ECOLOGICAL PSYCHOLOGY, 3(1), 35-54

COMMENTARY

Task-Specific Dynamics and the Study of Perception and Action: A Reaction to von Hofsten (1989)

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In a recent discussion of motor development, von Hofsten (1989) distinguished two approaches which he called the perception-action and dynamic systems approaches, respectively. In this reaction, we suggest that the proposed distinction is inappropriate. We argue that research on perception and action in terms of task-specific dynamics is uniquely suited to the characterization of problems inherent to the coupling of perception and action. The problems discussed include the problem of stability and transitions in behavior; the problem of perceptual information about physical properties of the action system; and the role of the brain in the context of the degrees of freedom problem, the problem of multiple scales of analysis, and the heterogeneity of the components of the human action system including the brain.

Recently, a special issue of *Developmental Psychology* appeared that was devoted almost entirely to the study of motor development. In an invited commentary on a collection of articles on the topic, von Hofsten (1989) distinguished

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two approaches which he called the "perception-action" and "dynamic systems" approaches, respectively. According to von Hofsten, the perception-action approach focuses on questions of function and stresses the tight coupling between motor development and perceptual development, while the dynamic systems approach is more concerned with morphological questions and the emergence of form.

This distinction implies that the dynamic systems approach is not focused on the functional coupling of perception and action. This suggestion is incorrect. If the dynamic systems approach can be distinguished from the rest of perception-action research, it is on the basis of dynamical methods of analysis by virtue of which the approach is uniquely suited to a characterization of problems inherent to the coupling of perception and action, problems that ultimately must be confronted by any approach. Our objective is to provide reasons for discarding the distinction between a perception-action approach and a dynamic systems approach by showing what the dynamic systems approach has to offer and has already offered with respect to problems in research on perception and action. To the extent, then, that the dynamic systems approach does address the issues that von Hofsten viewed as the characteristic focus of the perception-action approach (i.e., questions of function and the coupling of perception and action), the proposed distinction is moot. Counter to von Hofsten, we argue that a construal of perception-action systems in terms of task-specific dynamics provides a formulation of issues central to an understanding of the functional coupling of perception and action, a formulation that yields a generative program of perception-action research.

Von Hofsten's portrayal of the dynamic systems approach suggested that the approach is deficient in the following respects: that it has primarily addressed phase transitions in behavior with an implied neglect of stability, a fundamental property of functionally effective behavior; that it is only concerned with the measurement and analysis of simple physical variables with an implied exclusion of informational variables, fundamental variables in the perceptual guidance of action; and that it does not sufficiently appreciate the role of the brain because its level of analysis is holistic or exclusively molar, and because all elements of a dynamic system are assumed to be of the same kind. Inspired by these criticisms, we choose to structure our rebuttal as follows.

First, we identify what seemed to be the basic source of disagreement, namely the role of brain- and neural-like accounts in our science, and discard it as a valid motive for distinguishing between a perception-action approach and a dynamic systems approach. Second, we formulate the main tenets of task-specific dynamics—our preferred term for the dynamic systems approach—and demonstrate how it effectively assesses (a) the stability of behavior, using perturbation and bifurication techniques, and (b) the coupling of perception and action, using the conceptual and analytical tools of dynamics. Third, and lastly, we discuss the joint issues of scales of analysis and the heterogeneity of system components in order to show the potential and scope of the approach.

Before starting, we should mention that, while we are aware that von Hofsten drew the distinction between perception-action and dynamic systems approaches in a specific context with specific aims in mind, at the same time, we realize that this distinction would not be restricted to the domain of developmental psychology, but would apply to the entire field of perception-action research. Moreover, we suspect that von Hofsten's assessment may be shared by others specifically working in or inspired by ecological psychology. Our intended audience, therefore, comprises the readership of this journal rather than *Developmental Psychology*.

