6 Dynamics and Coordinate Systems in Skilled Sensorimotor Activity

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EDITORS' INTRODUCTION

A lay-up by a professional basketball player is a spectacular example of bodily coordination involving literally thousands of cooperating components. Yet numerous kinds of everyday performance are just as magical: a mouse licking fur on its belly, a child speaking her first words, or even simply walking across uneven ground. How are such actions possible? How are all the elements involved controlled so as to participate in the overall action in just the right way?

Traditional computational cognitive science has had very little to say about this kind of problem. That approach inherits Descartes' sharp distinction between mind and body, in the form of a rigid separation between cognition and mere bodily motions. Cognition, the proper domain of cognitive science, is regarded as inner, abstract, representational, and rather difficult to study. Bodily motions are external, concrete, mechanistic, and relatively simple; the study of movement is thought to be someone else's problem entirely. Consequently, for most computational cognitive scientists, the nature of sensorimotor coordination—and hence the interaction of the cognitive system with its world—is simply shelved. Further, when the issue does come to be addressed, computationalists face the difficult problem of interfacing the cognitive system with the body, and in particular getting the symbols, which are the output of the cognitive system, to drive complex movements of real flesh and bone in real time.

In this chapter, Saltzman describes coordination from a dynamical perspective. He begins from the assumption that coordinated movements, such as the regular swinging of two limbs, or the pronunciation of a word, are naturally flowing behaviors of dynamical systems. But how, in any given case, is the dynamical system best described? What are the relevant variables and equations, and how are they tied together into complex systems?

Investigating these questions, Saltzman draws some surprising conclusions. For example, it is natural to suppose that the relevant variables in coordinated movement conceived as a dynamical system would correspond to concrete bodily features such as muscle states and joint angles, and that these features would influence one another by direct physical links. Yet Saltzman shows how patterns of coordination are in fact best captured by dynamical models that operate in a much more abstract, high-level

"task-space," and that the links between different components of a system must be characterized in informational terms.

In the second half of the chapter, the task-space analysis of coordination is described in some detail for one particularly common and yet subtle form of movement, namely the coordination of lips, jaw, tongue, etc. in speaking. Speech involves constricting the throat and mouth in various ways, and so the abstract task space in this case is defined over constriction types. Underlying these constrictions types, of course, are movements of the particular articulators (lips, etc.) involved in speaking; the dynamics in the task space governs the coordination of these lower-level articulators into specific speech gestures such as the closing of the two lips. In speaking whole words and sentences, multiple gestures must be combined in close succession, with the effect that the detailed movements of the articulators in one gesture shape those of their neighbors; in other words, the specific movements of articulators are heavily context-dependent. Saltzman describes how a dynamical model of speech coordination can smoothly accommodate such phenomena.

This work has a number of wider implications for cognitive science. First, sensorimotor coordination is a much more abstract, medium-independent business than is often assumed. Second, a dynamical account of coordinated movement virtually mandates adoption of a compatible dynamical account of more "central" aspects of cognition, such as assembly of the "gestural score" that drives the speech gestures themselves. Thus, a dynamical perspective on coordinated movement not only reduces the conceptual distance between cognition on the one hand and mere bodily movement on the other, it forces reconceptualization of the nature of the inner cognitive processes themselves in dynamical terms. It thus turns out that cognition is not best thought of as something fundamentally distinct from movements of the body; rather, bodily coordination (and thereby interaction with the world) is really part of cognition itself.

6.1 INTRODUCTION

Skilled sensorimotor activities entail the creation of complex *kinematic* patterns by actors using their limbs and speech articulators. Examples of kinematic patterns include trajectories over time of a reaching hand's position, velocity, or acceleration variables, the spatial shape of the path taken by a handheld pen during handwriting, or the relative timing of the speech articulators to produce the phonemes /p/, /e/, and /n/ in the word "pen." The term *dynamics* is used to refer to the vector field of forces that underlies and gives rise to an action's observable kinematic patterns. In this chapter, a dynamical account of skilled activity is reviewed in which skilled behavior is characterized as much as possible as that of a relatively autonomous, self-organizing dynamical system. In such systems, task-appropriate kinematics are viewed as emerging from the system's underlying dynamical organization (Beek, 1989; Saltzman and Munhall, 1989; Schöner and Kelso, 1988; Turvey, 1990). Thus, the emphasis in the present account is on a dynamical description, rather than a kinematic one, of sensorimotor skills. For example, an extreme and admittedly

exaggerated "straw man" counterhypothesis is that of a central executive or homunculus that produces a given movement pattern with reference to an internal kinematic template of the form, tracing out the form provided by the template, and using the articulators as a physiological and biomechanical pantograph to produce a larger version of the pattern in the external world.

An adequate account of skilled sensorimotor behaviors must also address the multiplicity of coordinate systems or state spaces, and the mappings or transformations that exist among them, that appear to be useful in describing such behaviors. For example, a reaching movement can be described simultaneously in terms of patterns of muscle activations, joint angle changes, spatial motions of the hand, etc., and in terms of the ways these patterns relate to one another. This chapter focuses on the roles of both dynamics and coordinate systems in skilled sensorimotor activities. Evidence is reviewed in this chapter supporting the claim that the dynamics of sensorimotor control and coordination are defined in highly abstract coordinate systems called *task spaces* that are distinct from, yet related to, the relatively concrete physiological and biomechanical details of the peripheral musculoskeletal apparatus. It is further hypothesized that such spaces are the media through which actions are coupled perceptually to task-relevant surfaces, objects, and events in the actor's environment.

The chapter is divided into roughly two parts. The first is focused on concepts of dynamics as they have been applied to understanding the performance of single or dual sensorimotor tasks, where each task is defined in a one-to-one manner with a single articulatory degree of freedom. For example, a single task could be defined as the oscillation of a hand about the wrist joint or of the forearm about the elbow joint; a dual task could be defined as the simultaneous oscillations of both the right and left hand, or of the elbow and hand of a given arm. The second part of the chapter is focused on how the notions of dynamics and coordinate systems can be combined or synthesized to account for the performance of single or multiple tasks, where each task is defined over an entire effector system with many articulatory degrees of freedom. For example, in the production of speech the task of bringing the lips together to create a bilabial closure for /p/ is accomplished using the upper lip, lower lip, and jaw as articulatory degrees of freedom.

6.2 DYNAMICS

Why place so much emphasis on the dynamics of sensorimotor coordination and control? A dynamical account of the generation of movement patterns is to be preferred over other accounts, in particular the notion of internal kinematic templates, because dynamics gives a unified and parsimonious account of (at least) four signature properties of such patterns:

1. *Spatiotemporal form.* A movement's spatiotemporal form can be described both qualitatively and quantitatively. For example, qualitatively different hand motions are displayed in situations where the hand moves discretely to

a target position and then stops, and where the hand moves in a continuous, rhythmic fashion between two targets. Quantitative differences are reflected in the durations and extents of various discrete motions, and in the frequencies and amplitudes of the rhythmic motions.

2. *Stability.* A movement's form can remain stable in the face of unforeseen perturbations to the state of the system encountered during movement performances.

3. *Scaling.* Lawful warping of a movement's form can occur with parametric changes along performance dimensions such as motion rate and extent.

4. *Invariance and variability.* A dynamical framework allows one to characterize in a rigorous manner a common intuition concerning skilled actions in general. This intuition is that there is a subtle underlying invariance of control despite an obvious surface variability in performance.

