset of upper lip motion for a medial consonant is measured relative to the interval (in ms) between onsets of jaw motion for flanking vowels. Figure 3, taken from Tuller and Kelso (1984), plots these events for one of four speakers who produced the utterances /babab/, /bapab/, and /bawab/, at two speaking rates and with emphatic stress placed on either the first or second syllable. The data for all four subjects were very similar. This figure shows that over changes in speaking rate and stress, the measured intervals change considerably, as do the magnitude of the events themselves, but the function relating these events is linear. That is, the metrics (amplitude, velocity, duration) of the events change, but the relative timing does not. Note that this is a strictly temporal description relating discrete movement events. Like most, if not all of the work on relative timing, measurements are confined to the onsets and offsets of articulator movement (see, e.g., Schmidt 1982).

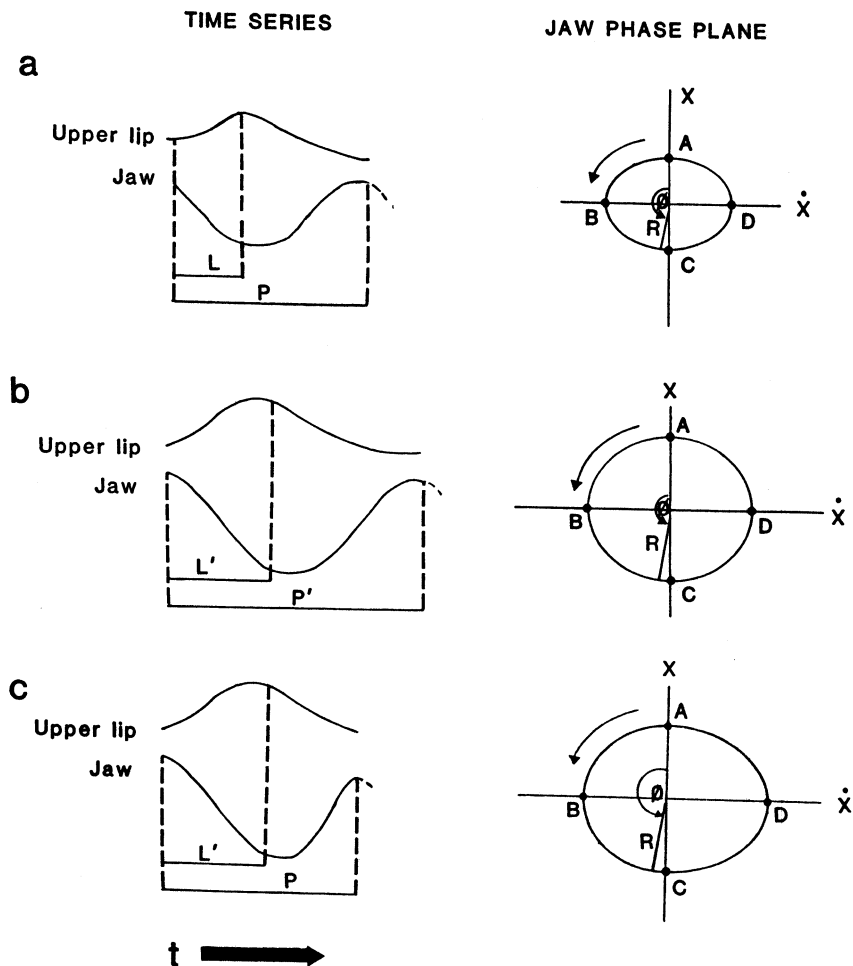


Fig. 4. Left: Time series representations of idealized utterances. Right: Corresponding jaw motions displayed on the "functional" phase plane, i.e., position (x) on the vertical axis and velocity (\dot{x}) on the horizontal axis. Parts a, b, and c represent three tokens with vowel-to-vowel periods (P and P') and consonant latencies (L and L') that are not linearly related. Phase position (Φ) of upper lip movement onset relative to the jaw cycle is indicated (see text; from Kelso and Tuller 1985b)

