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Chapter 7

A "Dynamic Pattern" Perspective on the Control and Coordination of Movement

J. A. SCOTT KELSO, BETTY TULLER, and KATHERINE S. HARRIS

I. Introduction

That speech is the most highly developed motor skill possessed by all of us is a truism: but how is this truism to be understood? Although the investigation of speech production and that of motor behavior have proceeded largely independently of each other, they share certain conceptions of how skilled movements are organized. Thus, regardless of whether one refers to movement in general or to speech as a particular instance, it is assumed that for coordination to occur, appropriate sets of muscles must be activated in proper relationships to others, and correct amounts of facilitation and inhibition have to be delivered to specified muscles. That the production of even the simplest movement involves a multiplicity of neuromuscular events overlapping in time has suggested the need for some type of organizing principle. By far the most favored candidates have been the closed-loop servomechanism accounts provided by cybernetics and its allied disciplines, and the formal machine metaphor of central programs. The evidence for these rival views seems to undergo continuous updating (e.g., Adams, 1977; Keele, 1981) and so will not be of major concern to us here. It is sufficient to point out the current consensus on the issue, namely, that complex sequences of movement may be carried out in the absence of peripheral feedback, but that feedback can be used for monitoring small errors as well as to facilitate corrections in the program itself (e.g., Keele, 1981; Miles & Evarts, 1979).

But at a deeper level, none of these models offers a principled account of the coordination and control of movement. The arguments for this position have

been laid out in detail elsewhere (Fowler, Rubin, Remez, & Turvey, 1980; Kelso, Holt, Kugler, & Turvey, 1980; Kugler, Kelso, & Turvey, 1980; Turvey, Shaw, & Mace, 1978) and will be elaborated here only inasmuch as they allow us to promote an alternative. To start, let us note that programs and the like—though intuitively appealing—are only semantic *descriptions* of systemic behavior. They are, in Emmett's (1980) terms, "externalist" in nature and are quite neutral to the structure or design characteristics of that which is being controlled. By assuming, a priori, the reality of a program account, we impose from the outside a descriptive explanation that allows us to interpret motor behavior as rational and coherent. But it would be a categorical error to attribute to the concept *program* causal status. Nevertheless, it is commonplace in the analysis of movement for investigators to observe some characteristic of an animal's performance, such as the extent of limb movement, and conclude that the same characteristic is represented in the motor program (e.g., Taub, 1976). In like vein, the observation that lip rounding precedes the acoustic onset of a rounded vowel and therefore coarticulates with preceding consonants is explained by the presence of the feature [+ rounding] in the plan for a speech gesture (cf. Fowler, 1977). Such an interpretative strategy is akin to that of the observer of bee behavior who attributes the product of a behavior—honey arranged in hexagonal form—to a hexagon program possessed by all bees. A more careful analysis would reveal that hexagonal tessellation, or "close packing," occurs whenever spherical bodies of uniform size and flexible walls are packed together. That is to say, close packing is a consequence of dynamic principles that allow for the minimization of potential energy (least surface contact), and it is dynamics that determines the emergence of hexagonal patterns such as honeycombs (for further examples of complex form arising from dynamic principles, see Thompson, 1942; Kugler et al., 1980; Stevens, 1974).

The gist of the message here is that if we adopt a formal machine account of systemic behavior, we take out, in Dennett's (1978, p. 15) words, a "loan on intelligence" that must ultimately be paid back. Rather than focusing our level of explanation at an *order* grain of analysis in which all the details of movement must be prescribed (see Shaw & Turvey, 1981), a more patient approach may be to seek an understanding of the relations among systemic states as necessary a posteriori facts of coordinated activity (see Rashevsky, 1960; Shaw, Turvey, & Mace, 1981). In essence we would argue, as Greene (Note 1) does, that in order to learn about the functions of the motor system we should first seek to identify the informational units of coordination.

Although the latter topic—coordination—has received some lip service in the motor control literature, a rigorous analysis of muscle collectives has (with few exceptions) not been undertaken as a serious scientific enterprise. We venture to guess that one of the reasons for such a state of affairs is that extant models of movement control (and skill learning) assume that the system is already coordinated. Thus, servomechanism accounts speak to the positioning of limbs or articulators in terms of, for example, some reference level or spatial target.

but are mute as to how a set of muscles might attain the desired reference or target. Similarly, program descriptions of motor behavior assume that the program represents a coordinated movement sequence and that muscles simply carry out a set of commands (e.g., Keele, 1981; Schmidt, 1975). Any systemic organization of the muscles themselves is owing to the program—a *fait accompli* that explains nothing.

But what does an adequate theory of movement coordination (and skilled behavior as well) have to account for? Fundamentally, the problem confronting any theorist of systemic behavior in living organisms is how a system regulates its internal degrees of freedom (Bernstein, 1967; Boylls, 1975; Greene, 1972; Iberall & McCulloch, 1969; Tsetlin, 1973; Turvey, 1977; Weiss, 1941). A first step toward resolving this issue in motor systems is to claim—following the insights of the Soviet school (e.g., Bernstein, 1967; Gelfand, Gurfinkel, Tsetlin, & Shik, 1971; Tsetlin, 1973)—that individual variables, say muscles, are partitioned into collectives or synergies where the variables within a collective change relatedly and autonomously. Combinations of movements are produced by changes in the mode of interaction of lower centers; higher centers of the nervous system do not command; rather they tune or adjust the interactions at lower levels (Fowler, 1977; Greene, 1972, Note 1; Kelso & Tuller, 1981; Tsetlin, 1973; Turvey, 1977). As Gelfand et al. (1971) suggest, learning a new skill (within the foregoing style of organization) consists of acquiring a convenient synergy, thus lowering the number of parameters requiring independent control (see Fowler & Turvey, 1978, for a skill learning perspective and Kugler, Kelso, & Turvey, 1982, for a developmental analysis). Before going any further, we should note that the term *synergy* is used here in a way that is different from Western usage: A synergy (or coordinative structure as we prefer to call it) is not limited to a set of muscles having similar actions at a joint, nor is it restricted to inborn reflex-based neurophysiological mechanisms (Easton, 1972). Rather, synergies and coordinative structures connote the use of muscle groups in a behavioral situation: They are functional groupings of muscles, often spanning several joints that are constrained to act as a single unit. To paraphrase Boylls (1975), they are collections of muscles, all of which share a common pool of afferent and/or efferent information, that are deployed as a unit in a motor task.

In this chapter we do not propose to continue the polemic for a coordinative structure style of organization. The evidence for coordinative structures in a large variety of activities is well documented (e.g., for speech, see Fowler, 1980; for locomotion, see Boylls, 1975; for postural balance, see Nashner, 1977; for human interlimb coordination, see Kelso, Southard, & Goodman, 1979a, 1979b) and the rationale for such an organizational style is compelling, though perhaps not accepted by all. Instead we want to focus first on the following question: When groups of muscles function as a single unit, what properties (kinematic and electromyographic) do they exhibit? We intend to show that there are certain features of neuromuscular organization that are common to many, if not all, modes of coordination, including human speech. Second, and

more important, we shall attempt to provide a principled rationale for why coordinative structures have the properties that they have. Such an account will not be in the algorithmic language of formal machines, where each aspect of the movement plan is explicitly represented. Rather we shall develop the argument—based on dynamic principles that have their groundings in homeokinetic physics (Iberall, 1977; Kugler et al., 1980; Yates & Iberall, 1973) and dissipative structure (dynamic pattern) theory (Katchalsky, Rowland, & Blumenthal, 1974; Prigogine & Nicolis, 1971)—that real systems (as opposed to formal machines) consist of ensembles of coupled and mutually entrained oscillators and that coordination is a natural consequence of this organization.

Although in previous work coordinative structures have been linked to dissipative structures (Kelso, Holt, Kugler, & Turvey, 1980; Kugler et al., 1980; see also Kugler et al., 1982), here we shall prefer Katchalsky's term *dynamic pattern* (cf. Katchalsky et al., 1974). Traditionally, the word *structure* has referred only to static *spatial* patterns that are at or near thermodynamic equilibrium. In contrast, the term *dissipative structure* applies also to the temporal domain and refers to open nonequilibrium systems that require energy to maintain spatiotemporal patterns. Thus the term *dynamic pattern* is preferred not only because it removes the ambiguity between classical notions of the term *structure* and Prigogine's dissipative structures, but also because it captures the flavor of what is, in effect, a functional or dynamic organization. We are persuaded of the importance of dynamic patterns because they provide an accurate description of the appearance of qualitative change, or emergent properties, that cannot be understood with reference to quantitatively known component processes.

According to Katchalsky et al. (1974; see also Yates, 1980; Yates & Iberall, 1973) there are three essential ingredients for a system to display dynamic patterns. First, there should be a sufficiently large density of interacting elements or degrees of freedom. Second, the interactions should be nonlinear in nature; and finally, free energy should be dissipated. As we shall see, the "stuff" of the motor system—synergies or coordinative structures—consists of precisely these ingredients.

The continuous dissipation and transformation of energy results in a fundamental property of living systems—cyclicity—and motivates the physical theory that complex systems are ensembles of nonlinear, limit cycle oscillators (homeokinetics; e.g., Iberall & McCulloch, 1969; Soodak & Iberall, 1978). This claim necessarily suggests that coordinated movement will be subject to particular kinds of constraints whose form we will attempt to elucidate shortly. But it is to the general issue of constraints that we turn first.

## II. Coordinative Structures as Constraints

As Mattingly (1980) points out in his review of *Gödel, Escher, Bach: An Eternal Golden Braid* (Hofstadter, 1979), it has long been recognized by

linguistic theoreticians that a formal theory of grammar that allows an unrestricted use of recursive devices would be simply too powerful. Such a theory would permit the grammars that occur in natural languages, as well as an infinite number of grammars that bear no relation whatsoever to natural languages. Thus the claim that programs can be developed to model the human mind is vacuous: Without the incorporation of constraints, one program may be as good as any other, and none may have anything to do with how real biological systems work.