In order to illustrate these points, the behavior of several simple classes of dynamical systems are reviewed (Abraham and Shaw, 1982; Baker and Gollub, 1990; Thompson and Stewart, 1986; see also Norton, chapter 2). Mathematical models based on these systems have been used to provide accounts and to simulate the performance of simple tasks in the laboratory. In such models, the qualitative aspects of a system's dynamics are mapped onto the functional characteristics of the performed tasks. For example, discrete positioning tasks can be modeled as being governed globally by *point attractor* or *fixed point* dynamics. Such dynamical systems move from initial states in a given neighborhood, or *attractor basin*, of an attracting point to the point itself in a time-asymptotic manner. Similarly, sustained oscillatory tasks can be modeled using *periodic attractor* or *limit cycle* dynamics. Such dynamics move systems from initial states in the attractor basin of an attracting cycle to the cycle itself in a time-asymptotic manner (see examples 8 and 9 in Norton, chapter 2, for representative equations of motion and sets of state trajectories for fixed-point and limit-cycle systems, respectively). The performance of simultaneous rhythms by different effectors can be modeled as the behavior of a system of *coupled* limit-cycle oscillators, in which the motion equation of each oscillator includes a coupling term(s) that represents the influence of the other oscillator's ongoing state. For example, the coupling term in oscillator-i's equation of motion might be a simple linear function, $a_{ij}x_j$, of the position of oscillator-j, where x_j is the ongoing position of oscillator-j and a_{ij} is a constant coefficient that maps this position into a coupling influence on oscillator-i. In what follows, the discussion is focused initially on single degree-of-freedom oscillatory tasks, and then moves to comparable, dual degree-of-freedom tasks.

Single Degree-of-Freedom Rhythms

In a typical single degree-of-freedom rhythmic task, a subject is asked to produce a sustained oscillatory movement about a single articulatory degree

of freedom, e.g., of the hand or a handheld pendulum about the wrist joint. Usually, the rhythm is performed at either a self-selected "comfortable" frequency or at a frequency specified externally by a metronome; in both cases, the amplitudes of the performed oscillations are self-selected according to comfort criteria. Such movements can be characterized as limit-cycle oscillations, in that they exhibit characteristic frequencies and amplitudes (Kugler and Turvey, 1987) that are stable to externally imposed perturbations (Kay, Saltzman, and Kelso, 1991; Scholz and Kelso, 1989). For example, after such rhythms are subjected to brief mechanical perturbations, they return spontaneously to their original preperturbation frequencies and amplitudes. Additionally, limit-cycle models capture the spontaneous covariation or scaling behavior that is observed among the task's kinematic observables. For example, at a given movement frequency there is a highly linear relationship between a cycle's motion amplitude and its peak velocity, such that cycles with larger amplitudes generally display greater peak velocities. Such a relationship is inherent in the dynamics of near-sinusoidal limit-cycle oscillations. Further, across a series of different metronome-specified frequencies, the mean cycle amplitude decreases systematically as cycle frequency increases (Kay, Kelso, Saltzman, et al., 1987). Such scaling is a natural consequence of the structure of the limit cycle's *escapement*, a nonlinear damping mechanism that is responsible for offsetting frictional losses and for governing energy flows through the system in a manner that creates and sustains the limit cycle's rhythm.

Dual Degree-of-Freedom Rhythms

These tasks consist simply of two single degree-of-freedom tasks performed simultaneously, e.g., rhythmic motions of the right and left index fingers, usually at a common self-selected or metronome-specified frequency and with self-selected amplitudes. Additionally, subjects are requested typically to perform the task with a given relative phasing between the component rhythms (Kelso, 1984; Rosenblum and Turvey, 1988; Sternad, Turvey, and Schmidt, 1992; Turvey and Carello, chapter 13). For example, for bimanual pendulum oscillations performed at a common frequency in the right and left parasagittal planes (see figure 13.7, Turvey and Carello, chapter 13), an *inphase* relationship is defined by same-direction movements of the components, i.e., front-back movements of the right pendulum synchronous with front-back movements of the left pendulum; similarly, an *antiphase* relationship is defined by simultaneous, opposite-direction movements of the components. Models of such tasks begin by specifying each component unit as a separate limit-cycle oscillator, with a 1 : 1 frequency ratio defined between the pair of oscillators. If this were all there was to the matter, one could create arbitrary phase relations between the component limit cycles, simply by starting the components with an initial phase difference equal to the desired phase difference. This is an inadequate description of dual rhythmic performances, however, since the

behavioral data demonstrate that it is only possible to easily perform 1:1 rhythms that are close to inphase or antiphase; intermediate phase differences are not impossible, but they require a good deal of practice and usually remain more variable than the inphase and antiphase pair.

What makes the inphase and antiphase patterns so easy to perform, and the others so difficult? What is the source of this natural cooperativity? It turns out that these are the same questions that arise when one considers the phenomenon of *entrainment* between limit-cycle oscillators. This phenomenon was observed by the 17th century Dutch physicist Christiaan Huygens, who noticed that the pendulum swings of clocks placed on the same wall tended to become synchronized with one another after a period of time. This phenomenon can be modeled dynamically by assuming that each clock is its own limit-cycle oscillator, and that the clocks are coupled to one another because of weak vibrations transmitted through the wall. Such coupling causes the motions of the clocks to mutually perturb one another's ongoing rhythms, and to settle into a cooperative state of entrainment. These observations suggest that the appropriate theory for understanding the performance of multiple task rhythms is that of coupled limit-cycle oscillators. In this theory, when two limit cycles are coupled bidirectionally to one another, the system's behavior is usually attracted to one of two *modal* states. In each modal state, the components oscillate at a common mode-specific frequency, and with a characteristic amplitude ratio and relative phase. Most important for the present discussion, if the component oscillators are roughly identical and the coupling strengths are roughly the same in both directions, then the two modes are characterized by relative phases close to inphase and antiphase, respectively. It is possible, however, that the frequencies and amplitudes observed in the modal states can be different from those observed when the components oscillate independently of one another.

Thus, we are led to view the inphase and antiphase coordinative patterns in 1:1 dual oscillatory tasks as the attractive modal states of a system of coupled limit-cycle components. Note that the coupling that creates this modal cooperativity is involuntary and obligatory, in the sense that these modal states are hard to avoid even if the task is to perform with a relative phasing in between those of the naturally easy modes. Such intermediate states are possible to perform, but require much practice and remain more variable than the modal states. What is the structure of the intercomponent coupling? What is the source or medium through which this coupling is defined?

Coupling Structure Coupling structure refers to the mathematical structure of the coupling functions that map the ongoing states of a given oscillator into perturbing influences on another. It turns out that many types of coupling will create stable modes with relative phases close to inphase and antiphase. For example, even the simple linear positional coupling mentioned earlier, $a_{ij}x_j$, will work, where x_j is the ongoing position of oscillator-j and a_{ij}

is a constant coefficient that maps this position into a perturbation of oscillator-*i*'s motion.