A BASIC DISAGREEMENT

Von Hofsten's distinction between a perception-action approach and a dynamic systems approach seems to have been motivated by his interpretation of the role of the brain and its explanatory value in issues of control and coordination. Right at the start of his characterization of the perception-action approach, von Hofsten summarized its rationale in the following way: "The successful solution of action problems in evolution is always a question of (a) developing or accessing the right tool for action and (b) controlling the tool to achieve the goal of the action," where "Controlling the tool requires both an adequate neural mechanism or network and adequate information to drive the system" (p. 950). "Tools" was meant to refer to anatomical structures used to perform various tasks (e.g., wings used to fly and hands used to grasp objects), having physical properties that, in combination with environmental properties, pose problems for the brain to solve:

> "*Physical constraints, including body parameters, define the implementation problems of actions, whereas the constraints set up by the brain are there to solve those problems.* It is the size of the hand in relation to the object to be grasped that defines the domain of possible grasp patterns, but it is the task of the brain to form the hand into the specific grasp pattern used. (p. 951)

Apparently, for von Hofsten, the brain events have ultimate explanatory value in accounting for phenomena of perception and action. This conviction is at odds with the central tenets of the dynamic systems approach in which solutions to problems of coordination and control are thought to emerge from the collective interaction of the various components of the action system, including the nervous system. The approach views the action system as a self-organizing control system whose organization (movement behavior) results from the assembly and disassembly of many degrees of freedom associated with the muscles, the joints, the circulatory system, as well as the nervous system. Stable low-dimensional organization is hypothesized to emerge via the intrinsically dissipative dynamics associated with interactions of the nonlinear components (Kay, 1988; Kugler, Kelso, & Turvey, 1980, 1982). This state of affairs allows one to investigate the formative principles that govern biological systems at the ecological scale of analysis—the scale at which animals and their environments are defined (cf. Gibson, 1979/1986; Turvey, Carello, & Kim, 1989)—without the need to have explicit knowledge of all the participating components at more microscopic scales of analysis.

These propositions undercut the thesis that neural-like terms, per se, constitute an explanation of perception and action and promote, in contrast, a search for the laws of pattern formation at multiple biological scales. Development and evolution are themselves viewed as dynamical processes that create and mold—with a minimum set of general principles, but at different time scales—the design characteristics of biological behavior, as well as the neural structures from which these characteristics can be effectively assembled. Thus, the developing nervous system is understood as harnessing dynamical laws underlying behavioral patterns rather than being the ultimate cause of such patterns.

Of course, these contrasting opinions about the nervous system are important because they determine the way in which one goes about studying perception and action (and, therefore, are certainly worthy of discussion), but they do not provide an acceptable basis for the distinction between a perception-action approach and a dynamic systems approach. It is entirely inappropriate to reserve the perception-action qualifier for work that rests on the assumption that neural (as opposed to dynamical) accounts have ultimate explanatory value. The defining characteristic of the perception-action approach is that it is concerned with issues of function and the coupling of perception and action. Hence, the only appropriate criterion of whether work qualifies as perception–action research is whether or not issues of function and the coupling of perception and action are being addressed in a meaningful way. Task-specific dynamics certainly satisfies that criterion. Let us see how.

TASK-SPECIFIC DYNAMICS

The key problem in the study of perception and action is the assembly of functionally effective modes of action. This includes the problem of cooperativity. Task-specific dynamics is concerned, broadly speaking, with the identification of the functionally specific ways in which an action system and its component subsystems are constrained in achieving task goals. It is intended to provide a description of goal-directed behavior which reveals how properties of the environment and properties of the animal are related and temporarily organized into a special-purpose machine or task-specific device (Bingham, 1988; Runeson, 1977; Solomon, Turvey, & Burton, 1989).

In any given behavior, the relevant task-specific device is defined over both animal and environmental components. Two important points are associated with this characteristic of task-specific devices. First, task-specific dynamics are not a property of the animal alone and are not the sort of thing that the animal can carry around within itself. Certainly, the inherent dynamics of the animal are so transported, but they alone are not sufficient to establish the dynamics corresponding to the performance of a given task (compare this with von Hofsten's notion of tools).[1] Second, information about the dynamical resources used to establish a given dynamic is required in like manner whether the resources are inherent to the action system or incidental to the task at hand. For example, the inertial properties inherent to the dynamics of the shoulder are constantly in flux as the configuration of the wrist and elbow joints change. The need for information in this circumstance is not different from the need for information about changes in inertial properties induced by grasping an object. In an echo of Heraclitus's observation that "one cannot step into the same river twice," Bernstein (1967) referred to "repetition without repetition" in the context of forms of movement. Action is an intrinsically creative business. At any instant, generated states of the system are as likely to be novel as not. The assembly and control of any emerging performance requires perceptual information about both the inherent and incidental properties of the substantial elements of the events comprising the performance.

