

Skill Acquisition and Development: The Roles of State-, Parameter-, and Graph-Dynamics

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ABSTRACT. The development of motor skills can be portrayed as a dynamical process that involves three types of dynamics: state dynamics, parameter dynamics, and graph dynamics. The time scales associated with each type of dynamics are discussed, and an outline is provided of the role played by each type in the developing organism. In particular, the role of parameter dynamics and graph dynamics in producing qualitative, bifurcational changes in behavior is described. It is concluded that all three types of dynamics are required for a complete description of skill acquisition and development.

Key words: dynamics, skill acquisition, skill development

The focus of this article is on the dynamics of motor skill learning and development, with specific emphasis on the types of dynamics that govern changes in behavioral patterns over time. Within this framework, coordinated patterns of biological movement are identified with *morphogenetic* phenomena (e.g., Arbib, 1984; Bernstein, 1967/1984; Kugler, Kelso, & Turvey, 1980, 1982), where the term morphogenesis "refers to the process by which pattern and form are generated in biological systems" (Rosen, 1981, p. 161). This position echoes that of the Russian physiologist N. A. Bernstein (1967/1984) in its insistence that skilled biological movements be "regarded as morphological objects . . . [that] . . . do not exist as homogeneous wholes at every moment but *develop* in time, that in their essence they incorporate time coordinates" (1984 ed., pp. 178-179; italics added). Physically rooted, dynamical accounts of morphogenesis as a self-organizing process have a relatively long history (e.g., Turing, 1952) and currently are being pursued vigorously (e.g., Lengyel & Epstein, 1991; see Murray, 1989, for a recent overview of work in this area).

In the following sections, we provide a brief overview of dynamical concepts applicable to issues of skill acquisition and development. In doing so, we review the possible origins of the qualitative changes that are observed in behavioral forms and use the example of vocal tract growth to highlight some of the problems posed by physical growth for skill acquisition.

Three Types of Dynamics

The developing human organism can be viewed as a complex, evolving dynamical system (e.g., Fentress, 1989; Goldfield, 1989, in press; Kugler et al., 1982; Newell, 1986; Newell, Kugler, Van Emmerik, & McDonald, 1989; Thelen, 1989a, 1989b). Dynamical systems possess three types of dynamics: state dynamics, parameter dynamics, and graph dynamics (Farmer, 1990). The term *state dynamics* refers to the processes that directly shape patterns of motion in a dynamical system's state variables (e.g., position and velocity variables for mechanical systems, node activation variables for connectionist systems). *Parameter dynamics* refers to the processes that directly govern motion patterns in a dynamical system's parameters (e.g., stiffness or equilibrium position for mechanical systems, internode connection weights for connectionist systems). *Graph dynamics* refers to the processes that directly influence the evolution of a system's actual "architecture" (e.g., the number of oscillators in a mechani-

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cal system of coupled oscillators, the number of nodes in connectionist systems).

The three types of dynamics can also be characterized according to their own intrinsic time scales. Typically, motion of the state variables is considered to occur faster than parameter motion, whereas evolution of system architecture is considered to occur even more slowly or not at all. Similarly, the performance, learning, and development of skilled activities can be viewed as events that unfold over successively longer time scales. It is useful heuristically to associate each type of sensorimotor event with a corresponding type of predominating dynamics, according to their respective orderings along the spectrum of time scales. In the following sections, we explore this mapping between types of dynamics and sensorimotor events in greater detail while noting, however, that the mapping is not a strictly rigid one. For example, all three types of dynamics can be identified as contributing to the real-time assembly and performance of skilled activities (see the State Dynamics section that follows).¹

State Dynamics

State dynamics refers to the on-line processes of coordination and control that shape spatiotemporal patterns of movement during skilled motor performances. For example, when a cup is lifted to the lips, the angular positions and velocities at the elbow and shoulder joints vary throughout the motion in a manner that is specific to the task at hand. In a dynamical perspective, such skilled performances are viewed as being governed according to the dynamics of *coordinative structures* (e.g., Fowler, 1977; Kugler et al., 1980, 1982; Saltzman & Kelso, 1987; Saltzman & Munhall, 1989; Turvey, 1977, 1990). A coordinative structure can be defined as a temporarily and flexibly assembled functional organization that is defined over a group of muscles and joints and that converts these components into a task-specific, coherent multiple-degree-of-freedom ensemble. In the context of the present article, the assembly of a coordinative structure would involve the graph-dynamic specification of a system's architecture and the parameter-dynamic specification of the system's parameter set. These specifications serve to establish the boundary conditions for an upcoming performance (or to reset the boundary conditions during an ongoing performance).