In addition to entrainment, however, human rhythmic tasks display *phase transition* behaviors that place additional constraints on the choice of coupling functions. In an experimental paradigm pioneered by Kelso (Kelso, 1984; Scholz and Kelso, 1989), subjects begin an experimental trial by oscillating two limb segments at the same frequency in an antiphase pattern, and then increase the frequency of oscillation over the course of the trial. Under such conditions, the antiphase coordination abruptly shifts to an inphase coordination when the oscillation frequency passes a certain critical value. A comparable shift is not seen, however, when subjects begin with an inphase pattern; under these conditions, the inphase coordination is maintained as frequency increases. The abrupt phase transition from antiphase to inphase patterns when frequency is increased can be characterized mathematically as a *bifurcation* phenomenon in the underlying dynamical system. In dynamical models of such phenomena the coupling functions are required typically to be nonlinear (Haken, Kelso, and Bunz, 1985; Schöner, Haken, and Kelso, 1986). To summarize briefly, entrainment can be created by limit cycles coupled bidirectionally in many ways, but entrainment with bifurcations require typically nonlinear coupling structures.

Coupling Medium What is the source of interoscillator coupling during the performance of simultaneous rhythmic tasks? What are the coordinates along which such coupling is defined? One possibility is that the coupling medium is mechanical in nature, as in the case of Huygens' pendulum clocks, since it is known that biomechanical *reactive coupling* exists among the segments of effector systems during motor skill performances (Bernstein, 1967/1984; Hollerbach, 1982; Saltzman, 1979; Schneider, Zernicke, Schmidt, et al., 1989). Such coupling is defined in segmental or joint-space coordinate systems. A second possibility is that the coupling is neuroanatomical, as in the case of the crosstalk or overflow between neural regions controlling homologous muscle groups that has been hypothesized to underlie mirroring errors in bimanual sequencing tasks such as typing or key-pressing (MacKay and Soderberg, 1971), or associated mirror movements in certain clinical populations (Woods and Teuber, 1978). Such coupling is defined in muscle-based coordinate systems.

An experiment by Schmidt, Carello, and Turvey (1990) indicated that matters might not be so straightforward. In this experiment, subjects performed rhythmic motions at their knee joints, but the major innovation of the paradigm was to have the set of two rhythms defined across subjects rather than within subjects. Thus, one subject would perform rhythmic oscillations at one knee joint while watching a nearby partner do the same (see figure 13.9, Turvey and Carello, chapter 13). There were two types of task. In one type, the partners were asked to oscillate their respective legs at a mutually comfortable common frequency either inphase or antiphase with one another,

and to increase or decrease the oscillation frequency by self-selected amounts in response to a signal supplied by the experimenter; in the second type of task, a metronome was used to specify both the frequencies and time schedule of frequency scaling. Surprisingly, all the details of entrainment and bifurcation phenomena were observed in this between-person experiment as had been observed previously in the within-person experiments. Clearly, joint-space (biomechanical) and muscle-space (neural) coordinates were not the media of interoscillator coupling in this experiment. Rather, the coupling must have been due to visual *information* that was specific to the observed oscillatory states of the pendulums themselves. The same point has received further support in subsequent studies in which similar behaviors are displayed by subjects who oscillate an index finger either on or off the beat provided auditorily by a metronome (Kelso, Delcolle, and Schöner, 1990), or who oscillate a forearm inphase or antiphase with the visible motion of a cursor on a cathode-ray tube (CRT) screen (van Riel, Beek, and van Wieringen, 1991). All these studies underscore the conclusion that the coupling medium is an abstract one, and that coupling functions are defined by perceptual information that is specific to the tasks being performed.

Coordinative Dynamics Just as the coupling medium is not defined in simple anatomical or biomechanical terms, several lines of evidence support the hypothesis that the limit-cycle dynamics themselves are also not specified in this manner. That is, the degrees of freedom or state variables along which the oscillatory dynamics are specified, and that experience the effects of interoscillator coupling, are not defined in simple anatomical or biomechanical coordinates. Even tasks that, at first glance, might appear to be specified at the level of so-called articulatory joint rotational degrees of freedom have been found to be more appropriately characterized in terms of the orientations of body segments in body-spatial or environment-spatial coordinate systems. For example, Baldissera, Cavallari, and Civaschi (1982) studied the performance of simultaneous 1:1 oscillations about the ipsilateral wrist and ankle joints in the parasagittal plane. Foot motion consisted of alternating downward (plantar) and upward (dorsal) motion. Hand motion consisted of alternating flexion and extension. The relationship between anatomical and spatial hand motions was manipulated across conditions by instructing subjects to keep the forearm either palm down (pronated) or palm up (supinated). Thus, anatomical flexion or extension at the wrist caused the hand to rotate spatially downward or upward during the pronation condition, but spatially upward or downward during supination. It was found that the easiest and most stably performed combinations of hand and foot movements were those in which the hand and foot motions were in the same spatial direction, regardless of the relative phasing between upper and lower limb muscle groups. Thus, the easiest and most natural patterns were those in which hand and foot motions were spatially inphase. It was more difficult to perform the spatially antiphase combinations, and occasional spontaneous transitions

were observed from the spatially antiphase patterns to the spatially inphase patterns. Related findings on combinations of upper and lower limb rhythmic tasks were more recently reported by Baldissera, Cavallari, Marini, et al. (1991) and by Kelso and Jeka (1992).[1]

Thus, the dynamical systems for coordination and control of sensorimotor tasks, and the medium through which these systems are coupled, cannot be described in simple biomechanical or neuroanatomical terms. Rather, they are defined in abstract, spatial, and informational terms. This point becomes even clearer when one examines the performance of tasks that are more realistic and complex than the relatively artificial and simple tasks that have been reviewed above.

Speech Production

Consider the production of speech and what is entailed during the speech gesture of raising the tongue tip toward the roof of the mouth to create and release a constriction for the phoneme /z/, using the tongue tip, tongue body, and jaw in a synergistic manner to attain the phonetic goal. Such systems show a remarkable flexibility in reaching such task goals, and can compensate adaptively for disturbances or perturbations encountered by one part of the system by spontaneously readjusting the activity of other parts of the system in order to still achieve these goals. An elegant demonstration of this ability was provided in an experiment by Kelso, Tuller, Vatikiotis-Bateson, et al. (1984; see also Abbs and Gracco, 1983; Folkins and Abbs, 1975; Shaiman, 1989). In this experiment, subjects were asked to produce the syllables /bæb/ or /bæz/ in the carrier phrase "It's a ____ again," while recording (among other observables) the kinematics of upper lip, lower lip, and jaw motion, as well as the electromyographic activity of the tongue-raising genioglossus muscle. During the experiment, the subjects' jaws were unexpectably and unpredictably perturbed downward as they were moving into the final /b/ closure for /bæb/ or the final /z/ constriction for /bæz/. It was found that when the target was /b/, for which lip but not tongue activity is crucial, there was remote compensation in the upper lip relative to unperturbed control trials, but normal tongue activity (figure 6.1A); when the target was /z/, for which tongue but not lip activity is crucial, remote compensation occurred in the tongue but not the upper lip (figure 6.1B). Furthermore, the compensation was relatively immediate in that it took approximately 20 to 30 ms from the onset of the downward jaw perturbation to the onset of the remote compensatory activity. The speed of this response implies that there is some sort of automatic "reflexive" organization established among the articulators with a relatively fast loop time. However, the gestural specificity implies that the mapping from perturbing inputs to compensatory outputs is not hard-wired. Rather, these data imply the existence of a task- or gesture-specific, *selective* pattern of coupling among the component articulators that is specific to the utterance or phoneme produced.