In a similar vein, current theories of motor control fail to embody the concept of constraint: They do not capture the distinction between those acts that occur and those that are physically possible but never will occur. The motor program notion, for example, is a description of an act—specified in terms of the contractions of muscles—that is too powerful because it can describe acts that could never be performed by an actor. Theoretically, the motor program is as viable for unorganized convulsions as it is for coordinated movement (cf. Fowler, 1977). Boylls (1975) expresses an identical view of servomechanistic models. The concept of coordinative structure (in his terms, muscle linkages)

by no means represents a conventional engineering approach to the control of motor performance, because the brain is not viewed as having the capacity to transfer an existing state of the musculature into any other arbitrary state, however biomechanically sound. Most such unconstrained states would have no behavioral utility. Hence the linkage paradigm . . . naturally assumes that evolution has economized the motor system's task through constraints restricting its operation to the domain of behaviorally useful muscle deployments. (p. 168)

If the proper unit of analysis for the motor system is indeed the coordinative structure, then the difference between coordinated and uncoordinated movement—between control and dyscontrol—is defined by what acts are actually performed, since the coordinative structure by definition is functional in nature.

We should clarify what we mean by *functional* here, for some may view it as a buzzword that glosses over underlying mechanisms. This would be a misunderstanding, for as Fentress (1976) has taken pains to point out, mechanism itself is a functional concept and can only be considered in relative terms. Thus what constitutes a mechanism at one level of analysis becomes a system of interrelated subcomponents at a more refined level of analysis.<sup>1</sup> Questions pertaining to mechanisms (e.g., are coordinative structures mechanisms?) are applicable only when the context for the existence of a particular mechanism is precisely defined (Kelso & Tuller, 1981). This brings us to an important point: Coordinative structures are functional units in the sense that the individual degrees of freedom constituting them are constrained by particular behavioral goals or effectivities (Turvey & Shaw, 1979). Sharing the same degrees of

<sup>1</sup>For example, the structure DNA can be taken as a mechanism at one level of analysis, but at another level DNA is more appropriately described as a set of interacting components such as proteins and enzymes.

freedom without reference to the effectivity engaged in by an actor would not constitute a functional unit.

Nowhere is this claim (insight?) more apparent than in modern ethological research, where there is growing recognition that nervous systems are organized with respect to the relations among components rather than to the individual components themselves (cf. Bateson & Hinde, 1976; Rashevsky, 1960). Thus, in seeking to understand the nature of behavior, some ethologists consider it more appropriate to look for generalities across dimensions that are physically distinct but normally occur together (e.g., pecking and kicking during fights) rather than across dimensions that share the same physical form (e.g., pecking for food and pecking in fights; cf. Fentress, Note 2). In our attempts to relate divergent levels of organization in biological systems we do well to keep the "functional unit" perspective to the forefront, for such units may well have been the focus of natural selection. Moreover, the implications for the acquisition of skill and motor learning are apparent. For example, if one were to ask whether speaking is a complex act, one answer would be that it is complex for the child who is learning to speak but simple for the adult who has already acquired the necessary coordination to produce the sounds of the language. In the sense that the degrees of freedom of the speech apparatus are subject to particular constraints in the adult speaker (which it is our role to discover), then there is reason to believe that his or her neuromuscular organization is actually *simpler* than that of the child *for the same act* (see Yates, 1978, on complexity). Similarly, it is quite possible that so-called complex tasks that fit existing constraints may be much more easily acquired than the "simple" tasks we ask subjects to perform in a laboratory. We turn now to consider exactly what form such constraints appear to take.

### III. Properties of Coordinative Structures

#### A. Local Relations

If, as Gurfinkel, Kots, Paltsev, and Fel'dman (1971) argue, there are many different synergies or coordinative structures, then the key problem for a science of movement is to detect them and to define the context in which they are naturally realized. What should we be looking for and how should we be looking? If the constraint perspective is correct, then we may well expect to see—in any given activity—a constancy in the relations among components of a coordinative structure even though the metrical values of individual components may vary widely. For example, the temporal patterning of muscle activities may be fixed independent of changes in the absolute magnitude of activity in each muscle. Similarly, the temporal patterning of kinematic events may be fixed independent of changes in the absolute magnitude or velocity of individual movements.

One obvious strategy for uncovering relations among components is to change the metrical value of an activity (e.g., by increasing the speed of the action). In this fashion, we can observe which variables are modified and which variables, or relations among variables, remain unchanged. Notice that if one searches for canonical forms of an activity, then changing metrical properties obscures the basic form by altering properties of individual components that would otherwise remain stable. For example, in the study of speech, changes in speaking rate and syllable stress pose major problems for researchers looking for invariant acoustic definitions of phonemes. Alternatively, these changes may provide the major ways that invariance can be observed; some aspects of phonemes must change and other aspects must remain the same in order to preserve phonemic identity over changes in speaking rate and stress.

The properties of coordinative structures have been more fully articulated in a number of recent papers (Fowler, 1977; Kelso, Holt, Kugler, & Turvey, 1980; Kugler et al., 1980; Turvey et al., 1978). Here we shall present only a small inventory of activities that reveal those properties. We shall try to show—at macroscopic and microscopic levels of behavior—that certain relations among variables are maintained over changes in others. In addition, a primary goal will be to extend this analysis, in a modest way, to the production of speech and beyond that to the intrinsic relations that hold across the systems for speaking, moving, and seeing.

Electromyographic (EMG) investigations of locomotion illustrate the properties of coordinative structures discussed briefly above. For example, in freely locomoting cats (Engberg & Lundberg, 1969), cockroaches (Pearson, 1976), and humans (Herman, Wirta, Bampton, & Finley, 1976), increases in the speed of locomotion result from increases in the absolute magnitude of activity during a specific phase of the step cycle (see Grillner, 1975; Shik & Orlovskii, 1976), but the timing of periods of muscle activity remains fixed relative to the step cycle. In keeping with the notion of coordinative structures, the temporal patterning of muscle activities among linked muscles remains fixed over changes in the absolute magnitude of activity in individual muscles.

The literature on motor control of mastication offers an abundance of data understandable within a constraint perspective. For example, Luschei and Goodwin (1974) recorded unilaterally from four muscles that raise the mandible in the monkey. The cessation of activity in all four muscles was relatively synchronous whether the monkey was chewing on the side ipsilateral or contralateral to the recorded side. In contrast, the amplitude of activity in each muscle was very sensitive to the side of chewing. In other words, the timing of activity periods of the four muscles remained fixed over large changes in amplitude of the individual muscle activities.

Similar timing relations have been reported in human jaw-raising muscles. Moller (1974) observed that the timing of activity in the medial pterygoid and anterior temporalis muscles relative to each other remains unchanged during natural chewing of an apple, although the individual chews are of varying durations and amplitudes: the muscles acting synergistically to raise the jaw

generally show fixed temporal patterns of activity over substantial changes in the magnitude of activity. Thexton's (1976) work suggests that this constancy of temporal relations holds for antagonistic muscle groups as well. Specifically, the timing of activity in the muscles that lower and raise the jaw is not sensitive to changes in consistency of the chewed food, although the amplitudes of activity in the muscles that raise the jaw decrease markedly as the food bolus softens.

The two activities discussed, locomotion and mastication, are easily described as fundamental patterns of events that recur over time. The observed pattern is not strictly stereotypic because it is modifiable in response to environmental changes, such as bumps in the terrain or changes in consistency of the food. This style of coordination, in which temporal relationships are preserved over metrical changes, may also hold for activities that are less obviously rhythmic and whose fundamental pattern is not immediately apparent. Examinations of kinematic aspects of two such activities, handwriting and typewriting, reveal these properties of coordinative structures.

At first blush, the control of handwriting does not appear to be in terms of a fundamental motor pattern that recurs over time. The linguistic constraints are considered primary, precluding the possibility of regularly occurring motor events. However, when individuals are asked to vary writing speed without varying movement amplitude, the relative timing of certain movements does not change with speed (Viviani & Terzuolo, 1980). Specifically, the tangential velocity records resulting from different writing speeds reveal that overall duration changed markedly across speeds. But when the individual velocity records are adjusted to approximate the average duration, the resulting pattern is invariant. In other words, major features of writing a given word occur at a fixed time relative to the total duration taken to write the word. The same timing relationships are preserved over changes in magnitude of movements, over different muscle groups, and over different environmental (frictional) conditions (Denier van der Gon & Thuring, 1965; Hollerbach, 1980; Wing, 1978).

The control of typewriting, like handwriting, does not appear to be in terms of a fundamental motor pattern that recurs over time. But Terzuolo and Viviani (1979) looked for possible timing patterns in the motor output of professional typists and found that for any given word, the set of ratios between the times of occurrence of successive key-presses remained invariant over changes in the absolute time taken to type the word. When weights were attached to the fingers, the temporal pattern of key-presses (the set of time ratios) was unaffected, although the time necessary to type the words often increased. Thus, temporal relationships among kinematic aspects of typewriting appear to be tightly constrained, although the time necessary to accomplish individual keystrokes may change.

A synergistic or coordinative structure style of organization appears to hold over diverse motor acts. The question remains whether this view can be applied to the production of speech. Specifically, do temporal relationships among some aspects of articulation remain fixed over metrical changes in the individual variables? Two obvious sources of metrical change in speech that have been



extensively investigated are variations in syllable stress and speaking rate. If the view of systemic organization that we have elaborated here holds for speech production, we would expect to see a constancy in the temporal relationships among articulatory components (muscle activities or kinematic properties) over stress and rate variations. Allow us first to step back and examine briefly a general conception of how changes in stress and rate are accomplished.