Given an appropriate set of initial conditions for the state variables (and an appropriate set of boundary conditions), state dynamics offers a theoretically unified explanation both of the displayed behavioral forms, such as the pattern of angular motions at the elbow and shoulder, and of the stability of these forms to perturbations encountered during the performances. For example, sudden perturbations to the speech articulators have been shown to induce spontaneous, compensatory adjustments by remote articulators to achieve phonetic

goals on a time scale that is on the order of tens of milliseconds (Abbs & Gracco, 1983; Folkins & Abbs, 1975; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; Munhall, Löfqvist, & Kelso, 1986; Shaiman, 1989).² The state dynamics of such compensatory behaviors, as well as of other naturally occurring aspects of interarticulatory coordination, have been simulated using a so-called *task-dynamic* model of speech production (e.g., Saltzman, 1986; Saltzman & Munhall, 1989). More generally, dynamical models have also been formulated for simulating skilled rhythmic and nonrhythmic motions of the limbs or speech articulators, using both conventional (e.g., Haken, Kelso, & Bunz, 1985; Kay, Kelso, Saltzman, & Schöner, 1987; Saltzman & Kelso, 1987; Saltzman & Munhall, 1989; Schöner, Haken, & Kelso, 1986) and connectionist (e.g., Bullock & Grossberg, 1988; Jordan, 1986, 1990; Kawato, 1989; Kawato, Furukawa, & Suzuki, 1987) equations of motion.

Parameter Dynamics

Parameter dynamics refers to the longer time scale processes involved in motor performance as well as in skill acquisition and sensorimotor adaptation. To perform a given skill, the action system must be parameterized appropriately (i.e., as part of the process of assembling a coordinative structure, mentioned in the section on state dynamics). A given "bout" of action is hypothesized to be governed by a task-specific set of parameters that remain relatively constant, compared to the state variables, during the particular performance. For example, it seems reasonable to hypothesize that the act of reaching to a single target is constrained throughout the evolution of the system's state variables (i.e., the angular positions and velocities of the arm joints) by a constant parameter that represents the spatial position of the target. Similarly, in a sustained rhythmic oscillation at a single limb joint (e.g., the wrist), the frequency parameter would remain constant throughout the cycling motion of the state variables.

In learning a new skill, the action system must acquire the appropriate parameterization. What type of dynamical system has the parameter-dynamic properties required for such learning? As Jordan (1990) pointed out, connectionist models are naturally suited to capture parsimoniously within a single framework not only the slower time scale processes of parameter dynamics, but also the fast time scale processes of state dynamics. Motor learning in connectionist terms is an issue of using *supervised* or *unsupervised* learning algorithms to train a network until its internode weights attain values appropriate for guiding accurate performance on a desired task. Relatedly, Schöner (1989) has described a more conventional, nonconnectionist dynamical model for learning the parameter values that are appropriate for producing bimanual oscillatory movements with desired values of relative phasing between the hands.