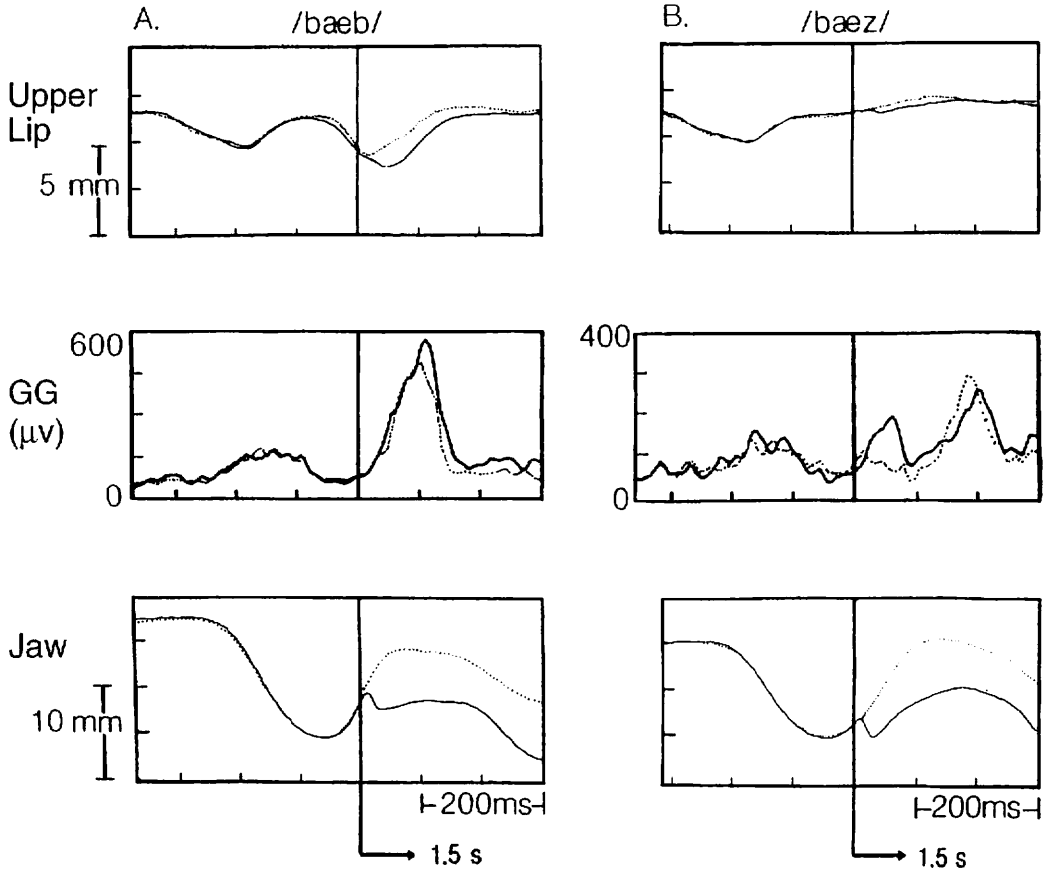

Figure 6.1 Experimental trajectory data for the unperturbed (dotted lines) and perturbed (solid lines) utterances /bæb/ (*A*) and /bæz/ (*B*). (*Top row*) Upper lip position. (*Middle row*) Genioglossus muscle activity. (*Bottom row*) Jaw position. Panels in each column are aligned with reference to the perturbation onset (solid vertical lines). Perturbation duration was 1.5 seconds. (Adapted from Kelso, J. A. S., Tuller, B., Vatikiotis-Bateson, E., et al., 1984).

What kind of dynamical system can display this sort of flexibility? Clearly, it cannot be a system in which task goals are defined independently at the level of the individual articulators. For example, if one were to model a bilabial closing gesture by giving each articulatory component (upper lip, lower lip, and jaw) point-attractor dynamics and its own target position, then the system would attain a canonical closure in unperturbed simulations. However, the system would fail in simulations in which perturbing forces were added to one of the articulators during the closing gesture. For example, if a simulated braking force were added to the jaw that prevented it from reaching its target, then the overall closure goal would not be met even though the remaining articulators were able to attain their own individual targets.

Appropriately flexible system behavior can be obtained, however, if the task-specific dynamics are defined in coordinates more abstract than those defined by the articulatory degrees of freedom. Recall that, in earlier discussions of coupled limit-cycle dynamics, the term *modal state* was used to characterize the cooperative states that emerged from the dynamics of the coupled system components. Modal patterns defined the systems' preferred

or natural set of behaviors. The problem at hand, therefore, is to understand how to create modal behaviors that are tailored to the demands of tasks encountered in the real world. This can be accomplished if one can design task-specific coupling functions among a set of articulatory components that serve to create an appropriate set of task-specific system modes. The remainder of this chapter is devoted to describing one approach to the design of task-specific dynamical systems, called *task dynamics*, that has been used with some success to model the dynamics of speech production. This modeling work has been performed in cooperation with several colleagues at Haskins Laboratories (New Haven, Conn.) as part of an ongoing project focused on the development of a gesturally based, computational model of linguistic structures (Browman and Goldstein, 1986, 1991, and chapter 7; Fowler and Saltzman, 1993; Kelso, Saltzman, and Tuller, 1986a,b; Kelso, Vatikiotis-Bateson, Saltzman, et al., 1985; Saltzman, 1986, 1991; Saltzman and Kelso, 1987; Saltzman and Munhall, 1989). For recent reviews, related work, and critiques, see also de Jong (1991), Edwards, Beckman, and Fletcher (1991), Hawkins (1992), Jordan and Rosenbaum (1989), Mattingly (1990), Perkell (1991), and Vatikiotis-Bateson (1988).

6.3 TASK DYNAMICS

The discussion of task dynamics for speech production is divided into two parts. The first focuses on the dynamics of interarticulatory coordination within single speech gestures, e.g., the coordination of lips and jaw to produce a bilabial closure. The second part focuses on the dynamics of intergestural coordination, with special attention being paid to periods of *coproduction* when the blended influences of several temporally overlapping gestures are evident in the ongoing articulatory and acoustic patterns of speech (Bell-Berti and Harris, 1981; Fowler, 1980; Fowler and Saltzman, 1993; Harris, 1984; Keating, 1985; Kent and Minifie, 1977; Öhman, 1966, 1967; Perkell, 1969; Sussman, MacNeilage, and Hanson, 1973). For example, in a vowel-consonant-vowel (VCV) sequence, much evidence supports the hypothesis that the period of control for the medial consonant is superimposed onto underlying periods of control for the flanking vowels. Since vowel production involves (mainly) the tongue body and jaw, and most consonants involve the jaw as well, then during periods of coproduction the influences of the overlapping gestures must be blended at the level of the shared articulators.