Many current theories of speech motor control share the assumption that changes in speaking rate and syllable stress are independent of the motor commands for segmental (phonetic) units. Articulatory control over changes in speaking rate and syllable stress is considered as "the consequence of a timing pattern imposed on a group of (invariant) phoneme commands" (Shaffer, 1976, p. 387). Lindblom (1963), for example, suggests that each phoneme has an invariant "program" that is unaffected by changes in syllable stress or speaking rate (tempo). Coarticulation results from the temporal overlap of execution of successive programs.<sup>2</sup> Thus, when a vowel coarticulates with a following consonant, it is because the consonant program begins before the vowel program is finished (see also Kozhevnikov & Chistovich, 1965; Stevens & House, 1963). According to these views, when speaking rate increases or stress decreases, the command for a new segment arrives at the articulators before the preceding segment is fully realized. The articulation of the first segment is interrupted, resulting in the articulatory undershoot and temporal shortening characteristic of both unstressed syllables and fast speaking rates. This scheme predicts that the relative temporal alignment of control signals for successive segments, and their kinematic realizations, will change as stress and speaking rate vary, a prediction contrary to the constancy in temporal relationships observed in locomotion, mastication, handwriting, and typewriting.

There exists EMG evidence, albeit quite limited, that the coordinative structure style of organization may hold for speech production, that is, that temporal relationships among aspects of intersegmental articulation remain constant over changes in stress and speaking rate. Experiments by Tuller, Harris, and Kelso (1982) and Tuller, Kelso, and Harris (1982) explored this question directly by examining possible temporal constraints over muscle activities when stress and speaking rate vary. The five muscles sampled are known to be associated with lip, tongue, and jaw movements during speech.

When speakers were asked to increase their rate of speech or to decrease syllable stress the acoustic duration of their utterances decreased as expected. The magnitude and duration of activity in individual muscles also changed markedly. However, the relative timing of muscle activity was preserved over changes in both speaking rate and syllable stress. Specifically, the relative

<sup>2</sup>Although Lindblom's later work does not adhere to the originally described model (e.g., Lindblom, 1974), it has strongly influenced recent experimental work (e.g., Fant, Stathmar, & Karlsson, 1974; Gav, 1978; Gay, Ushijima, Hirose, & Cooper, 1974; Harris, 1978) and, we believe, is representative of a class of theories of speech motor control.

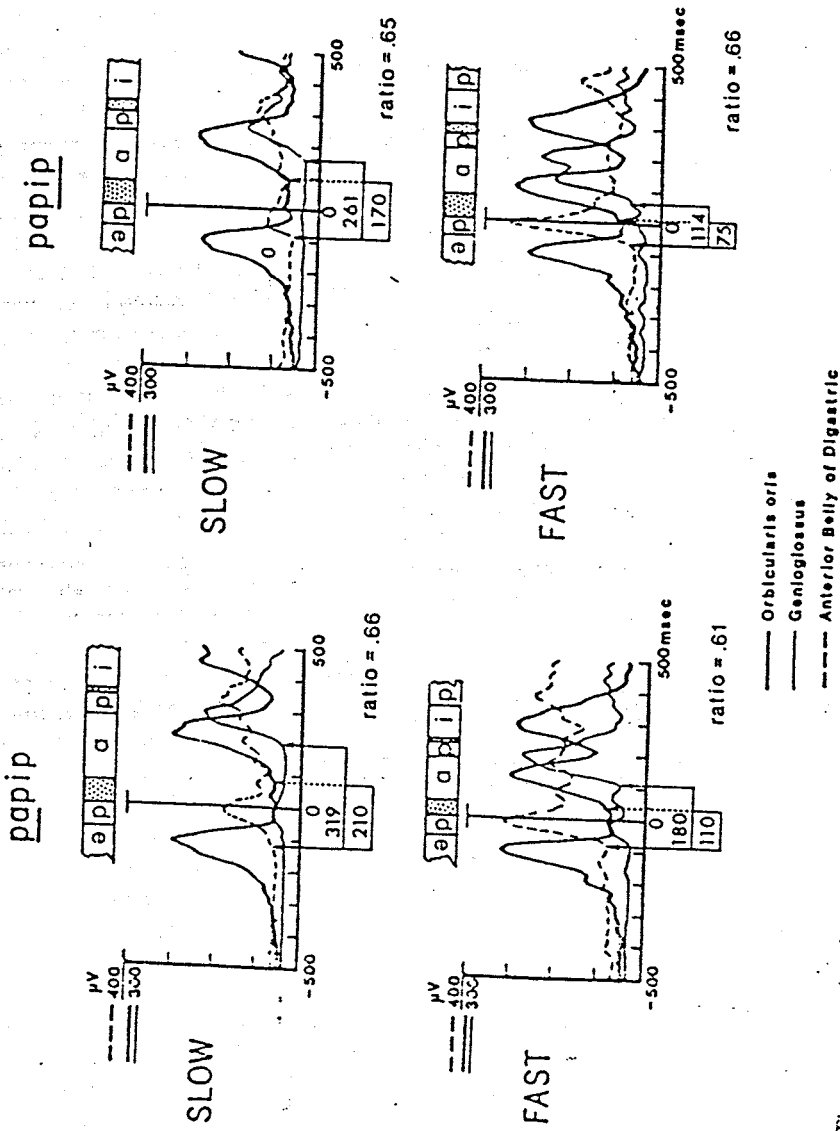


Figure 7-1. The utterance /papip/ spoken by one subject at two rates with two stress patterns. Each muscle trace represents the average of 12 repetitions of the utterance. Arrows indicate onsets of activity for anterior belly of digastric (jaw lowering for /a/; broken line), orbicularis oris (lip movement for /p/; thick line), and genioglossus (tongue fronting for /i/; thin line). The ratio of the latency of consonant-related activity relative to the vowel-to-vowel period is indicated for each stress and rate condition. (From Tuller, Kelso, & Harris, 1982.)

timing of consonant activity and activity for the flanking vowels remained fixed over suprasegmental change.

The preservation of relative timing of muscle activities is illustrated in Figure 7-1, which is essentially a  $2 \times 2$  matrix of stress and rate conditions for the utterance /papip/. Each muscle trace represents the average of 12 tokens produced by one subject. Arrows indicate the onsets of activity for /a/ (anterior belly of digastric), /p/ (orbicularis oris inferior), and /i/ (genioglossus). Onset values, defined as the time when the relevant muscle activity increased to 10% of its range of activity, were determined from a numerical listing of the mean amplitude of each EMG signal, in microvolts, during successive 5-msec intervals.

As is apparent from the figure, the onset of consonant-related activity was strongly linked to the timing of activity for the flanking vowels. In this case, the ratio of latency to period was unaffected by suprasegmental changes, although variations in duration and peak amplitude of activity in individual muscles were evident. In all cases, the relationship maintained was highly linear, though not necessarily ratiomorphic. This preservation of relative timing of consonant- and vowel-related muscle activity was observed for all utterances and muscle combinations sampled, and was independent of the large variations in magnitude and duration of individual muscle activity (for details see Tuller, Kelso, & Harris, 1982). These data fit the primary characteristic of coordinative structures outlined above; namely, there is a constancy in the relative temporal patterning of components, in this case muscle activities, independent of metrical changes in the duration or absolute magnitude of activity in each muscle.

In the brief review of locomotion, mastication, handwriting, and typewriting, we noted that these activities show temporal constraints at either an EMG or a kinematic level, constraints that fit a coordinative structure style of organization. Activities such as speech, handwriting, and typewriting, usually described as less stereotypic or repetitive than locomotion or mastication, can also be described within a synergistic or coordinative structure style of control (see also Kelso, Southard, & Goodman, 1979a, 1979b). In the next section we will attempt to extend this type of analysis to the relations that hold across different structural subsystems, such as the systems for speaking, moving, and seeing.

## B. Global Relations

The inventory presented above offers a view of motor systems that Gelfand and Tsetlin (1971) refer to as *well organized*. Thus the working parameters of the system appear to fall into two distinct groups: essential parameters that determine the form of the function (also called the structural prescription, cf. Boylls, 1975; Kelso et al., 1979a, 1979b; Grimm & Nashner, 1978; Turvey et al., 1978), and nonessential parameters that lead to marked changes in the values of the function but leave its topology essentially unchanged. It is possible

that a subdivision of this nature does not exist for every function; nevertheless, the distinction between essential and nonessential variables (between coordination and control—see Kugler et al., 1980) is apparent in a wide variety of activities.

As a historical note, we remark that the distinction between variables of coordination and control is not entirely new (although there is little doubt of our failure to appreciate it). Over 40 years ago von Holst (1937/1973), following his extensive studies of fish swimming behavior, hypothesized the presence of a duality between frequency and amplitude of undulatory movement (see also Webb, 1971). Invariantly, amplitude of fin movement could be modulated (sometimes by as much as a factor of 4) by, for example, the application of a brief pricking stimulus to the tail, without affecting frequency in any way. Von Holst (1937/1973) concluded that this behavior may be explained as follows: "The automatic process (a central rhythm) determines the frequency, whilst the number of motor cells excited by the process at any one time defines—other things being equal—the amplitude of the oscillation" (pp. 88–89). There seems little doubt that neurophysiological research of the last decade has borne out von Holst's thesis—in general, if not in detail—with its discovery of numerous central rhythm generators (see Davis, 1976; Dellow & Lund, 1971; Grillner, 1975; Stein, 1978). We shall have much more to say about the nature of **rhythmical activity** in the next section: for the moment let us consider the possibility that the partitioning of variables into essential and nonessential is a basic design strategy for motor systems.