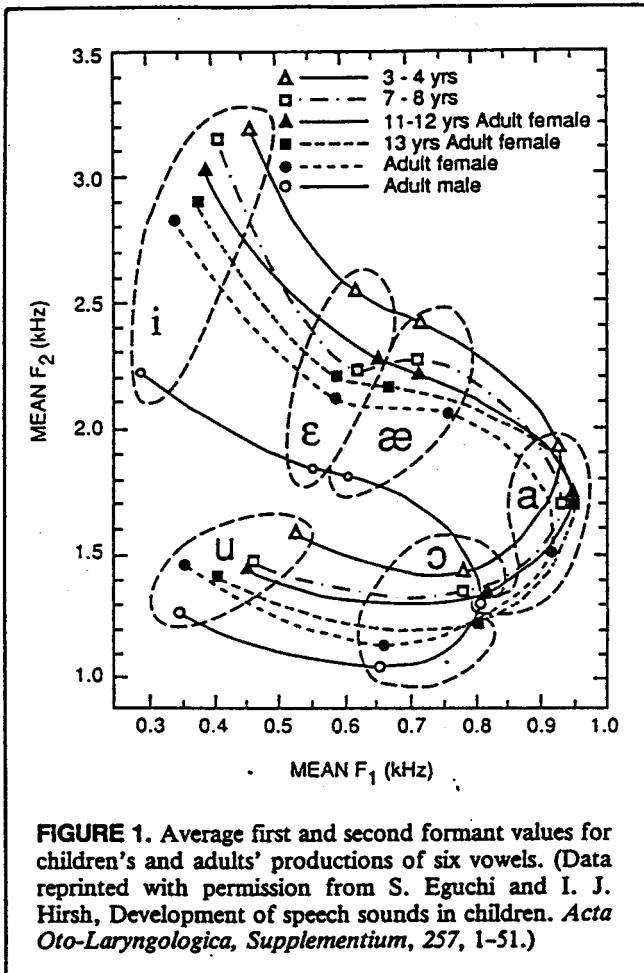


FIGURE 1. Average first and second formant values for children's and adults' productions of six vowels. (Data reprinted with permission from S. Eguchi and I. J. Hirsh, *Development of speech sounds in children. Acta Oto-Laryngologica, Supplementum, 257, 1-51.*)

Once skills are acquired, the corresponding parameterizations cannot remain fixed. For example, it is necessary that these parameter sets change adaptively in the face of developmental and exercise-induced changes in the geometry and biomechanics of the body. In these instances, the parameters that must be learned and continually updated are elements of direct and inverse transformations among coordinate systems relevant to skilled motor activity (e.g., Saltzman, 1979). Such sensorimotor transformations include the mappings between: (a) retinocentric or head-centered visual coordinates and the musculoskeletal coordinates of the arm-hand effector system for visual guidance of reaching and (b) acoustic and articulatory coordinates of the vocal tract for speech production and perception. Note that such parameter learning allows the actor to adapt to changing sensorimotor mappings regardless of the origin of these changes, be they naturally induced by development or exercise or artificially induced by experimental manipulation (e.g., by requiring the actor to view the world through lenses or prisms that systematically distort the visual field). The processes of sensorimotor adaptation and recalibration can be simulated by the parameter dynamics of connectionist systems (e.g., Bailly, Laboissière, & Schwartz, 1991; Grossberg, 1986;

Jordan, 1990; Kawato, 1989; Kawato et al., 1987; Kohonen, 1988; Kuperstein, 1988).

We turn now to a more detailed examination of one particularly important development example of sensorimotor adaptation and recalibration: the learning of speech in the context of vocal tract growth.

Vocal tract growth. The vocal tract of the young child is dramatically different in size and shape from the vocal tract of an adult (see also Goldstein, 1980; Thelen, in press). This fact is behind one of the major puzzles of speech acquisition. How does a child learn to produce the set of phonetic distinctions that are present in its auditory-linguistic environment, when its immature vocal tract is unable to accurately produce these distinctions? Children's productions of vowels, for example, are clearly different from those of adult speakers, due to corresponding differences in vocal tract geometry. These acoustic differences are shown in Figure 1 (Eguchi & Hirsh, 1969), in which the first and second formants are the axes defining the vowel space. Note that the absolute positions of all the individual vowels are shifted between groups, as are the overall outlines traced by each collection of vowels.

The origin of these differences lay in the dimensions of the acoustic tube that produced these sounds, that is, the dimensions of the vocal tract. Figure 2 plots some of the growth patterns for individual parts of the vocal tract, including: the length of the upper and lower lips (Subtelný, 1959), the length of the soft palate (Subtelný, 1957), the vertical distance between the hyoid and a plane defined