Thus, necessarily, task-specific devices are assembled through concurrent perception and control: perception of the emergent dynamic organization and the selection, through control, of dynamical resources for action.[2] Achieving goals in action requires, among other things, the marshaling of mechanical properties. For instance, long distance throwing requires the assembly of a complex organization that involves the progressive development and flow of mechanical energy along the body's link segments (Jöris, van Muyen, van Ingen Schenau, & Kemper, 1985). The assembly of such organization requires percep-

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[1] The performance of a restricted class of tasks like finger wiggling might be well approximated in an analysis that includes only components of the inherent dynamics. However, note that tasks must always be performed from a base of support and that the configuration, compliance, and frictional characteristics of such support surfaces are, by definition, part of the incidental dynamics of the relevant task-specific device (Bingham, 1988; Stoffregen & Riccio, 1988).

[2] The research program corresponding to an approach in terms of task-specific dynamics has been described previously in Bingham (1988) as well as in Beek (1989a). Dynamical approaches are described also in Kay et al. (1987), Kelso and Kay (1986), Kugler (1986), Kugler and Turvey (1987), Saltzman and Kelso (1987), Thelen (in press), Thelen, Kelso, and Fogel (1987), Schöner (1990), and Schöner and Kelso (1988c, 1988d). There is a family resemblance among these, with nontrivial differences. The diversity reflects the developing nature of the ideas and, admittedly, may provide a source of confusion for those not familiar with the problems and perspectives shared by these various proponents.

tual information about the effect of the introduction of particular mechanical properties on the resulting dynamical organization (Bingham, Schmidt, & Rosenblum, 1989). Only by acting and generating movements do we begin to uncover the mechanical properties that we must use (Bingham & Kay, 1989; Jensen, Ulrich, Thelen, Schneider, & Zernicke, 1990; Schneider, Zernicke, Ulrich, Jensen, & Thelen, in press; Thelen, 1989a, 1989b, in press).

The very problem of how movements serve in organizing the motor system, cited by von Hofsten as central to the perception–action approach, is obscured in his account rather than explicated. Only in the dynamical formulation of the problem can we see how action might subserve perception. By hypothesis, information about the emerging dynamical organization of the motor apparatus is available in qualitative kinematic properties generated by a given dynamic (Beek, 1989a, 1989b; Bingham, 1987a, 1987b, 1988; Kugler, 1986; Kugler & Turvey, 1987; Runeson, 1977; Runeson & Frykholm, 1983). The challenge empirically is to develop a taxonomy by measuring the qualitative properties that emerge in the context of specific tasks and to discover, by perturbation and interference, the significance of specific properties for the assembly and control of particular actions. The theoretical challenge is, on the one hand, to establish the nature of the mappings between particular dynamical organizations and corresponding qualitative kinematic properties (Kugler & Turvey, 1987; Shaw, Kugler, & Kinsella-Shaw, 1990), and, on the other hand, mappings from the kinematics of an event under study to the structure of arrays available to the various perceptual modes (Bingham, 1987a, 1988). These problems, we believe, can only be formulated, never mind addressed and resolved, by an approach to perception and action in terms of dynamics.

TRANSITIONS AND STABLE MODES: THE QUESTION OF FUNCTION

In his commentary, von Hofsten emphasized the need to focus on the functional nature of behavior. We would ask what makes a behavior functional? Among the required characteristics are, first, that a person be able to acquire the ability to perform the action, that is, that a person can find a way (via transitions and instability) to assemble the component parts of his or her body and the component parts of the environment into a behavioral mode and, second, that the assembled behavioral mode be stable enough to achieve the intended task goal. The problem of assembly of component parts into a functional unit is intimately related to the issue of the intrinsic stability (or instability) of the resulting behavior. The stability of a behavior is determined, in large part, by the nature of the dynamical constraints underlying the behavior.

In the past 10 years or so, these constraints have been investigated in two types of experiments. The first type of experiment involves the development of increasing instability in behavior due to the breaking of the dynamical constraints on behavior and the subsequent creation of novel constraints leading to a new behavioral mode (cf. Rosen, 1978). These are called *bifurcation experiments*. Bifurcation experiments have demonstrated how shifts between behavioral modes may be induced by small changes in a control parameter, namely frequency of oscillation (e.g., Kelso, 1984; Haken, Kelso, & Bunz, 1985; Schmidt, Carello, & Turvey, 1990). One of the behaviors studied involved the coordinated oscillation of one finger in each hand about a single joint (Kelso, 1984). At lower frequencies of oscillation, two stable modes were found to exist: oscillation in phase or in antiphase. At higher frequencies, only a single stable mode was found, namely, oscillation in phase. Thus, in the transition from high to low frequencies of oscillation, the underlying dynamics bifurcates yielding two stable modes. Alternatively, as the participant oscillating the fingers in the antiphase mode at low frequency gradually increases the frequency, the constraints determining the antiphase mode are broken sending the performance into the in-phase mode.