In Section III.A we presented a brief inventory of activities that highlighted the nature of constraints on large numbers of muscles. Yet these activities illustrate the partitioning of variables within local collectives of muscles—muscles acting at single or homologous limbs or within a single structural subsystem. The arguments that a synergistic style of organization constitutes a design for the motor system would surely be strengthened if it could be shown that the same classification of variables into essential and nonessential holds for more than one structural subsystem. We turn then to examine a potential relationship that has intrigued numerous investigators, namely, that between speaking and manual performance.

There is reason to believe that the two activities may be linked by virtue of their privileged status as unique functions of the left hemisphere. This fact has been used to suggest that language lateralization arises as a result of the requirement for unilateral motor control of a bilaterally innervated vocal apparatus (Liberman, 1974).

Relatedly, in their well-known "functional cerebral space" model, Kinsbourne and Hicks (1978a, 1978b) suggest that because the human operator has access to a limited amount of functional cerebral space, excitation from putative cortical control centers that are close together (e.g., for speaking and controlling the right hand) is likely to overflow and cause intrahemispheric interference. Conversely, the greater the functional distance between control centers, the less likely is contamination from one center to the other and the

better is performance on simultaneous tasks. Experiments showing that right-hand superiority in balancing a dowel on the index finger is lost when subjects are required to speak while doing the task (e.g., Kinsbourne & Cook, 1971; Hicks, 1975; Hicks, Provenzano, & Rybstein, 1975) all seem to support some type of functional space or intrahemispheric competition model.

These experiments also motivate a view of cerebral function in which speaking is considered dominant over the manual task. Unfortunately, the dependent measures employed—dowel balancing or number of taps on a key—do not allow us to examine possible interactions with speaking (e.g., whether pauses in tapping and pauses in speaking co-occur). This design deficiency is in part to blame for the focus on manual performance as it reflects intrahemispheric interference with little or no emphasis on possible complementary effects on speech dynamics. Indeed, the failure to find effects on global measures of vocal performance (e.g., number of words generated in response to a target letter in 30 sec) has led some investigators to conclude that interference is a "one-way street," with "cognitive tasks having priority over motor systems" (Bowers, Heilman, Satz, & Altman, 1978, p. 555).

From our perspective it makes little sense to talk of interference, competition, and rigid dominance relations in a coordinated system. If speech and movement control systems are governed by the same organizational principles, the issue for lateralization concerns the tightness of fit between these systems when control is effected by one limb or the other. Although we shall not speak to the laterality issue directly at this point, we do want to illustrate that apparent competition and interference between the subsystems for speaking and manual performance may be more correctly viewed as an effect of their mutual collaboration.

Consider the following experiment, in which subjects<sup>3</sup> are asked to produce cyclical movements of a comfortable frequency and amplitude with their right index finger while simultaneously uttering a homogeneous string of syllables ("stock," "stock," etc.).<sup>4</sup> Obviously, subjects have no problem whatsoever in following these instructions. Now imagine that the subject is told to vary the stress of alternate syllables in a strong-weak manner (phonetically, /'stak, stak, 'stak, stak.../) while maintaining amplitude and frequency of finger movement constant. The waveform data for one such subject are shown in Figure 7-2. It is quite obvious that finger movements are modulated—in spite of instructions not to do so—such that they conform to the speech stress pattern:

<sup>3</sup>We have tested a total of seven subjects in a number of different experimental situations. Although we shall not present averaged data here, the figures shown are representative of the performance of all of our subjects. In fact, some subjects show greater effects than those illustrated here.

<sup>4</sup>The apparatus for recording finger movements has been described in detail elsewhere (Kelso & Holt, 1980). Basically, the finger slips into a sleeve whose axis of rotation is coupled to a potentiometer, thus enabling us to obtain a full complement of kinematic characteristics. Both finger and speech waveforms were recorded on FM tape for later off-line analysis on a PDP 11-45 computer.

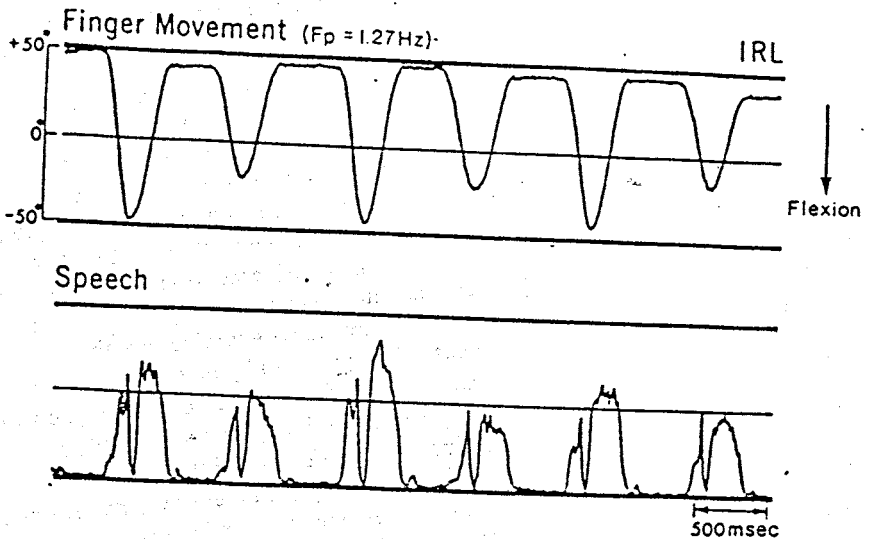


Figure 7-2. Alternate stress of speaking: Simultaneous finger movement (top) and integrated speech waveform (bottom) produced by a subject when told to vary the stress of alternate syllables but maintain the amplitude and frequency of finger movements constant.

that is, longer finger movements accompany stressed syllables, and shorter finger movements accompany unstressed syllables. Is this the outcome of the speech system "driving," as it were, the motor system? A parallel experiment in which subjects were asked to keep stress of speaking constant but to vary the extent of finger movement (i.e., alternating long and short excursions) suggests not. Often the result was that the change in amplitude of finger movement was accompanied by a change in the pattern of syllable production such that there was increased stress<sup>5</sup> with the longer finger movement. The waveform data for one such subject are shown in Figure 7-3.

These data speak to several issues. Of primary importance is the demonstration of *mutual interactions* among the subsystems for speaking and manual performance. Interestingly, this theme is also borne out in recent work on aphasic patients by Cicone, Wapner, Foldi, Zurif, and Gardner (1979). Speech and gesture seem to follow an identical pattern in aphasia: Anterior (Broca's) aphasics seem to gesture no more fluently than they speak, and posterior (Wernicke's) aphasics (who generate much empty speech) gesture far more than normals.

But the broader impact of these data on speaking and manual activity is not

<sup>5</sup>We use the word *stress* here guardedly because we have not yet performed listener tests on subjects' productions. It is clear, however, that the amplitude of the audio waveform is modulated according to what the finger is doing.

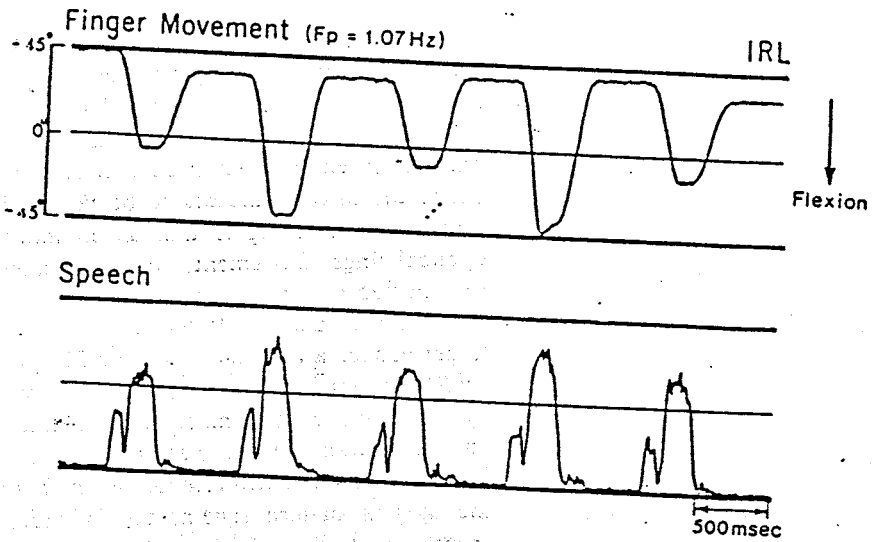


Figure 7-3. Alternate extent of finger movements: Simultaneous finger movement (top) and integrated speech waveform (bottom) produced by a subject when told to vary the extent of alternate finger movements but produce all syllables exactly like all other syllables.

only their indication that the two activities share a common organizational basis (see also Studdert-Kennedy & Lane, 1980, for additional commonalities between spoken and signed language); rather it is that the same design theme emerges in "coupled" systems as in "single" systems (such as those for walking, chewing, handwriting, typewriting, and speaking, reviewed in the preceding section). When an individual speaks and moves at the same time, the degrees of freedom are constrained such that the system is parameterized as a total unit. The parameterization in this case, as in the case of single systems, takes the form of a distribution of force (as reflected in the mutual amplitude relations) among all the muscle groups involved.

An important property of collectives of muscles is their ability to establish and maintain an organization in the face of changes in contextual conditions. Thus Kelso and Holt (1980) show that human subjects can achieve invariant end positions of a limb despite changes in initial conditions, unexpected perturbations applied during the movement trajectory, and both of these in the absence of awareness of limb position. The organization of limb muscles in this case appears to be qualitatively similar to a nonlinear vibratory system (for more details and further evidence see Bizzi, Dev. Morasso, & Polit, 1978; Cooke, 1980; Fel'dman, 1966; Kelso, 1977; Kelso, Holt, & Flatt, 1980; Polit & Bizzi, 1978; Schmidt, 1980; see also below). Similarly, in the well-known speech experiment of Folkins and Abbs (1975), loads applied to the jaw yielded "compensatory responses" in the lips to preserve ongoing articulation. In fact,

the movement of the jaw and lower lip covaried in such a way that the sum of their displacements tended to remain constant (but see Sussman, 1980, for possible methodological problems with compensation studies).