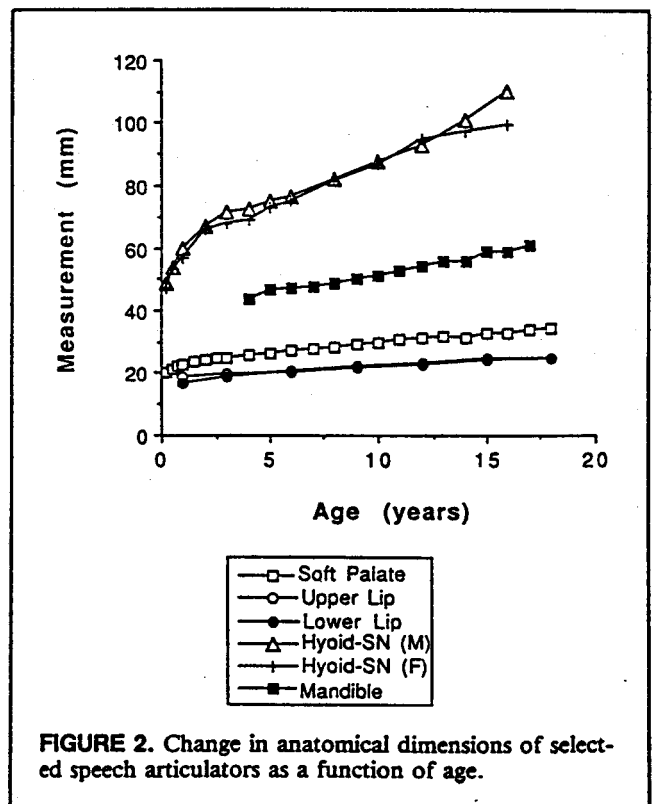


FIGURE 2. Change in anatomical dimensions of selected speech articulators as a function of age.

by the center of the sella tercia and the nasion (a measure of the pharynx) (King, 1952), and the mandibular skeletal effective length (Moyers, Bookstein, & Hunter, 1988). It is clear from these plots that the articulators all increase in size, yet do so in a nonuniform manner. For example, the changes in the lips' dimensions are small and largely occur early in development, whereas the pharynx exhibits much larger changes in size throughout the childhood years. For the pharyngeal measure, the data are broken down by sex. Although King's data were not collected beyond the age of 16, the male-female difference in the length of the pharyngeal cavity is evident. This difference and the greater laryngeal cavities of adult males compared with those of women and children are the major determinants of the acoustic vowel differences seen in Figure 1 (Fant, 1966; Nordström, 1977).

The effects of such anatomical changes on the control of nonspeech oral functions are manifold. Consider the relative descent of the larynx in the vocal tract. In the neonatal vocal tract, the larynx is high, with the lingual surface of the epiglottis against the superior surface of the soft palate (Sasaki, Levine, Laitman, & Crelin, 1977). The human newborn is thus an obligate nose breather. During the first year of life, the pharyngeal cavity lengthens and the larynx descends in the vocal tract so that the epiglottis and soft palate are normally approximated no longer during breathing. The development of oral tidal respiration accompanies the anatomical transformation.

The control of the oral cavity for speech must undergo similar functional changes because of the anatomical changes. For example, the changes in the size and form of the mandible alter many biomechanical characteristics, such as the mass, the center of mass, muscle moment arms, and so forth. Because rotation and translation of the mandible are the result of a careful balance between the forces generated by the various muscles (Flanagan, Ostry, & Feldman, 1990), it is clear that growth must be accompanied by a parameter-dynamic process of adaptive recalibration to maintain this muscular balance.

Graph Dynamics

Graph dynamics is responsible for changes in the architecture of a dynamical system, that is, in the size, composition, and connectivity of the set of equations used to represent the system. The size of a system is indexed by the dimensionality of the system's state space, that is, by the dimensionality of the set of motion equations used to model system behavior.³ Thus, size differences are exemplified by comparing the equation sets that describe the dynamics for a finger moving in isolation with those that describe a finger moving in conjunction with another finger. Composition differences are exemplified by comparing the coupled dynamics of two fingers with those of a finger and toe. Connectivity differences are exemplified by the comparison between the dynamics of a pair of unidirectionally and bidirectionally coupled fingers. Roughly speaking, system architec-

ture is responsible for the structure of the (intrinsic and coupling) functions that define a system's equations of motion. The structure of these functions determines the range of qualitative dynamical forms (e.g., static, periodic) that the system can exhibit, with the precise form displayed at any given time being determined by the current values of the parameters and state variables.

The architecture of a given system may grow or shrink in size as state variables are gained or lost, in accordance with graph-dynamic processes analogous to cell birth or death, respectively. Additionally, a given subsystem that previously occupied an isolated portion of a larger state space may become coupled to the rest of this space by the growth of nonnegligible coupling functions. Conversely, a large network might be partitioned into a set of isolated subnetworks by the loss of such coupling terms. Recent work on connectionist networks has focused on incorporating graph-dynamic processes that allow network architectures to evolve adaptively. These processes include the creation of new nodes (Fahlman & Lebiere, 1990; Hanson, 1990; Kassebaum, Tenorio, & Schaefer, 1990; Tenorio & Lee, 1989) as well as internode connections (Bodenhausen & Waibel, 1991). A particularly elegant connectionist model has been proposed recently in the context of modeling gene expression in the blastoderm of *Drosophila melanogaster*, and promises to offer a well-articulated modeling framework—combining state-, parameter-, and graph-dynamics—for investigating more generally the dynamics of biological development (Mjolsness, Sharp, & Reinitz, 1990).