A very different view of articulatory "timing" emerges when a reanalysis of the movements using phase plane trajectories is employed (Kelso and Tuller 1985a). Figure 4 illustrates the mapping from time domain to phase plane trajectories. On the left, hypothetical jaw and upper lip motions (position as a function of time) are shown for an unstressed /bab/ (top left) and a stressed /bab/ (bottom left). On the right are shown the corresponding idealized phase plane trajectories. In this figure we have reversed the typical orientation of the phase plane so that displacement is shown on the vertical axis and velocity on the horizontal axis. Thus, downward movements of the jaw are displayed as downward movements of the phase path. The vertical crosshair indicates all points of zero velocity and

the horizontal crosshair indicates zero position (midway between minimum and maximum displacement). As the jaw moves from its highest to its lowest point (from A to C) velocity increases to a local maximum (B), then decreases to zero when the jaw changes direction of movement (C). Similarly, as the jaw is raised from the low vowel /a/ into the following consonant constriction, velocity peaks approximately midway through the gesture (D) then returns to zero (A). It is useful to transform the Cartesian position-velocity coordinates into equivalent polar coordinates, namely, a phase angle, $\phi = \tan^{-1} [\dot{x}/x]$ and a radial amplitude, $R = [x^2 + \dot{x}^2]^{1/2}$. The phase angle is a key concept in the reanalysis of interarticulator timing because it signifies position on a cycle of states.

Notice in Fig. 4 that the phase plane trajectory preserves some important differences between stressed and unstressed syllables. For example, maximum displacement of the jaw for the unstressed vowel is less than displacement for the stressed vowel and maximum articulator velocity differs noticeably between these two orbits. In contrast, note that the different *durations* taken to traverse the orbit as a function of stress are not represented in this description. Time, although implicit and recoverable from the phase plane description, does not appear explicitly. Jaw cycles of different durations are characterized as single orbits on the plane and they are topologically equivalent.

Now one can pose the question of how the upper lip "knows" when to begin its movement for the medial consonant by asking *where* on the cycle of jaw phase angles the lip motion for medial consonant production begins. One possibility is that upper lip motion begins at the same phase angle of the jaw across different jaw motion trajectories (that is, across rate and stress). In other words, the information for timing of a remote articulator, such as the upper lip, would not be time itself, nor absolute position of another articulator (e.g., the jaw), but rather a relationship defined over the position-velocity *state* (or, in polar coordinates, the phase angle) of the other articulator. It is also important to recognize that the motion need not be perfectly sinusoidal in order to apply a phase angle analysis. In fact, the jaw motions actually observed are usually not sinusoidal; the displacements at zero velocity are affected by the stress and rate characteristics of the surrounding vowels. For this reason, we normalize each jaw cycle's amplitude and peak velocity to unity.

When the original Tuller and Kelso (1984) data were reanalyzed in this fashion, the result was that phase angle was indeed constant across both rate and stress variations. The complete statistical analysis is presented in Kelso et al. (1986). The mean phase position of the upper lip relative to the jaw was found to be constant and the standard error of the mean tiny. It should be emphasized that a critical phase angle description in no way entails, or is predicted by, the relative timing results. Instead, it constitutes an alternative description of the data set. For example, two utterances that have *identical* vowel-to-vowel periods and consonant latencies can nonetheless show very different phase positions for upper lip movement onset relative to the cycle of jaw states. Specifically, the phase angle analysis incorporates the full space-time trajectory of motion; the relative timing analysis ignores trajectory, once movement has begun.

There are at least two empirical advantages of this result over others' and our relative timing description. First, in the relative timing analysis, the overall correlations across rate and stress conditions are very high, but the within-condition slopes tend to vary somewhat. In the phase

analysis, on the other hand, the mean phase angle is the same across conditions. Second, although the relative timing scenario is described by two parameters, a slope and an intercept (Fig. 3), the phase description requires only a single parameter (phase angle). Thus, if nothing else, the phase description is more parsimonious.