Is the preservation of such "equations of constraint" in the face of unexpected changes in environmental context also characteristic of coupled systems? In short, the answer appears to be yes, at least if the following experiment is representative. Imagine that as an individual is synchronizing speech and cyclical finger movements (in the manner referred to earlier), a sudden and unexpected perturbation is applied to part of the system. In this case a torque load (approximately 60 ounce-inch of 100-msec duration) is added to the finger in such a way as to drive it off its preferred trajectory (see Kelso & Holt, 1980, for details of this technique). In order for the finger to return to its stable cycle, additional force must be supplied to the muscles. Qualitatively speaking, an examination of the movement waveform of Figure 7-4 reveals that the finger is back on track in the *cycle following the perturbation*. Of interest, however, is the speech pattern (again, the individual audio envelopes in Figure 7-4 correspond to the syllable /stak/ spoken at preferred stress and frequency). We see that the audio waveform is unaffected in the cycle in which the finger is perturbed: It is in the following cycle that a dramatic amplification of the waveform occurs. This result is compatible with the present thesis that systems, when coupled, share a mutual organization and that this organization may be preserved over efference (as in the stress-amplitude experiments) or afference (as in the present experiment). Thus a peripheral disturbance to one part of the

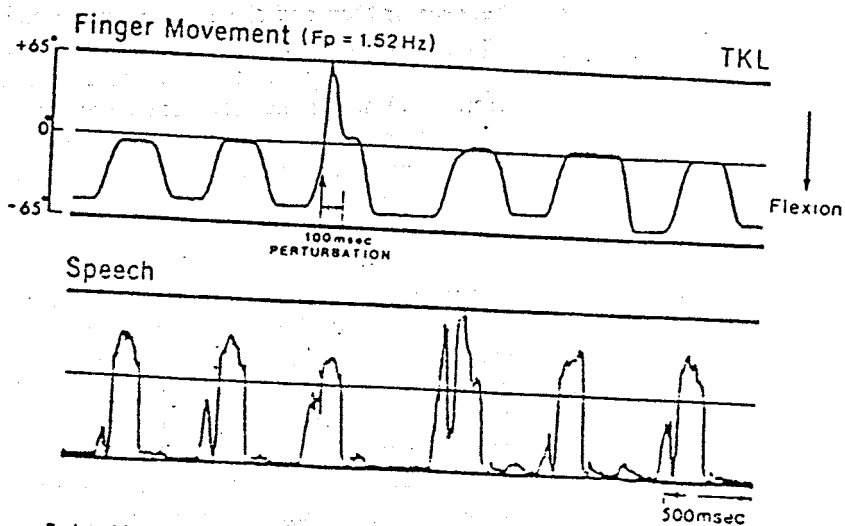


Figure 7-4. Unexpected finger perturbation: Simultaneous finger movement (top) and integrated speech waveform (bottom) produced during a sudden, unexpected finger perturbation. Notice the increase in amplitude of the syllable in the cycle following the perturbation.



system (requiring an additional output of force to overcome it) will have a correlated effect on other parts of the system to which it is functionally linked. Note that as in the previous experiments on speaking and moving, there is no support whatsoever for a one-way dominance of speech over manual performance. Were that the case, there is little reason to expect speaking to be modified in any way by finger perturbations.

Why then does the adjustment (maladjustment may be a more appropriate word) to speaking occur on the cycle *after* the perturbation? Some insight into this issue may be gleaned from a clever experiment on locomotion by Orlovskii and Shik (1965). Dogs were fitted with a force brake at the elbow joint and then were allowed to locomote freely on a treadmill. A brief application of the brake during the transfer-flexion phase not only retarded the movement of the elbow but also that of the shoulder, suggesting that both joints are constrained to act as a unit within the act of locomotion. Spinal mechanisms were implicated because the joints returned to their original velocities within 30 msec of the brake application. But of even greater interest was the *next* locomotory cycle, some 800-900 msec following the original perturbation. Here the transfer-flexion phase was delayed again, as if the perturbation (along with an appropriate response) had reoccurred. Note that had the brake actually been applied, this "phantom braking response" (Boylls, 1975) would have constituted an *adaptation*; indeed, this phenomenon of modifying current acts based on perturbations occurring in antecedent ones is called *next-cycle adaptation*.

Although our understanding of such phenomena is still rather primitive (see Boylls, 1975, pp. 77-79, for one speculation of a neural type), the present equations-of-constraint perspective on coupled systems offers at least a descriptive account (see also Saltzman, 1979). From the mutual relations observed in the stress and finger amplitude experiments, we can generate the following simple constraint equation:

$$f(x,y) = k$$

where the variables  $x$  and  $y$  represent the set of muscles (subsystems) for speaking and manual activity, respectively, such that a specific change in  $x$  will be accompanied by a corresponding change in  $y$  to preserve the function,  $f$ , constant. Now imagine that at time  $t_1$  the variable  $y$  is altered via a peripheral perturbation such that a change in its value (in the form of an increase in muscular force) is necessary to overcome the disturbance. As a consequence of "mechanical" constraints (e.g., neural conduction times, mechanical properties of muscles) the variable  $x$  cannot immediately adopt an appropriate value *on the perturbed cycle*. On the next cycle, however, the variable  $x$  takes on a complementary value as a necessary consequence of the fact that force is distributed among both systems.

Let us clarify one important aspect of this simple formulation. The interrelations observed here are not meaningfully described as "compensatory." That is,  $x$  is not incremented because it has to compensate for changes in  $y$ . The synergistic relations observed between speaking and manual activity are not

based on a causal logic (because  $y$ , then  $x$ ). Rather, the coherency between systems is captured by an *adjunctive* proposition (since  $y$  is incremented, then  $x$  must also be incremented).<sup>6</sup> In the stress-finger amplitude experiment,  $x$  and  $y$  were simultaneously adjusted; in the perturbation experiment, as a consequence of inherent neuromechanical factors,  $x$  was not adjusted until the next cycle, even though  $y$  had returned to its preferred state. In both cases the basic notion is the same. That is, the *complementary* relations observed are a consequence of the total system functioning as a single, coherent unit.

The global relations between speaking and manual activity that we have identified above are, it seems, far from exotic, if we look for them through the right spectacles. Other systems with quite different structural designs appear to share the same style of coordination. Consider, as a final example, coordination between the eye and the hand. Imagine a situation in which the oculomotor system is partially paralyzed with curare and the subject asked to point ballistically at a target  $N$  degrees from visual center (Stevens, 1978). The typical result is that the limb overshoots the designated target—a phenomenon called *past pointing*. A common explanation of this finding is that the subject estimates the movement as farther than  $N$  degrees because the *intended eye* movement (registered by an internal copy of the command or corollary discharge of  $N$  degrees) and the actual eye movement ( $N-k$  degrees) are discrepant. If the subject uses the mismatch information to adjust the limb movement, he will overshoot the target. But an alternative to this hypothesis is offered on the basis of a set of experiments on past pointing in patients with partial extraocular paralysis<sup>7</sup> (see Perenin, Jeannerod, & Prablanc, 1977).

While Perenin et al. argue that the mechanism leading to spatial mislocalization involves "the monitoring of the oculomotor output itself" rather than corollary discharge, we believe that their results can be explained within the present framework. We contend that the *actual* amount of force required to move the partially paralyzed eye to a visual target accounts for past pointing. Thus in a task involving the coupling of oculomotor and limb subsystems, parameterization occurs over the total coupled system, so that the increase in force required to localize a partially paralyzed or mechanically loaded eyeball (cf. Skavenski, Haddad, & Steinman, 1972) is necessarily distributed to the system controlling the hand in a task that requires their coupled activity. There is no need to invoke a corollary discharge (Brindley, Goodwin, Kulikowski, &

<sup>6</sup>The idea that adjunctive logic rather than conditional or causal logic is necessary in order to capture the mutual compatibilities among system components is owing to Shaw and Turvey (e.g., Shaw & Turvey, 1981; Turvey & Shaw, 1979). There is growing acceptance of this view in ecological science (cf. Patten, Note 3; Patten & Auble, in press).

<sup>7</sup>We are indebted to Edward Reed for bringing these data to our notice. Reed properly argues that the integration of experiments on extraocular paralysis favoring corollary discharge theory (cf. Teuber, 1966) is based on an argument from exclusion: All other possible accounts are excluded, therefore corollary discharge theory is correct. We concur with Reed, and offer a simpler account of the data.

Leighton, 1976; Stevens, 1978) or an efference monitoring mechanism (Perenin et al., 1977); the eye-hand system is simply utilizing the design strategy that seems to work for many other activities that involve large numbers of degrees of freedom. In short, the fascinating aspect of the data linking the eye, the speech apparatus, and the hand is that the relations observed apply to systems whose structural features are vastly different, just as these same coordinative structure properties apply to more "local" collectives of muscles that share common structural elements.

#### IV. Rationalizing Coordinative Structures as "Dynamic Patterns"<sup>8</sup>

We have seen in the previous sections that a ubiquitous feature of collectives of muscles is the independence of the force or power distributed into the collective and the relative timing of activities (electromyographic and kinematic) within the collective. In fact, we have presented evidence suggesting that the motor system has a preferred mode of coordination: Where possible, scale up on power but keep relative timing as constant as possible. The flexibility of the system is attained by adjusting the parametric values of inessential variables without altering the basic form of the function as defined by its essential variables. It remains for us now to rationalize why nature has adopted this strategy. In particular let us consider why timing constraints are a principal characteristic of coordinated movement. In fact, this question could take a more general form: Why are humans inherently rhythmic animals?<sup>9</sup> A short excursion into dynamics offers an answer to these questions in terms of physical principles. As we shall see, the physics of systems in flux defines living creatures as rhythmic; no new mechanisms need be introduced to account for the inherent rhythmicity (Morowitz, 1979).