Typically, state- and parameter-dynamics have been the main foci of dynamical theories of skill performance, acquisition, and development. In terms of motor performance, however, it is clear that the system graph requires appropriate specification (i.e., as part of the process of assembling a coordinative structure, discussed in the state dynamics section). This can be considered, in part, to be a process of selecting and combining those subcomponents that can contribute successfully to accomplishing the task at hand. Such subcomponents include not only the set of end-effectors that actively participate in the task (e.g., the selection of the hand and finger surfaces that define grip configuration according to the size and shape of the grasped object; Newell, Scully, McDonald, & Baillargeon, 1989), but also the perceptual systems that are used to guide task performance (e.g., vision or haptics). Such graph-dynamic processes appear to occur also at the longer time scales of learning and development. For example, skilled use of a new tool or piece of sports equipment can entail expansion of the system graph during learning to incorporate the additional state variables and parameters associated with the implement itself. On a developmental time scale, Goldfield (1989, in press) has provided evidence supporting the claim that the onset of crawling during infancy results from the way in which three developing action systems (i.e., orienting with respect to the support surface, using the legs for pro-

pulsion/kicking, and using the hands to steer/reach; see Reed, 1982, for a more general discussion of action systems) combine and interact with each other in service of the task of locomotion. Thelen (1989b) summarized this point of view, pointing out that

development proceeds . . . as the opportunistic marshaling of the available components that best benefit the task at hand. Development is function-driven to the extent that anatomical structure and neurological mechanisms exist only as components until they are expressed in a context. Once assembled in context, behavior is, in turn, molded and modulated by its functional consequences (p. 947).

Bifurcations: The Roles of Parameter Dynamics and Graph Dynamics

As mentioned in the previous section, state dynamics and parameter dynamics typically have occupied center stage in dynamical theories of motor behavior. These types of dynamics have been considered sufficient to characterize most of the observed interesting behavioral forms as well as qualitative changes in these forms. Qualitative developmental changes in system behaviors are viewed primarily as bifurcation phenomena induced when parameter dynamics drive system parameters across certain critical boundaries in the system's parameter space. These boundary crossings can cause abrupt, qualitative changes of the patterns displayed by the system's state variables, even though the motions of the parameters across these boundaries are themselves smooth. The problem with this formulation is that qualitative, bifurcational changes in behavior patterns also have been demonstrated to result from graph-dynamic processes. Thus, any dynamical model of the emergence of new behavioral forms during development that ignores graph dynamics is likely to be an incomplete one.

Bifurcation phenomena can be divided into (at least) two nonmutually exclusive categories. One involves qualitative differences in the topologies of the behavioral forms exhibited by a given dynamical system and includes transitions among static, periodic, quasi-periodic, and chaotic forms. A specific theoretical example is the *Hopf bifurcation* between static and periodic forms (e.g., Thompson & Stuart, 1986). The second bifurcation category involves quantitative differences among a set of topologically identical forms exhibited by a system, and can include transitions in the number of such forms displayed by the system.

Perhaps the best known example of a bifurcation phenomenon in human movement belongs to this latter category. It is displayed during bimanual rhythmic movements when subjects begin an experimental trial by oscillating their fingers (or hands) at the same frequency in an out-of-phase manner (i.e., approximately synchronous flexion/extension of the right limb and extension/flexion of the left limb), and then increase the frequency of oscillation over the course of the trial (e.g., Kelso, 1984; Scholz & Kelso, 1989). Under such conditions, the

out-of-phase coordination abruptly shifts to an in-phase coordination (i.e., synchronous flexion/extension of the right and left limbs) when the oscillation frequency passes a certain critical value. A comparable shift is not seen, however, when subjects begin with an in-phase coordination; under these conditions, the in-phase oscillation is sustained as frequency increases. Thus, below the critical frequency, the system is bistable, in the sense that both in-phase and out-of-phase rhythmic modes are performable in a stable manner; above this frequency, the system is monostable, in that only the in-phase mode is stably attainable. The same pattern of results is obtained also when the tasks are defined across two people, with each person oscillating one leg and merely watching the other's rhythmic limb movements (Schmidt, Carello, & Turvey, 1990).