Interarticulatory Coordination: Single Speech Gestures

In the task-dynamical model, coordinative dynamics are posited at an abstract level of system description, and give rise to appropriately gesture-specific and contextually variable patterns at the level of articulatory motions. Since one of the major tasks for speech is to create and release constrictions in different local regions of the vocal tract, the abstract dynamics are defined in coordi-

Tract variables		Model articulators
LP	lip protrusion	upper & lower lips
LA	lip aperture	upper & lower lips, jaw
TDCL	tongue dorsum constrict location	tongue body, jaw
TDCD	tongue dorsum constrict degree	tongue body, jaw
LTH	lower tooth height	jaw
TTCL	tongue tip constrict location	tongue tip,body, jaw
TTCD	tongue tip constrict degree	tongue tip,body, jaw
VEL	velic aperture	velum
GLO	glottal aperture	glottis

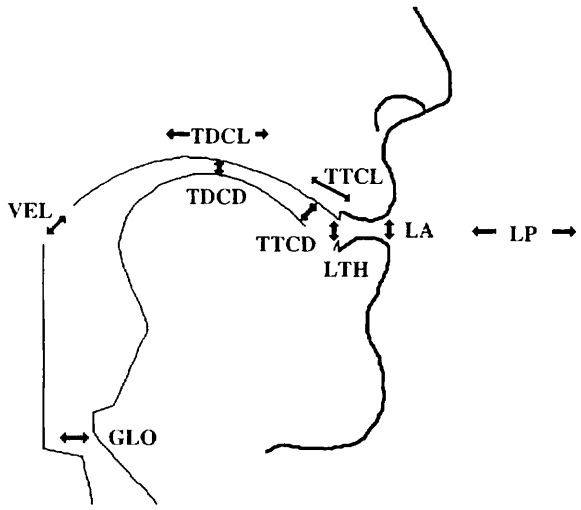

Figure 6.2 (*Top*) Table showing the relationship between tract variables and model articulators. (*Bottom*) Schematic midsagittal vocal tract outline, with tract-variable degrees of freedom indicated by arrows. (From Saltzman, E., 1991.)

nates that represent the configurations of different constriction types, e.g., the bilabial constrictions used in producing /b/, /p/, or /m/, the alveolar constrictions used in producing /d/, /t/, or /n/, etc. Typically, each constriction type is associated with a pair of so-called *tract-variable* coordinates, one that refers to the location of the constriction along the longitudinal axis of the vocal tract, and one that refers to the degree of constriction measured perpendicularly to the longitudinal axis in the midsagittal plane. For example, bilabial constrictions are defined according to the tract variables of lip aperture and lip protrusion (see figure 6.2). Lip aperture defines the degree of bilabial constriction, and is defined by the vertical distance between the upper and lower lips; lip protrusion defines the location of bilabial constriction, and is defined by the horizontal distance between the (yoked) upper and lower lips and the upper and lower front teeth, respectively. Constrictions are restricted to two dimensions for practical purposes, owing to the fact that the simulations use the articulatory geometry represented in the Haskins Laboratories software articulatory synthesizer (Rubin, Baer, and Mermelstein, 1981). This synthe-

sizer is defined according to a midsagittal representation of the vocal tract, and converts a given articulatory configuration in this plane, first to a sagittal vocal tract outline, then to a three-dimensional tube shape, and finally, with the addition of appropriate voice source information, to an acoustic waveform. As a working hypothesis, the tract-variable gestures in the model have been assigned the point-attractor dynamics of damped, second-order systems, analogous to those of damped mass-spring systems. Each gesture is assigned its own set of dynamic parameters: target or rest position, natural frequency, and damping factor. Gestures are active over discrete time intervals, e.g., over discrete periods of bilabial closing or opening, laryngeal abduction or adduction, tongue-tip raising or lowering, etc.

Just as each constriction type is associated with a set of tract variables, each tract variable is associated with a set of *model articulator* coordinates that constitutes an articulatory subset for the tract variable. The model articulators are defined according to the articulatory degrees of freedom of the Haskins software synthesizer. Figure 6.2 shows the relation between tract-variable and model articulator coordinates (see also figure 7.2 in Browman and Goldstein, chapter 7). The model articulators are controlled by transforming the tract-variable dynamical system into model articulator coordinates. This coordinate transformation creates a set of gesture-specific and articulatory posture-specific coupling functions among the articulators. These functions create a dynamical system at the articulatory level whose modal, cooperative behaviors allow them to flexibly and autonomously attain speech-relevant goals. In other words, the tract-variable coordinates define a set of gestural modes for the model articulators (see also Coker, 1976, for a related treatment of vocal tract modes).

Significantly, articulatory movement trajectories unfold as implicit consequences of the tract-variable dynamics without reference to explicit trajectory plans or templates. Additionally, the model displays gesture-specific patterns of remote compensation to simulated mechanical perturbations delivered to the model articulators (figure 6.3) that mirror the compensatory effects reported in the experimental literature (see figure 6.1). In particular, simulations were performed of perturbed and unperturbed bilabial closing gestures (Saltzman, 1986; Kelso, et al., 1986a,b). When the simulated jaw was "frozen" in place during the closing gesture, the system achieved the same final degree of bilabial closure in both the perturbed and unperturbed cases, although with different final articulatory configurations. Furthermore, the lips compensated spontaneously and immediately to the jaw perturbation, in the sense that neither replanning or reparameterization was required in order to compensate. Rather, compensation was brought about through the automatic and rapid redistribution of activity over the entire articulatory subset in a gesture-specific manner. The interarticulatory processes of control and coordination were exactly the same during both perturbed and unperturbed simulated gestures (see Kelso, et al., 1986a,b; and Saltzman, 1986, for the mathematical details underlying these simulations).

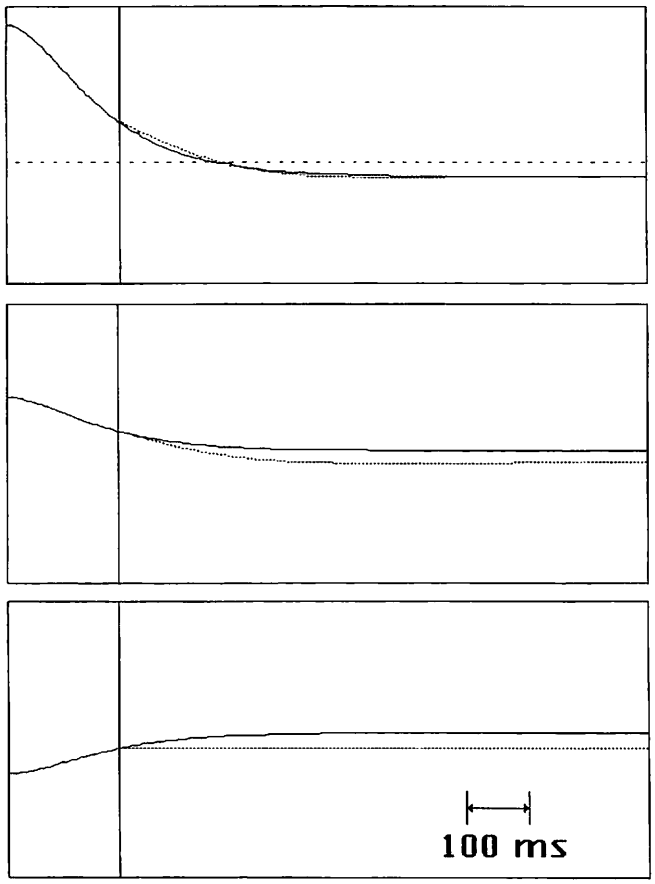

Figure 6.3 Simulated tract-variable and articulatory trajectories for unperturbed (solid lines) and perturbed (dotted lines) bilabial closing gestures. (*Top*) Lip aperture. (*Middle*) Upper lip. (*Bottom*) Jaw. Panels are aligned with reference to the perturbation onset (solid vertical lines). Dashed horizontal line in top panel denotes zero lip aperture, with negative aperture signifying lip compression. (Adapted from Kelso, J. A. S., Saltzman, E. L., and Tuller, B., 1986.)