Dynamics—the physics of motion and change—has not been considered particularly appropriate for an analysis of biological systems because until quite recently it has dealt almost exclusively with linear conservative systems. In simple mechanical systems such as a mass-spring, the equation of motion describes a trajectory toward an equilibrium state. Thus a linear system represented by the second-order differential equation

$$m\ddot{x} + c\dot{x} + kx = 0 \quad (1)$$

will decay in proportion to the magnitude of its viscous (frictional) term ( $c$ ), and

<sup>8</sup>Parts of this section also appear, with minor modifications, in Kelso (1981).

<sup>9</sup>We do not believe this to be a trivial question. Even "at rest" man is operating periodically (see Desmedt, 1978, for review on normal "resting" tremor). At more macroscopic levels we are subject to circadian phenomena (e.g., Aschoff, 1979). Even the structure of language—if recent generative theories are a yardstick (e.g., Liberman & Prince, 1977)—is inherently rhythmic.

oscillatory motion will cease. All this is predicated on the second law of thermodynamics—time flows in the direction of entropy. Yet living systems are characterized by sustained motion and persistence; as Schrödinger (1945) first remarked, they “accumulate negentropy.” Living systems are not statically stable; they maintain their form and function by virtue of their *dynamic stability*.

How might we arrive at a physical description of biological systems that does not violate thermodynamic law? Consider again the familiar mass–spring equation, but this time with a forcing function,  $F(\theta)$ :

$$m\ddot{x} + c\dot{x} + kx = F(\theta). \quad (2)$$

Obviously it is not enough to supply force to the system; to guarantee persistence (and to satisfy thermodynamic principles) the forcing function must exactly offset the energy lost in each cycle. Real systems meet this requirement by including a function—called an escapement—to overcome dissipative losses. The escapement constitutes a nonlinear element that taps some source of potential energy (as long as it lasts) to compensate for local thermodynamic losses. Thus, a pulse or “squirt” of energy is released via the escapement such that, averaged over cycles, the left-hand side of Equation 2 equals the right-hand side and sustained motion is thereby assured.

The foregoing description is of course the elementary theory of the clock (see Andranov & Chaiken, 1949; Iberall, 1975; Kugler et al., 1980; Yates & Iberall, 1973, for many more details), but it draws our attention to some fundamentally important concepts: First, stability can only be established and maintained if a system performs work; second, work is accomplished by the flow of energy from a high source of potential energy to a lower potential energy “sink;” third, stated as Morowitz’s theorem, the flow of energy from a source to a sink will lead to at least one cycle in the system (Morowitz, 1979).

That cyclical phenomena abound in biological systems is hardly at issue here (see Footnote 9, the chronobiology literature [Aschoff, 1979], and reviews by Oatley & Goodwin, 1971; Wilke, 1977). Nor is the notion—favored by investigators of movement over the years—that “clocks,” “metronomes,” or rhythm generators may exist for purposes of timing (e.g., Keele, 1980, for recent discussion; Kozhevnikov & Chistovich, 1965; Lashley, 1951). However, we might emphasize that the many extrinsic “clock” mechanisms are not motivated by thermodynamic physical theory. The view expressed here—which can only mirror the emphatic remarks of Yates (1980)—is that cyclicity in complex systems is ubiquitous because it is an *obligatory manifestation of a universal design principle for autonomous systems*.

Such a foundation for complex systems leads us, therefore, away from more traditional concepts. The Bernard–Cannon principle of homeostasis, for example, which provides the framework on which modern control theory—with its reference levels, comparators, error correction mechanisms, and so on—is built, is obviated by a dynamic regulation scheme in which internal states are a

consequence of the interaction of thermodynamic engines (Soodak & Iberall, 1978). The latter scheme, appropriately termed *homeokinetic*, conceives of systemic behavior as established by an ensemble of nonlinear oscillators that are entrained into a coherent harmonic configuration. For homeokinetics, many degrees of freedom and the presence of active, interacting components is hardly a "curse" in Bellman's (1961) terms; rather it is a necessary attribute of complex systems.

That the constraints imposed on coordinated activity—whether of speech or limbs (or both)—should take the form of a dissociation between power and timing is now less mysterious within this framework than before. Coordinative structures *are* nonlinear oscillators (of the limit cycle type, see below) whose design necessarily guarantees that the timing and duration of "squirts" of energy will be independent of their magnitude within a fixed time frame (a period of oscillation; see Kugler et al., 1980). Referring back to Equation 2, we see that the magnitude of the forcing function will be some proportion of the potential energy available, but the forcing function itself is not dependent on time (Iberall, 1975; Yates & Iberall, 1973). Nonconservative, nonlinear oscillators are truly *autonomous* devices in a formal mathematical sense; time is nowhere represented in such systems (Andranov & Chaiken, 1949) and energy is provided in a "timeless" manner.

An example may be helpful at this point. It comes from a fascinating experiment by Orlovskii (1972) on mesencephalic locomotion in the cat. If one selectively stimulates the hindlimb areas of Red and Dieters nuclei in a stationary cat, the flexor and extensor synergies (corresponding to swing and stance phases, respectively) can be energized. During induced locomotion, however, continuous stimulation of one site or the other has an effect *only when the respective synergies were actually involved in the step cycle*. Supraspinal influences (the energy supply) are tapped only in accordance with the basic design of the spinal circuitry. It is the latter—as in real clocks—that determines *when* the system receives its pulse of energy as well as the duration of the pulse (see also Boylls, 1975, for a discussion of spinal "slots," and Kots's 1977 analysis of the cyclic "quantized" character of supraspinal control, pp. 225–229).

The organization realized by coordinative structures—as we have noted—is not obtained without cost: nonlinear dynamic patterns emerge from the dissipation of more free energy than is degraded in the drift toward equilibrium. Thus the stability of a collective is attained by the physical action of an ensemble of "squirt" systems in a manner akin to limit cycle behavior (cf. Katchalsky et al., 1974; Prigogine & Nicolis, 1971; Soodak & Iberall, 1978). It remains for us now to illustrate—albeit briefly and in a very preliminary way—some of the behavioral predictions of the dynamic perspective on coordinated movement. These necessarily fall out of the properties of nonlinear limit cycles—a topic that we can address here only in a rather terse way.

Homeokinetic theory characterizes biological systems as ensembles of non-

linear oscillators coupled and mutually entrained at all levels of organization. It predicts the discovery of numerous cyclicities and evidence of their mutual interaction. As noted above, the only cycles that meet the nonlinear, self-sustaining, dynamic stability criteria that homeokinetics demands are called *limit cycles* (Goodwin, 1970; Soodak & Iberall, 1978; Yates & Iberall, 1973), and it is from their properties that insights into behavior might emerge. Here we give a sampling of work in progress (Kelso, Holt, Rubin, & Kugler, 1981). By and large, the research involves cyclical movements of the hand alone or in combination with speech (see Section III.B).

### A. Response to Perturbations and Changes in Initial Conditions

As Katchalsky et al. (1974) note, the essential difference between linear or nonlinear conservative oscillators and limit cycle oscillators (which obey nonlinear dissipative dynamics) is that perturbations applied to a conservative oscillator will move it to another orbit or frequency, whereas a limit cycle oscillator will maintain its orbit or frequency when perturbed. An examination of Figure 7-5 helps clarify this point. In Figure 7-5A, we show the position versus time and velocity versus position functions for linear and nonlinear types of oscillators. In Figure 7-5B the spiral trajectory in the phase plane represents an oscillation that continuously decreases in amplitude until it comes to a standstill. This is the phase trajectory (velocity vs. position relation) of a stable, damped oscillation. A change in any parameter in the equation describing this motion—for example, the damping coefficient—would drastically change the form of the solution and thus the phase trajectory. In such linear systems there is then no *preferred* set of solutions in the face of parameter changes. In sharp contrast, nonlinear oscillators of the limit cycle type possess a family of trajectories that all tend asymptotically toward a *single* limit cycle despite quantitative changes in parameter values (see Figure 7-5C). Thus, a highly important property of limit cycle oscillators is their *structural stability* in the face of variations in parameter values.

We have shown, in a set of experiments on two-handed cyclical movements (Kelso et al., 1981), that the limbs (in this case the fingers) maintain their preferred frequency and amplitude relations no matter how they are perturbed. Perturbations took the form of brief (100 msec) or constant (applied at a variable point during the cycle and maintained throughout) torque loads unexpectedly applied to one hand or the other via direct-current (dc) torque motors situated above the axis of rotation of the metacarpophalangeal joints. In all four experiments there were no differences in amplitude or duration ( $1/f$  msec) before and after perturbation (for many more details, see Kelso et al., 1981). Moreover, the fact that nonlinear oscillators must degrade a large amount of free energy in order to offset the energy lost during each cycle suggests that they will be quickly resettable following a perturbation. This was precisely the case in our experiments. The fingers were in phase in the cycle

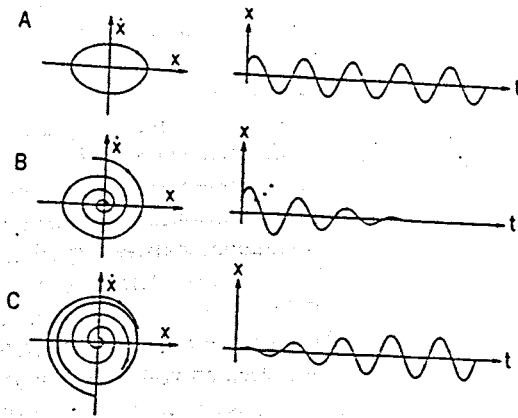


Figure 7-5. Phase plane trajectories (left) and corresponding position-time functions (right) for three different types of oscillation: A, idealized harmonic motion; B, damped harmonic motion; C, limit cycle oscillatory motion. (From Kelso et al., 1981.)

immediately following the perturbation, as revealed by cross-correlations between the limbs as a function of phase lag and by individual inspection of displacement-time waveforms. This capability to return to a stable, bounded phase trajectory despite perturbations, predicted by limit cycle properties, is an extension of our previous work (and that of others) on single trajectory movements (see Section III.B). The latter, it will be remembered, display the "equifinality" property in the face of perturbations, changes in initial conditions, and deafferentation (see Bizzi, this volume). The organization over the muscles is qualitatively like a nonlinear oscillatory system, regardless of whether one is speaking of discrete or cyclical movements (see Fel'dman, 1966; Fowler et al., 1980; Kelso & Holt, 1980; Kelso, Holt, Kugler, & Turvey, 1980).