The phase angle conceptualization also has a number of theoretical advantages over our original relative timing analysis. First, once articulatory motions are represented geometrically on the phase plane, duration is normalized across stress and speaking rate. Strictly speaking, the system's *topology* is unaffected by durational changes. Second, neither absolute nor relative durations have to be extrinsically monitored or controlled in this formulation. There is no need to posit a *timing* program. This fact potentially provides a grounding for, and a principled analysis of so-called intrinsic timing theories of speech production (e.g., Fowler et al. 1980; see also Kelso and Tuller 1985a). The present view is bolstered indirectly by demonstrations in the articulatory structures themselves of afferent bases for phase angle information (e.g., position and velocity sensitivities of muscle spindle and joint structures), but not for time-keeping information (e.g., time receptors; cf. Kelso 1978). It might well be the case that certain critical phase angles provide information for orchestrating the temporal flow of activity among articulators (beyond those considered here) and/or vocal tract configurations. (Note that the statement that lip motion starts at a particular phase angle of the jaw is equivalent to saying that it occurs when the rate of dilation of the jaw (i.e., \dot{x}/x) reaches a particular value. Lee's work (see this volume for references) similarly shows how the inverse of the rate of dilation of the optic image of a surface specifies time-to-contact $\tau(t)$ with that surface. The critical phase angle may be the *proprioceptive flow field* analogue of Lee's optic flow field variable so crucial to the visual guidance of action.) Such phase angles would serve as natural, i.e., dynamically specified, information sources for guaranteeing the stability of coordination in the face of scalar (metrical) changes. As in a candle (which provides a metric for time by a change in its *length*) or a water clock (where the metric is number of drops), the units of time for speech production might be defined entirely in terms of the *state* variables of the system. Thus, according to the present analysis, it is gestural phase angle (a space-time description) not gestural time (a purely temporal description) that captures the stable cooperative relations among articulators. This essential parameter, phase angle, will take on added significance in the final section.

THE CHANGE QUESTION

The previous sections focused on the stability characteristics within and among coordinative structures — a description of what remains stable in articulatory ensembles as the metrics of the activity are systematically scaled. Here the other side of the coin is addressed: How do new (or different) forms of spatiotemporal behavior come about? Although the invariance aspect of coordinative structures has been emphasized, it is nevertheless clear that such organizations are not strictly invariant, but change over time according to different time scales. Over the relatively long time span of early childhood, skills are acquired: the forms of motion that emerge must, in turn, be adapted to slow changes in body morphology that accompany growth. As adults, we can learn new skills (within limits), such as tennis and juggling, given sufficient practice. And finally, certain activities involve coordinative structures whose forms change swiftly and dramatically within the performance of a particular skill, as with gait transitions in

locomotion (e.g., Hoyt and Taylor 1981). It is this faster kind of change that I want to address here. The reasons are as follows. First, one can design experiments to examine the necessary and sufficient conditions that may underlie such rapid changes in organization (see below). In contrast, slower kinds of change that occur with learning and development often require longitudinal studies and intervening variables can play a significant role. Second, it seems possible that fast and slow changes in perception-action systems follow similar kinds of principles, except that the time scales are very different. Just as evolution may occur in qualitative "jumps" (see, Eldredge and Gould 1972), so also may skill learning and development. What constitutes a jump at one time scale, however, can be nearly continuous or quasistatic in another. Nevertheless, principles of change in spatiotemporal behavior may provide a test field for comparing the motor program/central pattern generator account of motor control with the "movement as cooperative phenomenon" approach promoted here. A fundamental prediction of this approach is that movement patterns, like other cooperative phenomena (see, e.g., Haken 1975; Prigogine 1980) exhibit qualitatively new modes of organization when certain parameters are scaled past critical bounds. Unlike the motor program construct, however, no *a priori* prescription exists before the new mode of organization appears (see, Kelso 1981a; Kugler et al. 1980).