Intergestural Coordination, Activation, Blending

How might gestures be combined to simulate speech sequences? In order to model the spatiotemporal orchestration of gestures evident in even the simplest utterances, a third coordinate system composed of gestural *activation* coordinates was defined. Each gesture in the model's repertoire is assigned its own activation coordinate, in addition to its set of tract variables and model articulators. A given gesture's ongoing activation value defines the strength with which the gesture "attempts" to shape vocal tract movements at any given point in time according to its own phonetic goals (e.g., its tract-variable target and natural frequency parameters). Thus, in its current formulation the task-dynamical model of speech production is composed of two functionally distinct but interacting levels (see figure 6.4). The *intergestural coordination* level is defined according to the set of gestural activation coordinates, and the *interarticulatory coordination* level is defined according to both model articulatory and tract-variable coordinates. The architectural relationships among these coordinates are shown in figure 6.5.

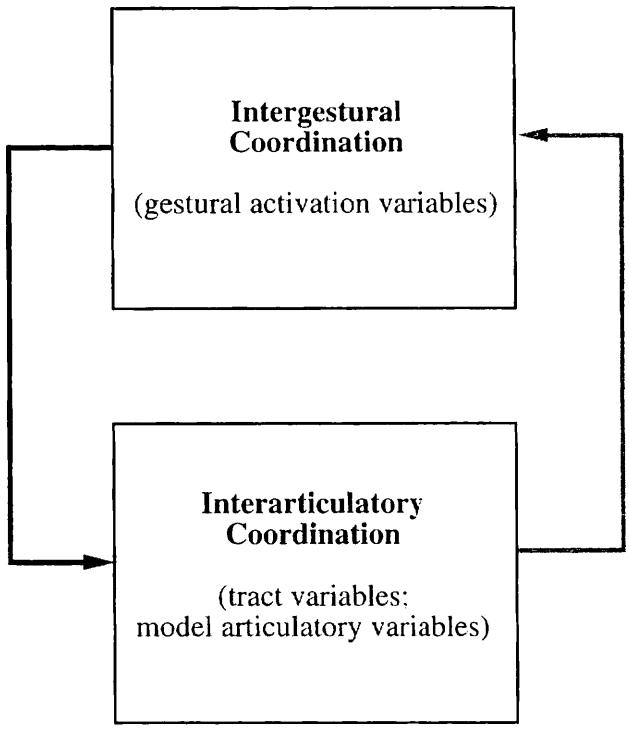

Figure 6.4 Schematic illustration of the two-level dynamical model for speech production, with associated coordinate systems indicated. The darker arrow from the intergestural to the interarticulator level denotes the feedforward flow of gestural activation. The lighter arrow indicates feedback of ongoing tract-variable and model articulatory state information to the intergestural level. (From Saltzman, E. L., and Munhall, K. G., 1989.)

In current simulations, the gestural activation trajectories are defined for simplicity's sake as step functions of time, normalized from zero to one. Thus, outside a gesture's temporal interval of activation (i.e., when activation is zero), the gesture is inactive or "off" and has no influence on vocal tract activity. During its activation interval, when its activation value is one, the gesture is "on" and has maximal effect on the vocal tract. Viewed from this perspective, the problem of coordination among the gestures participating in a given utterance, e.g., for tongue-dorsum and bilabial gestures in a vowel-bilabial-vowel sequence, becomes that of specifying patterns of relative timing and cohesion among activation intervals for those gestures (see Saltzman and Munhall, 1989, for further details of the manner in which gestural activations influence vocal tract movements). Currently, intergestural relative timing patterns are specified by *gestural scores* that are generated explicitly either "by hand," or according to a linguistic gestural model that embodies the rules of Browman and Goldstein's *articulatory phonology* (Browman and Goldstein, 1986, 1991, and chapter 7). The manner in which gestural scores represent the relative timing patterns for an utterance's set of tract-variable gestures is shown in figure 6.6 for the word "pub."

Using these methods, the task-dynamical model has been shown to reproduce many of the coproduction and intergestural blending effects found in the speech production literature. In the model, coproduction effects are

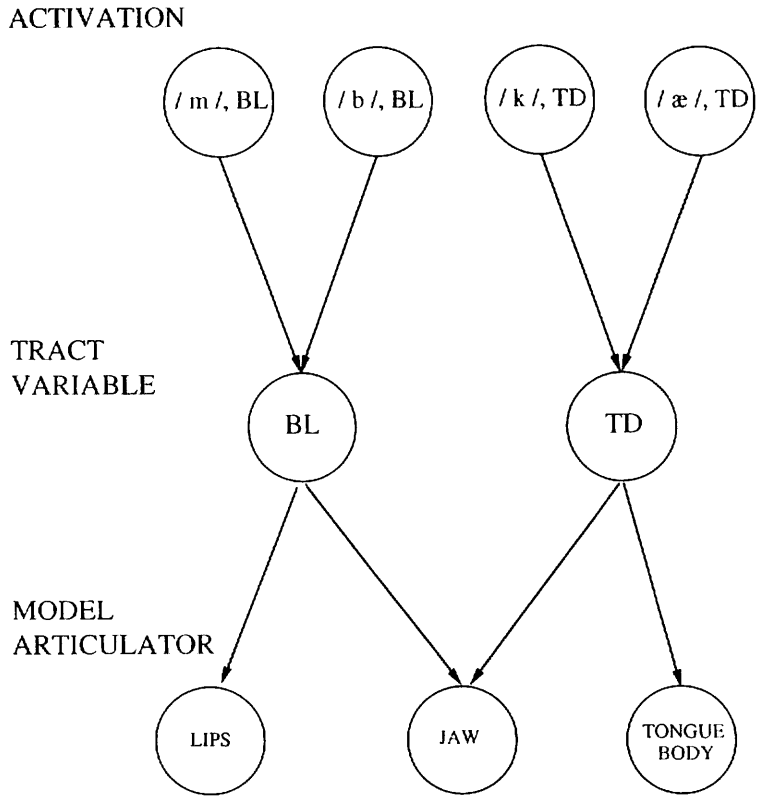

Figure 6.5 Example of the "anatomical" relationships defined among model articulatory, tract-variable, and activation coordinate systems. BL and TD denote tract variables associated with bilabial and tongue-dorsum constrictions, respectively. Gestures at the activation level are labeled in terms of both linguistic identity (e.g., /k/) and tract-variable affiliation (e.g., TD). (From Saltzman, E., 1991.)

generated as the articulatory and acoustic consequences of temporal overlap in gestural activations; blending occurs when there is spatial overlap of the gestures involved, i.e., when the gestures share model articulators in common. Blending would occur, for example, during coproduction of vowel (tongue and jaw) and bilabial (lips and jaw) gestures at the shared jaw articulator. The magnitude of coproduction effects is a function of the degree of spatial overlap of the gestures involved, i.e., the degree to which articulators are shared across gestures. Minimal interference occurs as long as the spatial overlap is incomplete. This is the case when gestures are defined along distinct sets of tract variables, and the gestures share none, or some, but not all articulators in common (see figure 6.2). In this situation, the coproduced gestures can each attain their individual phonetic goals. Figure 6.7A illustrates the behavior of the model for two VCV sequences in which symmetrical flanking vowels, /i/ and /æ/, vary across sequences, the medial consonant is the alveolar /d/ in both sequences, and the time courses of vowel and consonant activations are identical in both sequences. Vowels are produced using the tract variables of tongue-dorsum constriction location and degree, and the associated jaw and tongue-body model articulators; the alveolar is produced using the tract variables of tongue-tip constriction location and degree, and