## B. Entrainment Properties

We have characterized coordination in biological systems as arising from cooperative relationships among nonlinear oscillator ensembles. As already intimated, the chief mode of cooperation among self-sustaining oscillators is entrainment or synchronization. Strictly speaking, the latter terms are not synonymous: Synchronization is that state which occurs when both frequency and phase of coupled oscillators are matched exactly; entrainment refers to the matching of frequencies, although one oscillator may lead or lag behind the other.

When coupled oscillators interact, *mutual entrainment* occurs (the "magnet" or "M" effect of von Holst, 1937, 1973) with only a small frequency detuning

(Minorsky, 1962). Another form of mutual interaction occurs if the frequency of one oscillator is an integer multiple of another to which it is coupled, a property termed subharmonic entrainment or frequency demultiplication. These preferred relationships are ones that coupled oscillators assume under conditions of maximal coupling or phase locking. Years ago, von Holst discovered conditions of maximal coupling or phase locking. Years ago, von Holst discovered coordinative states in fish fin movements that correspond to the different types of entrainment discussed here (see von Holst, 1937/1973). The most common mode of coordination he termed *absolute coordination*, a one-to-one correspondence between cyclicities of different structures. The second and much less common interactive mode he called *relative coordination*. Here the fins exhibit different frequencies, although at least one corresponds to that seen in the absolute coordination state. In more recent times, Stein (1976, 1977) has elaborated on von Holst's work, using the mathematics of coupled oscillators to predict successfully patterns of neuronal activity for interlimb coordination. The oscillator theoretic approach to neural control, as Stein (1977) remarks, is still in an embryonic state. In our experiments we have taken a step in what we hope is a positive direction by examining the qualitative predictions of the theory without immediate concern for its neural basis. The results are intuitively apparent to any of us who have tried to perform different cyclical movements of the limbs at the same time. Thus the cyclical movements of each limb operating singly at its own preferred frequency mutually entrain when the two are coupled together (von Holst's "M" effect). When an individual is asked to move his or her limbs at different frequencies, low-integer subharmonic entrainment occurs. The waveforms of both limbs shown in Figure 7-6 also suggest amplitude modulation (von Holst's *superimposition* effect). Thus on some coinciding cycles a "beat" phenomenon can be observed (particularly in the 2:1 ratio) in which the amplitude of the higher frequency hand increases in relation to noncoincident cycles. These preferred relationships are *emergent* characteristics of a system of nonlinear oscillators; the collection of mutually entrained oscillators functions in a single unitary manner.

Entrainment properties are not restricted to movements of the limbs, but are also evident (as predicted by the principles of homeokinetic physics) in systems that share little or no common structural similarity. Returning to our analysis of the interrelationships between speaking and manual activity, we have shown that subjects, when asked to speak (again the familiar syllable /stak/) at a different rate from their preferred finger rate, do so by employing low-integer sub- or superharmonics (see Figure 7-7). The situation is reversed (although not necessarily symmetrically) when the individual is asked to move the finger at a different rate from speaking. The ratios chosen are always simple ones (e.g., 2:1 or 3:1; see Figure 7-8). The strict maintenance of cyclicity as predicted by homeokinetic theory is abundantly apparent. Entrainment ensures a stable temporal resolution of simultaneous processes throughout the whole system. Moreover, entrainment of oscillators is limited to a relatively restricted frequency range captured in Iberail and McCulloch's poetics as an "orbital constellation."



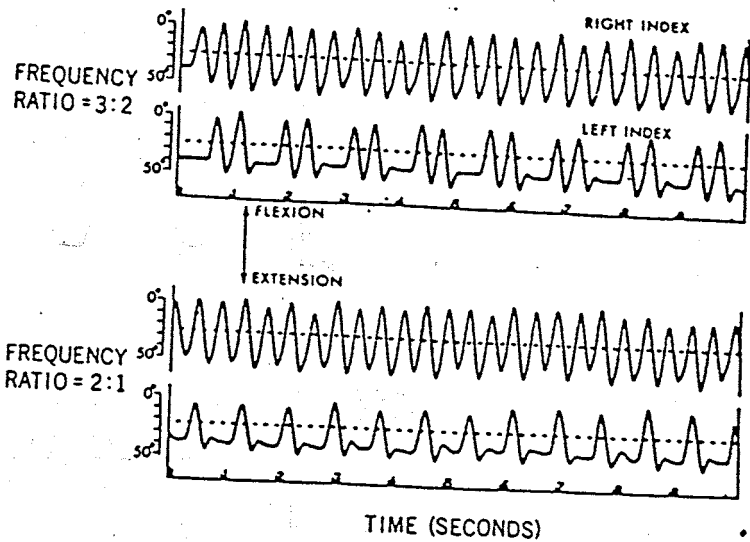


Figure 7-6. An example of one subject's response to instructions to move the fingers at different frequencies. On some coinciding cycles, a "beat" phenomenon can be observed in which the amplitude of the higher frequency hand increases in relation to non-coincident cycles (see especially 2:1 ratio).

Homeokinetic theory requires a dynamic system analysis that, to be used optimally, requires a research decision as to the likely limiting conditions for the spectrum of effects of interest. In the continuum of cyclical processes, coherency is determined by the longest period over which "thermodynamic bookkeeping" is closed: For those interested in the production of speech, a possible candidate oscillation over which articulatory cycles of shorter periods may cohere is the "breath group" (Lieberman, 1967) or, more globally, the respiratory cycle (Fowler, 1977; Turvey, 1980). The latter, tied as it is to metabolic processes, may well be the organizing period for *all* the activity patterns of an animal. It is well known, for example, that during exercise, respiration is often synchronized with movements of body parts (Astrand & Rodahl, 1970). But even when metabolic demands are not altered from a resting state, preliminary data indicate entrainment between breathing and limb movements (see also Wilke, Lansing, & Rogers, 1975).

In Figure 7-9 we see data from the now familiar task of speaking and performing cyclical finger movements. In the first case the subject is instructed to move the left index finger at a different rate from speech. The finger waveform is highly regular (3 Hz) except at one point where a pause is evident. From the acoustic signal it is obvious that the pause in finger movement coincides perfectly with respiratory inhalation. In a parallel condition in which the subject is instructed to speak at a different rate from finger movement, we see exactly

## CHANGE RATE OF SPEAKING

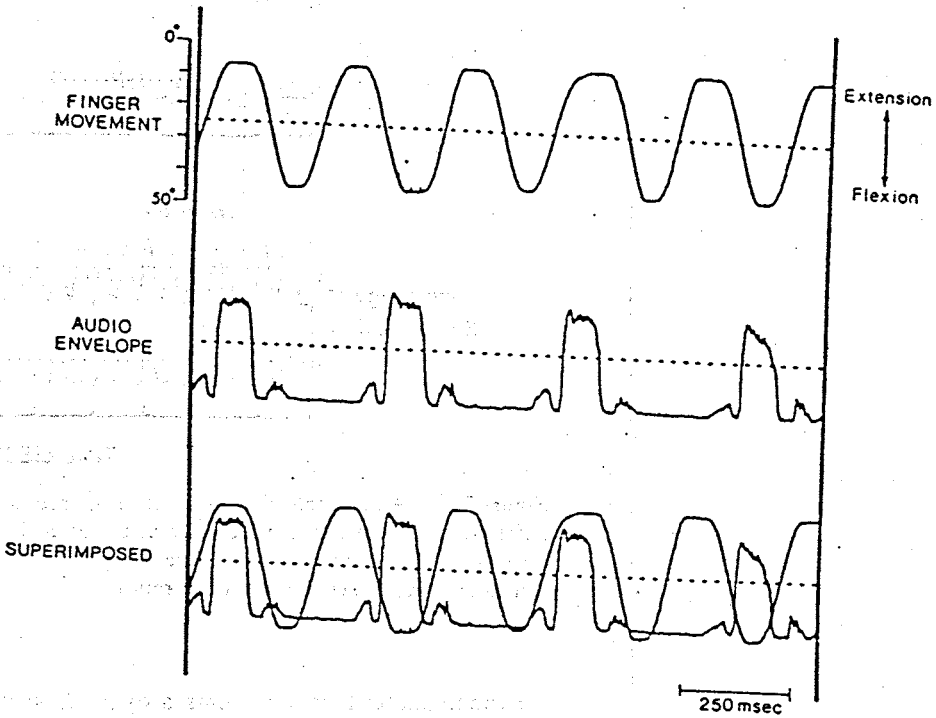


Figure 7-7. Simultaneous finger movement (top) and integrated speech waveform (center) produced by a subject asked to speak at a different rate from finger movement. The subject shown considered each flexion and extension as a separate finger movement. Thus, the finger-to-speech ratio is 3:1.

the same co-occurrence of breathing and a pause in the finger movements (see Figure 7-10). Aside from the fact that these data provide further and perhaps the most compelling evidence of entrainment in coupled systems, there is also the suggestion that *both* systems cohere to the longer time-scale activity, namely, breathing. Since the flow of oxygen constitutes a sustained temporal process in the system (the "escapement" for the thermodynamic power cycle), it seems reasonable to suppose that the respiratory cycle may play a cohering role around which other oscillations seek to entrain. But at this point the question is hypothetical in the face of nonexistent data.