Systems of conventional nonlinear, ordinary differential equations have been used to model the bifurcations observed in the examples just described (e.g., for the Hopf bifurcation, see Thompson & Stuart, 1986; for the bimanual transition, see Haken, Kelso, & Bunz, 1985, and Schöner et al., 1986). These models display abrupt changes in measured functions, or sets of functions, of the corresponding state variables when the systems' parameters are scaled smoothly and cross critical boundaries in parameter space.⁴ In these examples, the bifurcation-inducing parameter motions are specified explicitly by the theorist or numerical modeler in the motion equations representing the phenomena under investigation. Specifically, this involves scaling a linear damping coefficient in the motion equation for the Hopf bifurcation, and the natural frequency coefficients of both limbs' motion equations for the bimanual transitions.

Bifurcational changes in system behavior can also result from graph-dynamic alterations in the architecture of an observed dynamical system. For example, in the early stages of termite nest construction (e.g., Kugler & Turvey, 1987; Nicolis & Prigogine, 1977), the deposit of building material initially occurs in a homogeneous, random fashion within the nesting site. When the amount of deposited material, which is directly proportional to the number of participating termites, reaches a certain critical value, the uniform pattern gives rise to a spatially structured pattern of pillars and walls. In related work using a connectionist model, Schrager, Hogg, and Huberman (1987) measured the percentage of nodes in the network that were activated by input to a given single node (i.e., the *spatial event horizon* of the net), and found an abrupt jump in this measure as network size was smoothly increased one node at a time. Finally, bifurcations due to graph dynamics have been demonstrated in conventional dynamical models whose equations of motion are defined by sets of first-order, nonlinear, ordinary differential equations. Haken (1980) investigated the results of coupling two such sets of equations. Before coupling, the state behavior of each set was identically quiescent. Even simple linear

coupling was sufficient, however, to induce a qualitative change in the topological characteristics of the coupled system's aggregate behavior, compared to the behavioral forms displayed previously by the uncoupled subsystems. Given the presence of system noise or fluctuations, the effect of increasing the size of the system was to destabilize the quiescent behavioral modes of the subsystems and to drive the coupled system into a qualitatively different mode, for example, periodic behavior. Thus, in the context of this article's major concerns, it is possible that graph-dynamic changes occurring at different time scales (performance, learning, and development) can lead to the appearance of novel behavioral forms because of system bifurcations. Note, however, that such bifurcations need not always occur; for example, combining two quiescent dynamical subsystems can also result in a new, larger system that is also quiescent.

The lesson to be learned from these considerations of graph-dynamic bifurcations is similar to one associated with many-body physics (e.g., Anderson, 1972) and, perhaps not surprisingly, with classical Gestalt Psychology (e.g., Kohler, 1947) and General System Theory (e.g., von Bertalanffy, 1952; Weiss, 1969): The whole is greater than, or at least is different from, the sum of its parts. Actually, the examples described above are more consistent with the following, slightly revised lesson: The whole can be greater or different from the sum of its parts, but not necessarily. Sometimes, you just get more of the same.

Summary and Conclusions

An organism's repertoire of sensorimotor skills can be viewed as a complex ensemble of self-organizing, morphological objects (see Bernstein, 1967/1984; Kugler et al., 1980, 1982). Like most other aspects of such complex systems, skilled behaviors can be analyzed according to their state-, parameter-, and graph-dynamics. Within this framework, parameter dynamics provides a reasonable account of many of the changes that occur during skill learning and during sensorimotor adaptation and recalibration. Qualitative changes in behavioral forms can be viewed primarily as bifurcation phenomena (see also Note 2), and such phenomena have typically been interpreted as resulting solely from parameter-dynamic processes. One of the main purposes of the present article has been to draw attention to the fact that such phenomena can be shaped by both parameter dynamics and graph dynamics.

We conclude by considering further the role of graph dynamics in an organism that is rapidly developing in parallel at a number of levels—biomechanical, neurological, behavioral—all of which are presumably interrelated in an intimate fashion. Graph-dynamic changes at the musculoskeletal level, for example, may drive parameter-dynamic changes at the level of mappings among sensorimotor coordinate systems. In particular, limb growth can

be viewed as a graph-dynamic growth of tissues that, in turn, necessitates recalibration of the kinematic (e.g., joint angles to body-spatial position of the hand) and kinetic (e.g., joint angular acceleration to joint torques) coordinate transformations that are parameterized functions of limb lengths, moments of inertia, and the like. Similarly, graph-dynamic growth of the vocal tract (see the parameter dynamics section) necessitates parameter-dynamic changes in the kinematic mapping between acoustic and articulatory coordinates and in the kinetic mapping between muscle activation and resultant articulatory motion.