The concept of *mode* is quite crucial here. Modes are macroscopic descriptors for collective behavior in systems with many degrees of freedom. Modal descriptions are distinct from those at a microscopic level. For example, an oscillating string made up of 10^{22} atoms is described by "macro" quantities like wavelength and amplitude that are entirely different from the atomistic description (see, Haken 1977). Analogously, in certain biological activities the relative phase among movement components serves as a macroscopic description of the spatiotemporal order, say, among the limbs during the act of locomoting, or the articulators during speech. Thus, particular phasings among the legs of a quadruped correspond to particular modes or locomotory gaits. A microscopic description, on the other hand, requires minimally an identification of the ensemble's neuromuscular elements, their membrane and synaptic properties, and all the connections among them. Though it is commonplace for the neuroscientist to talk of neural circuits controlling behavior, it has proved difficult — even in the simplest neural networks — to relate specific patterns of electrical activity to behavioral action. Indeed, if one were to experimentally manipulate the parameters of a central pattern generator, one would be confronted (by some limited estimates) with a space that contains 46 parameters (Bullock 1976). Clearly some other principles — continuous perhaps with the treatment of cooperative phenomena in other natural systems — are needed to guide the selection of relevant parameters.

As Haken et al. (1985) note, this problem of relating neuronal events to global behavioral patterns — say, abrupt changes and other characteristic indices of a movement — is reminiscent of problems faced by physicists 50 years ago (and in many cases today as well). Even though the microscopic properties of atoms were thought to be theoretically understood, it still proved difficult to derive the system's macroscopic behavior from its microscopic features. In the field of synergetics, for example, which deals with the formation of order in open, nonequilibrium systems (e.g., Haken 1975) it has been shown that the behavior of complex systems can be successfully modeled by means of a few macroscopic quantities, — called *order parameters*, — in those situations where the system's behavior changes qualitatively.

Elsewhere, we have presented numerous examples, — drawn largely from Haken and Prigogine's work, — of dissipative or synergetic structures in physics, chemistry, and biology (Kelso and Tuller 1984a; see also, Kelso et al. 1980 and Kugler et al. 1980, for empirical and theoretical treatment of such structures in the realm of action systems). The mechanisms common to all these systems is that the values of one or more order parameters become unstable and undergo sudden discontinuous changes when control parameters are scaled (usually under experimental manipulation). The observed bifurcation results from the competition, as is were, between the "forces" or inputs that are systematically scaled (e.g., by increasing the velocity of a treadmill and forcing an animal to move faster), and the "forces" holding the system together (e.g., the order parameter describing, say, a synergistic modal pattern or locomotory gait). Thus, under the influences of continuous scaling, a given mode may suddenly become dominant, and capture or *slave* (in Haken's terms) the other modes. The significant, and *universal feature of such critical behavior is that around transition regions, where stability is lost, the behavior of the system is governed by the order parameters alone*. This implies a tremendous reduction in the degrees of freedom since the behavior of all the subsystems is now governed by a single order parameter.

These kinds of sharp, discontinuous behaviors are omnipresent in the action system when system-sensitive parameters are appropriately scaled, e.g., in voluntary limb movements (Kelso 1981b, 1984), speech (Kelso and Tuller 1984a), locomotion (e.g., Hoyt and Taylor 1981; Kugler et al. 1980) and posture (e.g., Nashner and McCollum 1985; Saltzman and Kelso 1985). For example, in recent work on bimanual activities, Kelso (1981b, 1984) had subjects move their right and left hands together at a comfortable rate in both an out-of-phase (180° phase difference) and in-phase (0° phase difference) modal pattern, and either with or without an added frictional resistance. The preferred frequencies and amplitudes of each hand were measured under the two resistance conditions. Subjects then attempted to perform the out-of-phase rhythmic movement at steadily increasing frequencies. Of special interest was the critical frequency at which the out-of-phase movements could no longer be sustained, and the rhythmic organization abruptly became in-phase. Though this critical phase transition frequency was different for subjects, when expressed in units of each subject's preferred frequency, the same dimensionless number was obtained. As in many physical and biological systems new "modes" or spatiotemporal orderings were observed when the system was scaled beyond equilibrium. Continuous scaling on frequency in Kelso's experiments resulted in the initial out-of-phase modal pattern (or phase relation) becoming unstable, until, at a critical point, bifurcation occurred and a different modal pattern appeared. Though not given a bifurcation interpretation, similar results have been obtained by Cohen (1971), Mackenzie and Patla (1983), and Baldissera et al. (1982).