Of equal importance to the issue of stability, is the second type of experiment which involves perturbations to systems that preserve the essential constraints (cf. Rosen, 1978). These are called *perturbation experiments*. These experiments have demonstrated how the functional integrity of the system can be preserved in the face of a variety of external perturbations, including changes in position and velocity, frequency, stiffness, viscosity of the medium moved through, number of balls juggled, length of pendulums swung, or resistance of contact surface written on (e.g. Beek, 1989a, 1989b; Bingham, Schmidt, Turvey, & Rosenblum, in press; Kay, 1986; Kay, Kelso, Saltzman, Schöner, 1987; Kelso, Holt, Rubin, & Kugler, 1981; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; Kugler & Turvey, 1987; Newell & van Emmerik, 1989; Rosenblum & Turvey, 1988; Thelen, Fisher, & Ridley-Johnson, 1984; Thelen, Skala, & Kelso, 1987).

For example, Kelso et al. (1984) demonstrated that speakers, whose articulators are perturbed, exhibit compensatory movement patterns in such a way that the acoustic output pattern remains relatively undistorted. The speed of the observed task-specific responses (i.e., 20 ms to 30 ms from the onset of the perturbation to the onset of the response) is difficult to explain in terms of a hard-wired input–output structure (i.e., a neural control loop). The alternative hypothesis, supported by the relative immediacy of the response, is that the compensation is achieved by muscle collectives that behave in a way qualitatively similar to nonlinear oscillators.

Using a similar paradigm, Newell and van Emmerik (1989) found that when the act of drawing a circle-eight is perturbed by suddenly increasing the resistance of the pen along the surface, the trajectory continues to pass through the locus of maximum curvature at the top of the eight despite distortions along remaining portions of the path. This result is consistent with other work purporting to show that local regions of high path curvature serve as organizing landmarks (or "anchor points," cf. Beek, 1989a) for limb movements involving complex paths of motion (Viviani & Cenzato, 1985).

Both of these examples illustrate how perturbation experiments are instrumental in revealing the organizational properties that are essential to various behavioral modes assembled to achieve required task goals. Perhaps somewhat less obvious in these examples is the fact that the organizational properties revealed by perturbation also introduce questions of perception and information.[3] This is more easily illustrated via perturbation experiments investigating absolute coordination.

The most pervasive pattern of interlimb coordination is that of absolute coordination in which two or more limbs move rhythmically together at the same frequency, as in walking, swimming, and flying. To investigate the organizational principles of absolute coordination, Kugler and Turvey (1987) developed an experimental procedure permitting the inertial properties of the swinging segments to be perturbed or varied between trials. Corresponding changes in the characteristic frequencies of the component limb oscillators resulted. The participants in the experiments held a pendulum in each hand. The task was to swing the two pendulums comfortably together, at a common frequency and in a fixed phase relation. The comfortable frequencies into which participants settled varied specifically with the mass and the length of the individual hand-held pendulums. Although individual participants varied somewhat in the absolute values of the frequencies they adopted, a given individual consistently and reliably reproduced the stable frequency corresponding to a given configuration of the inertial properties on trials that were separated by as much as months. How were participants able to perceive the comfort mode corresponding to their preferred frequencies? The result suggests that wrist-pendulum systems are guided primarily by haptic information specifying preferred and nonpreferred modes of operation. Kugler and Turvey (1987) suggested that the haptic information for this activity could be defined as a kinematic (or geometric) abstraction of the underlying mix of muscular and nonmuscular forces specifying the gradient of the resulting energy potential.