It is also likely that graph-dynamic changes at the neuronal level are tightly coupled to behavioral changes accompanying motor learning. Such a relationship is suggested by neurophysiological and behavioral data from the adult male canary, a songbird that displays seasonal variation in the stereotypy of its song repertoire (e.g., Alvarez-Buylla, Kirn, & Nottebohm, 1990; Nottebohm et al., 1990). The repertoire becomes unstable after breeding season during late summer and fall, during which time many previously learned song "syllables" disappear and new ones appear. Stereotypy of the new repertoire is established during the following winter and spring. These decreases and increases in stereotypy are accompanied by corresponding changes in brain nuclei related to the production and perception of song. In particular, the high vocal center (HVC) displays an apparent loss of neurons during song instability; preceding the establishment of song stereotypy, it displays a marked increase in neuronal birth. These patterns of variation in numbers of neurons can be interpreted as graph-dynamic changes at the neuronal level that are closely linked with corresponding changes in the behavioral repertoire.

The above two examples illustrate several ways that graph-dynamic changes occurring at both neural and nonneural levels might be related to the learning, calibration, and performance of observable sensorimotor behaviors. Such graph-dynamic changes have been documented amply in young and rapidly developing organisms. Thus, particularly during the early stages of sensorimotor development, it would seem prudent to include graph dynamics as an integral component of any theory of behavioral change.

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NOTES

1. Our purpose in adopting the nomenclature used in this paper is to provide a clearly defined framework within which to analyze the performance, learning, and development of skilled sensorimotor behavior. The categories of state-, parameter-, and graph-dynamics apply, however, to the analysis of any dynamical system—human or nonhuman, biological or nonbiological. Additionally, this categorization is orthogonal to those introduced by others in the field of movement science that reflect, roughly speaking, a dichotomy between the dynamics associated with externally imposed tasks and with internally preferred modes of system behavior, for example, inherent versus incidental (Bingham, 1988), resource versus task (Bingham, Schmidt, Turvey, & Rosenblum, 1991), intrinsic versus extrinsic (Schöner & Kelso, 1988), and task versus articulator (Saltzman & Kelso, 1987).

2. It is also possible to observe pattern changes in a system with a fixed parameter set and a fixed architecture. Such changes could result, not from system bifurcations, but from the presence of multiple stabilities in the state dynamics of the system (e.g., Thompson & Stewart, 1986). In this case, however, the multistable system would have to be pushed from one stable pattern to the other by an externally applied deterministic or stochastic force. Such a force would act to reset the system to an effectively new set of initial state values. In the context of skill learning, one can hypothesize that practice may entail the strategic application of such forces, thereby allowing the performer to explore the layout of stability regions in the currently active state space, and to possibly discover previously unknown regions of stability (e.g., Fowler & Turvey, 1978; Newell, Kugler, Van Emmerik, & McDonald, 1989; Thelen, 1989a).

3. A set of n first-order ordinary differential equations can be used to represent both a single, n th-order conventional ordinary differential equation and also a continuous-time, n -node, recurrent connectionist network. In both cases, the set of n first-order equations can be used to construct a system graph, with each equation representing a system node or vertex and the coupling terms in each equation representing the system connections or edges. An important difference exists between the conventional and connectionist representations, however. In the latter case, each of the first-order equations represents a corresponding network node that comprises an elemental information-processing unit of the system and that acts as a dynamical primitive of the network. In the former case, however, each first-order equation is simply the notational outcome of mechanically rewriting the original n th-order equation into first-order form, and the resulting set of n first-order equations does not represent dynamically equivalent units.

4. Parameter-induced bifurcations have also been demonstrated in connectionist dynamical models (e.g., Reggia & Edwards, 1990; Schrager, Hogg, & Huberman, 1987). For example, training-induced changes in the strengths of a given system's internode weights can change the number of stable patterns displayed by that system's state dynamics. These types of bifurcations have been described in terms of the "coalescence and dissociation" of the system's regions of stability (Huberman & Hogg, 1985, p. 272).

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