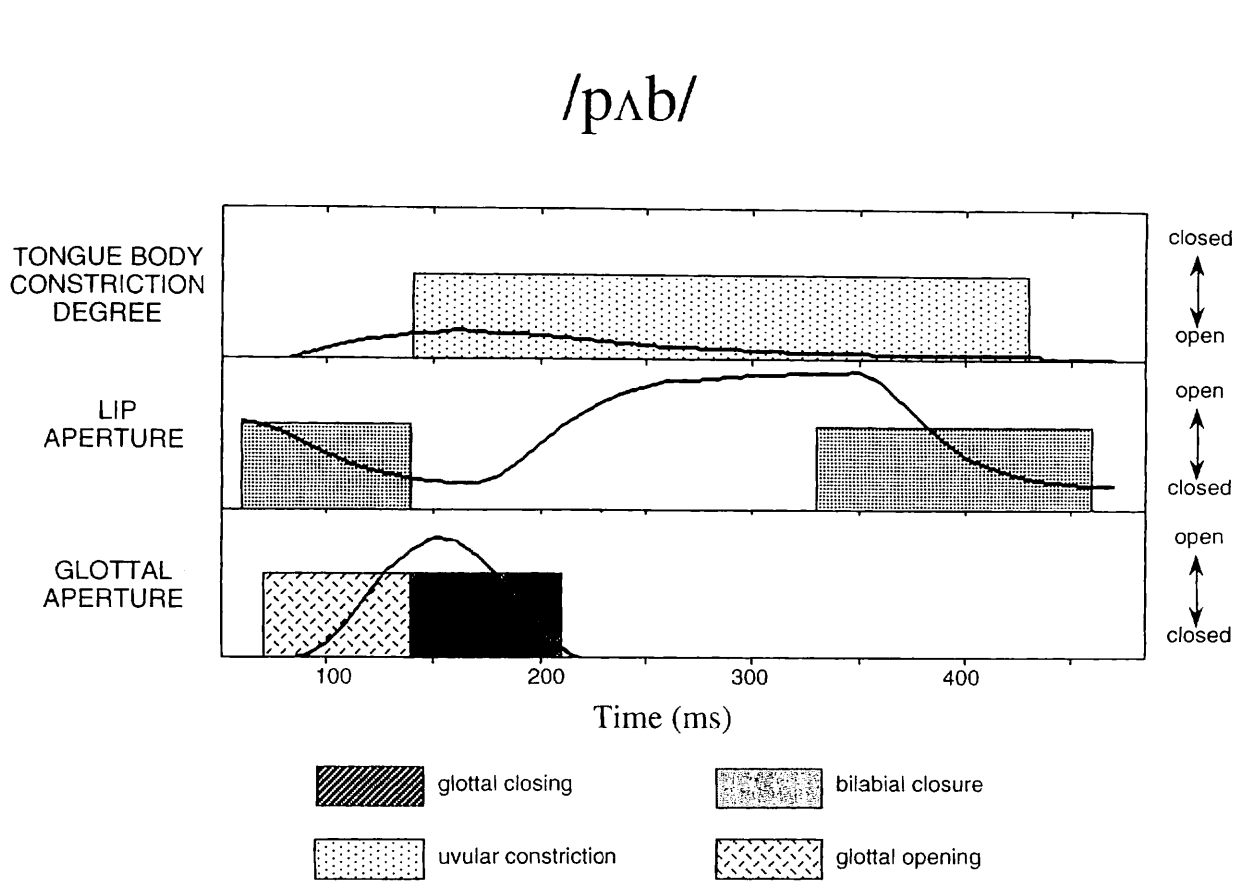

Figure 6.6 Gestural score for the simulated sequence /pʌb/. Filled boxes denote intervals of gestural activation. Box heights are either 0 (no activation) or 1 (full activation). The waveform lines denote tract-variable trajectories produced during the simulation. (From Saltzman, E. L., and Munhall, K. G., 1989a)

the associated jaw, tongue-body, and tongue-tip articulators. Thus, the vowel and consonant gestures share some but not all articulators in common. In this case, the alveolar's tongue-tip constriction goals are met identically in both sequences, although contextual differences in articulatory positions are evident, and are related to corresponding differences in the identities of the flanking vowels (for comparison, see the simulated tract shapes of isolated, steady-state productions of the vowels /i/ and /æ/, shown in figure 6.7C).

However, when coproduced gestures use the same sets of tract variables, all articulators are shared in common, and there is the potential for mutual interference in attaining competing phonetic goals. Figure 6.7B illustrates the behavior of the model for two VCV sequences that are identical to those shown in figure 6.7A, except that the medial consonant is the velar /g/. In this situation, consonant and vowels are produced using the same tongue-dorsum tract variables and the same jaw and tongue-body model articulators. During periods of coproduction the gestures compete for control of tongue-dorsum motion, resulting in contextual variation even in the attainment of the constriction target for /g/. The velar's place of constriction is altered by the identity of the flanking vowels, although the degree of constriction is not. Importantly, the simulations displayed in figure 6.7A and B mirror the patterns observed experimentally during actual VCV production (Öhman, 1967).

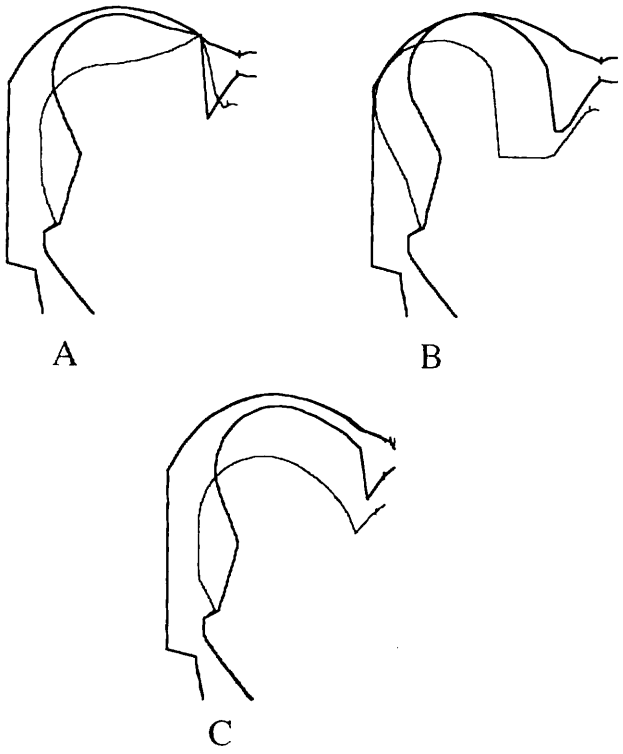

Figure 6.7 Simulated vocal tract shapes. (*A*) First contact of tongue tip and upper tract wall during symmetric vowel-alveolar-vowel sequences. (*B*) First contact of tongue-dorsum and upper tract wall during symmetric vowel-velar-vowel sequences. (*C*) Corresponding steady-state vowel productions. (Dark lines denote /i/ tokens; light lines denote /æ/ tokens.) (From Saltzman, E., 1991.)