We do not wish to give the impression, however, that the cohering role of the respiratory cycle gives it dominant status. On the contrary, it is well known that the respiratory cycle itself changes character to accommodate the demands of speech (e.g., Draper, Ladetoged, & Whitteridge, 1960). In fact, the entrainment of these systems cannot be explained solely on the basis of metabolic demands.

## CHANGE RATE OF FINGER MOVEMENT

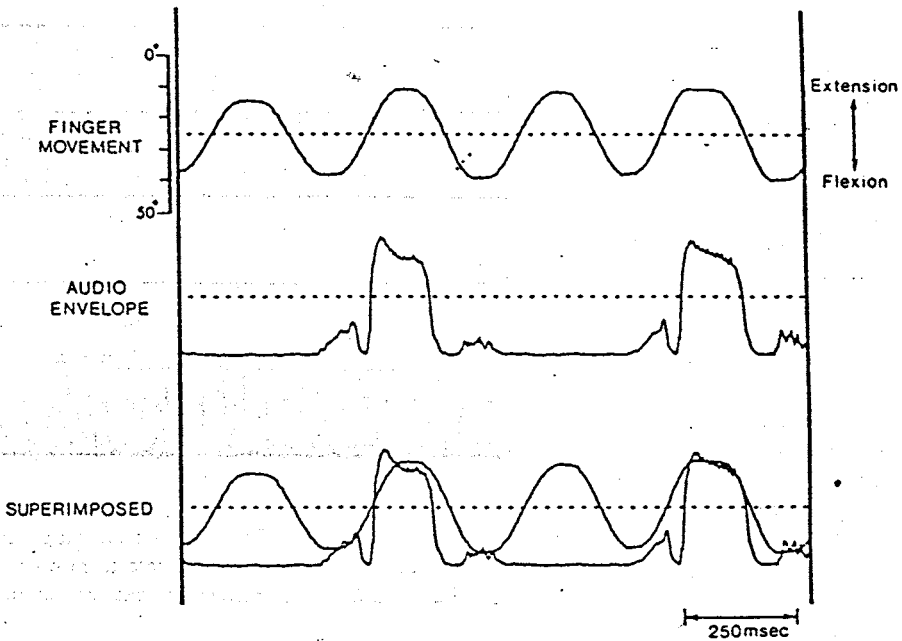


Figure 7-8. Simultaneous finger movement (top) and integrated speech waveform (center) produced by a subject when asked to move her finger at a different rate from her speaking. This subject shows a 2:1 ratio of finger movement to speech, each syllable synchronized with every second finger extension.

When subjects read silently (Conrad & Schönle, 1979), or when finger movements required are of minimal extent (Wilke, 1977), respiratory rhythms change in order to be compatible with the other activity. The point is that in an oscillator ensemble there is no fixed dominance relation. There are different modes of interaction (e.g., frequency and amplitude modulation) and there may be preferred phase relationships, as in the extreme case of maximal coupling or phase locking between two oscillators. A wide variety of behavioral patterns emerges from these interactions: there is structure and a complex network of interconnections but, strictly speaking, no dominance relation.

## V. Concluding Remarks

The major problem confronting a theory of coordination and control (whether it be of speech or limbs) is the determination of how stable spatiotemporal organizations are realized from a neuromuscular basis of very many degrees of

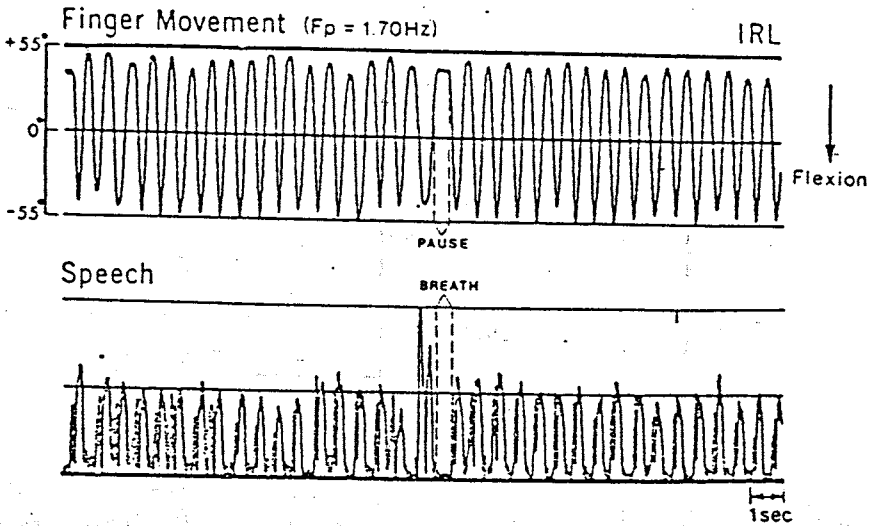


Figure 7-9. Simultaneous finger movement (top) and integrated speech waveform (bottom) produced by a subject when told to move her finger at a different rate from speaking. Pause in the finger movement and the simultaneous inhalation are indicated.

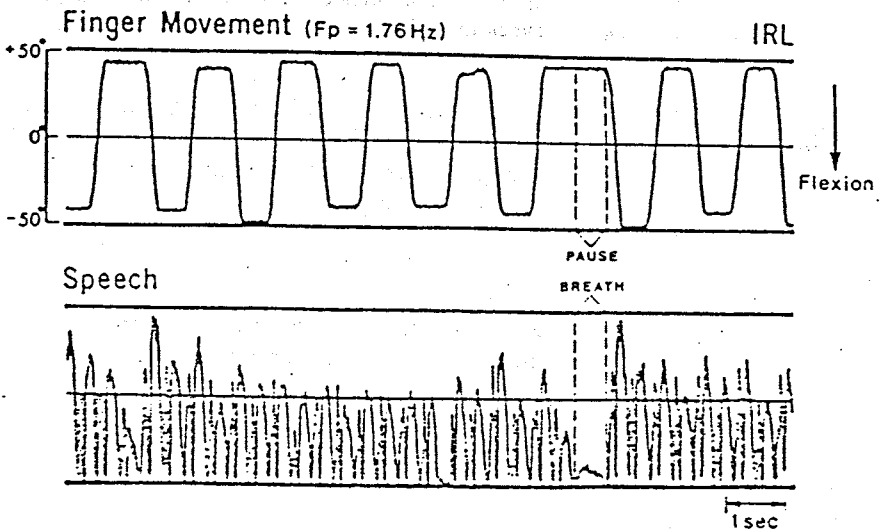


Figure 7-10. Simultaneous finger movement (top) and integrated speech waveform (bottom) produced by a subject when told to speak at a different rate from finger movement. A pause in the finger movement and the simultaneous inhalation are indicated.

freedom. Here we have offered the beginnings of an approach in which solutions to the degrees of freedom problem may lie not in machine-type theories but in the contemporary physical theories of dissipative structures and homeokinetics. A central characteristic of such theories is that complex systems consist of collectives of energy-flow systems that interact in a unitary way and, as a consequence, exhibit limit cycle oscillation. Many of the motor behaviors discussed in this chapter can be rationalized according to limit cycle properties. Common to all of them—including speech—is that certain qualitative properties are preserved over quantitative changes in the values of individual components (muscles, key-presses, kinematic attributes). This feature of coordinated activity exists across all scales of observation; it is as applicable to the microscale (e.g., physiological tremor) as it is to the gross movement patterns of locomotion. We suspect that the functional similarities observed across levels of analysis index the design of the motor system. Thus, even though the material composition varies dramatically from level to level, certain qualitative properties, like cycling, remain invariant (see Kugler et al., 1981; and for a similar view, Mandell & Russo, 1980).

Central to the view expressed here (see also Kelso, 1981; Kugler et al., 1980, 1982; Yates & Iberall, 1973) is that new forms of spatiotemporal organization are possible when scale changes and nonlinearities are present, and an energy supply is available. When a stable system is driven beyond a certain critical value on one of its parameters, bifurcation occurs and qualitatively new structures emerge (Guttinger, 1974). There are many examples of such phase transition phenomena in nature (see Haken, 1977; Prigogine, 1980; Winfree, 1980; for examples) and probably in movement as well. We know, for example, that at low velocities quadrupeds locomote such that limbs of the same girdle are always half a period out of phase. But as velocity is scaled up, there is an abrupt transition from an asymmetric to a symmetric gait (Shik & Orlovskii, 1976). The phase relations of the limbs change, but we doubt that a new "program" is required (Shapiro, Zernicke, Gregor, & Diestel, 1981) or that one needs to invoke a "gait selection" process (Gallistel, 1980). Emergent spatiotemporal order, in the view expressed here, is not owing to an a priori prescription, *independent of and causally antecedent to systemic behavior*. Rather it is an a posteriori fact of the system's dynamic behavior. As Gibson (1979) remarked, behavior is regular without being regulated.

The present perspective—with appropriate extensions (e.g., to a reconceptualization of "information" in naturally developing systems; Kugler et al., 1982)—is less antireductionistic than it is an appeal for epistemological change. Contemporary physics as characterized here does not assign priority to any privileged scale of analysis: There is no "fundamental unit" out of which one can construct a theory of systemic phenomena (see Buckley & Peat, 1979; Yates, 1978). Instead, homeokinetics and dissipative structure/dynamic pattern theory offer a single set of physical principles that can be applied at all levels of analysis. If there is reductionism, it is not in the analytical sense but rather to a minimum set of principles.

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