Recently, Haken et al. (1985) have modeled these bimanual phase transitions, using some of the central concepts and mathematical tools of synergetics and nonlinear oscillator theory. Using *relative phase* as an order parameter, they first specified a potential function corresponding to the layout of modal attractor states (i.e., the stable in-phase and out-of-phase patterns), and showed how that layout was altered as a control parameter (driving frequency) was scaled. (Note: There are several criteria for the identification of an order parameter. A main one is that the order parameter changes much more slowly than the subsystems it is said to govern. Relative phase fits this criterion well. Remember, it is the phasing structure of many different activities that remains invariant across scalar transformations. Thus, in the bimanual

experiments, relative phase changes much more slowly than the kinematic variables describing the motion of each hand.) From the behavior of the potential function Haken et al. then derived the equations of motion for each hand, and the nonlinear coupling between the hands. Analytic derivations and consequent numerical simulation revealed that if the system was "prepared" in the out-of-phase mode (i.e., by instruction to the subject), and driving frequency was increased slowly, the oscillation remained in that mode until the solution of the coupled equation of motion became unstable. At this point, a jump occurred and the only stable stationary solution produced by the system corresponded to the in-phase mode (see Haken et al. 1985, for more details). Ongoing empirical and theoretical work (Kelso and Scholz 1985; Schöner et al. 1986) has revealed that the nonlinear coupling strength as well as fluctuations (both intrinsically generated due to noise in system parameters and extrinsically generated due to an added random forcing function) play an important role in effecting the modal transitions between the hands.

Although it is tempting to ascribe transitions in phasing among the limbs to "switches" or (in the case of gait) a "gait selection process" (Gallistel 1980), such an account possesses a Kiplingesque "just so" quality. To assign a phenomenon, switching (an abrupt shift in spatiotemporal order) to a device or a mechanism that is said to perform the duty of explaining the phenomenon, is a questionable strategy at best. Yet modal shifts in coordination are often "explained" in this fashion, e.g., by motor programs (cf. Schmidt 1982, p. 316). The synergetic framework offered here asks instead: What are the necessary and sufficient conditions giving rise to order in biological activities? It is antithetical to views that try to account for complex behaviors by devices that embody (or represent) these behaviors. A principled account of new spatiotemporal patterns should not rest on the introduction of special mechanisms, even when such "mechanisms" are borrowed from current computer technology.

EPILOGUE (After Kelso and Tuller 1984a)

Unlike machines that are designed by people to exhibit special structures and functions, the structures and functions discussed here develop in a self-organized fashion.* Often a new mode emerges when a random event occurs in an unstable region of the system's parameter space and the fluctuation becomes amplified. Such is the case, one suspects, in the gait of a quadruped or in the bimanual experiments described here (see, Kelso and Scholz 1985, for a more complete treatment of critical fluctuations in the bimanual case). Near the unstable region, where it is energetically expensive to maintain a given mode, a small change in speed produces dramatic effects — a new mode arises. Literally, a phase transition occurs.

Throughout the present paper the emphasis has been on similarities, in terms of dynamic behavior, exhibited by articulatory systems which vary widely in their material composition. Common to all of them is their intrinsically nonlinear and dissipative nature, and the fact that they possess many degrees of freedom. These are features that the perception-action system shares with many other

* In fact, neuroscience is beginning to talk this way. A recent report has described systematic changes in topographic maps of sensorimotor cortex that occur due to finger ablation and cortical tissue removal, as evidence that the brain "has embedded processes ... that make it self-organizing" And that "the dominant view of the nervous system [as] a machine with static properties ... [is] incorrect" (Fox 1984, quoting Merzenich and colleagues' work). Times, it seems, are a-changing.

natural systems. The focus in this paper has been on the discovery and elaboration of principles that embrace cooperative phenomena, regardless of any particular structural embodiment. From such principles it may be possible to generate an account of the emergence and stability of movement patterns without hermeneutic devices that prescribe such patterns.

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