Additionally, such processes of within-tract variable blending are consistent with data on experimentally induced vowel production errors (Laver, 1980), in which blended vowel forms were produced that were intermediate between canonical forms.

Future Directions

In its current state, the task-dynamical model offers a useful and promising account of movement patterns observed during unperturbed and mechanically perturbed speech sequences, and during periods of coproduction. Significantly, explicit trajectory planning is not required, and the model functions in exactly the same way during simulations of unperturbed, mechanically perturbed, and coproduced speech gestures. Additionally, the model provides a way to reconcile much of the apparent conflict between observations of surface articulatory and acoustic variability on the one hand, and the hypothesized existence of underlying, invariant linguistic units on the other hand. Invariant units are specified in the form of context-independent sets of gestural parameters (e.g., tract-variable targets), and are associated with corresponding subsets of activation, tract-variable, and articulatory coordinates. Variability emerges in the tract-variable and articulatory movement patterns, as a result of both the utterance-specific temporal interleaving of gestural

activations provided by the gestural scores, and the accompanying dynamics of intergestural blending during coproduction.

One of the main drawbacks of the model from a dynamical perspective is that there are no dynamics intrinsic to the level of intergestural coordination that are comparable to the dynamics intrinsic to the interarticulatory level. The patterning of gestural activation trajectories is specified explicitly either "by hand" or by the rules embodied in the linguistic gestural model of Browman and Goldstein. Once a gestural score is specified, it remains fixed throughout a given simulation, defining a unidirectional, rigidly feedforward flow of control from the intergestural to interarticulatory levels of the model. The gestural score acts, in essence, like the punched paper roll that drives the keys of a player piano. Experimental data suggest, however, that the situation is not this simple. For example, transient mechanical perturbations delivered to the speech articulators during repetitive speech sequences (Saltzman, 1992; Saltzman, Kay, Rubin, et al., 1991), or to the limbs during unimanual rhythmic tasks (Kay, 1986; Kay et al., 1991), can alter the underlying timing structure of the ongoing sequence and induce systematic shifts in the timing of subsequent movement elements. These data imply that activation patterns are not rigidly specified over a given sequence. Rather, such results suggest that activation trajectories evolve fluidly and flexibly over the course of an ongoing sequence governed by an intrinsic intergestural dynamics, and that this intergestural dynamical system functions as a sequence-specific timer or clock that is bidirectionally coupled to the interarticulatory level.

Work is currently in progress (with colleagues John Hogden, Simon Levy, and Philip Rubin) to incorporate the dynamics of connectionist networks (Bailly, Laboissière, and Schwartz, 1991; Grossberg, 1986; Jordan, 1986, 1990, in press; Kawato, 1989) at the intergestural level of the model, in order to shape activation trajectories intrinsically and to allow for adaptive on-line interactions with the interarticulatory level. In particular, we have adopted the recurrent, sequential network architecture of Jordan (1986, 1990, in press). Each output node of the network represents a corresponding gestural activation coordinate. The values of these output nodes range continuously from zero to one, allowing each gesture's influence over the vocal tract to wax and wane in a smoothly graded fashion. Additionally, the ongoing tract-variable state will be fed back into the sequential net, providing an informational basis for the modulation of activation timing patterns by simulated perturbations delivered to the model articulatory or tract-variable coordinates. Thus, rather than being explicitly and rigidly determined prior to the onset of the simulated utterance, the activation patterns will evolve during the utterance as implicit consequences of the dynamics of the entire multilevel (intergestural and interarticulatory) system.

6.4 SUMMARY AND CONCLUSIONS

The dynamical approach described in this chapter provides a powerful set of empirical and theoretical tools for investigating and understanding

the coordination and control of skilled sensorimotor activities, ranging from simple one-joint rhythms to the complex patterns of speech production. The approach offers a unified and rigorous account of a movement's spatio-temporal form, stability of form, lawful warpings of form induced by scaling performance parameters, and the intuitive relation between underlying invariance and surface variability. Evidence was reviewed supporting the hypothesis that dynamical systems governing skilled sensorimotor behaviors are defined in abstract, low-dimensional task spaces that serve to create modal or cooperative patterns of activity in the generally higher-dimensional articulatory periphery. In this regard, the single and dual degree-of-freedom limb rhythms, considered in section 6.1, can be viewed as tasks with relatively simple mappings between their respective task (or modal) coordinates and articulatory coordinates. Such tasks are rare in everyday life, however. Most real-world activites (e.g., speech production, or the coordination of reaching and grasping for object retrieval and manipulation) involve tasks defined over effector systems with multiple articulatory degrees of freedom, and for which the mappings between task and articulatory coordinates are more complex.

The abstract nature of these coordinative dynamics was highlighted by the demonstration (Schmidt, et al., 1990) that entrainment between two limit-cycle rhythms can occur when the component rhythms are performed by different actors that are linked by visual information. These data suggest that the intent to coordinate one's actions with events in the external environment serves to create a linkage through which perceptual information, specific to the dynamics of these events, flows into the component task spaces that control these actions. The result is a coupled, abstract, modal dynamical system that seamlessly spans actor and environment. It is tempting to speculate that this perspective applies quite generally across the spectrum of biological behaviors.

ACKNOWLEDGMENTS

This work was supported by grants from the following sources: NIH Grant DC-00121 (Dynamics of Speech Articulation) and NSF Grant BNS-88-20099 (Phonetic Structure Using Articulatory Dynamics) to Haskins Laboratories. I am grateful to Claudia Carello, Philip Rubin, and Michael Turvey for helpful comments on earlier versions of this chapter.

NOTES

1. Similar results on rhythms produced at the elbow and wrist joints of the same arm were presented by Kelso, Buchanan, and Wallace (1991), when the forearm was either pronated or supinated across experimental conditions. Again, the easiest combinations to perform were those in which the motions of the hand and forearm were spatially inphase, regardless of the relative anatomical phasing between hand and forearm muscle groups. Furthermore, in trials involving experimentally demanded increases or decreases of coupled oscillation frequency, phase transitions were observed from the spatially antiphase to spatially inphase patterns in both pronation and supination conditions. Relatedly, MacKenzie and Patla (1983) induced

phase transitions in bimanual finger rhythms by increasing cycling frequency within trials, and showed that the transitions were affected systematically by the relative orientation of the fingers' spatial planes of motion.

The primacy of abstract spatial coordinates over anatomical or biomechanical coordinates has also been demonstrated for discrete targeting tasks. For example, Soechting (1982) reported evidence from a pointing task involving the elbow joint, suggesting that the controlled variable for this task is not anatomical joint angle per se, but rather the orientation angle of the forearm in body-referenced or environment-referenced coordinates.

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Guide to Further Reading

The Russian motor physiologist, N. A. Bernstein (1967/1984) produced a classic body of empirical and theoretical work that anticipated and inspired many of today's developments in movement science. It is still a great read. Turvey (1990) reviews and extends this perspective in a broad overview of issues faced in studying the dynamics of coordination, carrying the reader on a tour from Bernstein to the current state of the art. Readers interested in more detailed accounts of various recent trends in the field should consult Jordan (1990; a connectionist perspective on dynamics and coordinate systems in skilled actions), Saltzman and Munhall (1989; task dynamics and speech production), and Schöner and Kelso (1988; an overview of the "synergetics" approach to self-organizing systems, in the context of sensorimotor behaviors).

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