It is likely that the variant, as well as invariant, properties of behavior have relevant implications for perceptual processes. A general observation in perturbation experiments has been that biological systems secure stability of task execution by allowing relatively small variations to occur in the trajectories. Task-specific devices are characterized by a tendency to fluctuate about a preferred state. These fluctuations reflect the temporary, softly assembled nature

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[3] Intuitively, the speech example implies the existence of an abstract control space for the speech articulators in which the task goal is informationally, and thus perceptually, specified, whereas the writing example implies the existence of points of singularity in the work space that have to be informationally, and thus perceptually, supported in a similar fashion.

of task-specific devices. They can be beneficial in at least three ways: first, by allowing behavioral modes other than the current one to be discovered, that is, exploratory behavior (Newell, Kugler, van Emmerik, & MacDonald, 1989; Turvey et al., 1989); second, by allowing information specifying the location of the preferred state in control space to be continuously monitored (Beek, 1989a, 1989b); third, by allowing changes due to external perturbations to be accommodated (Beek, 1989a, 1989b). Presently, each of these theoretical possibilities remain as intriguing topics for future research. In sum, understanding behavioral change (cf. motor development) requires coincident understanding of how common modes of behavior can be stable, because stability and loss of stability are mutually defining concepts. Furthermore, only by understanding the variability in behavior as deriving from processes responsible in common for invariance will we uncover the manner in which stable modes of behavior are organized, how new modes of behavior emerge, and the means by which we switch intentionally between modes of behavior. Thus, an understanding of stability, fluctuations, and loss of stability is crucial to an understanding of the functional design of behavior and its parallel and serial ordering (cf. Kelso, 1989). At the same time, such knowledge is indispensable in understanding the coupling of perception and action. The stability of behavior and detectability of information about the behavior are ultimately on two sides of a single coin.

THE COUPLING OF PERCEPTION AND ACTION

Implicit in von Hofsten's perception-action versus dynamics distinction, is the notion that dynamics overlooks or underplays the role of perceptual information in the emergence of behavioral form. Allegedly, concern in the dynamic systems approach is with morphological questions and the identification of physical principles underlying pattern formation as opposed to principles of perceptual information. However, as is already apparent from the aforementioned arguments, an attempt to reserve study of the coupling between movement and perception for research performed under the rubic perception-action approach, in contrast to a dynamic systems approach, is entirely inappropriate.

Since its first formulation in the early 1980s (Kugler et al., 1980, 1982), the dynamical approach to perception and action has demonstrated a prime concern with the problem of perceptual information and its coupling to action, as reflected in extensive theoretical and empirical work. The need to describe the organizational role of perceptual information in terms of low-dimensional qualitative dynamics has been addressed repeatedly (Beek, 1989a, 1989b; Bingham, 1987a, 1987b, 1988; Kelso & Kay, 1986; Kugler, 1986; Kugler & Turvey, 1987; Riccio & Stoffregen, 1988; Schöner & Kelso, 1988a, 1988c, 1988d; Solomon, 1988; Stoffregen & Riccio, 1988; Turvey et al., 1989; Turvey, 1990) and empirical progress continues to be made in this effort (Bingham, 1987b; Bingham et al., 1989; Kugler & Turvey, 1987; Schmidt et al., 1990; Schöner, 1990; Schöner & Kelso, 1988a, 1988c, 1988d; Solomon & Turvey, 1988). We now highlight the main theoretical and empirical contributions.

As frequently emphasized, the encounters between animals and their environments involve a substantial use of information and often relatively little energy and momentum exchange. Therefore, the challenge is to identify the informative nonkinetic properties that guide and usefully constrain the kinetics of action (Kugler, 1986; Kugler & Turvey, 1987; Shaw & Kinsella-Shaw, 1988; Shaw et al., 1990; Turvey, 1977). Indeed, this challenge was anticipated by Bernstein (1967) in his introduction of the notion of a sensorimotor cycle to overcome the joint problems of non-univocality and context-conditioned variability, and by Gibson (1950, 1966, 1979/1986) in his pursuit of an analysis of optic flow as well as flows relevant to other perceptual modalities.

The problem of movement coordination involves an understanding of how, in the assembly of task-specific devices, perceptual information guides the production of movement and how, conversely, movement serves the generation and pickup of perceptual information. Technically, the problem is a mapping problem between informational flow fields and force fields. Ideally, our understanding of this problem should take the form of integrated models in which kinematic perceptual properties are directly linked to kinetic performatory properties and vice versa, but because of the difficulty of the problem and the lack of appropriate mathematical tools, such models are, to date, few and far between (Beek, 1989a; Bingham & Kay, 1989; Shaw & Kinsella-Shaw, 1988; Shaw et al., 1990).

Most studies on the topic do not attempt to go beyond the correlation (covariation) of perceptual variables (usually tau) and kinematic movement variables, that is, $x(t)$, $dx/dt(t)$, $d^2x/dt^2(t)$ (e.g, Bootsma & van Wieringen, 1990; von Hofsten, 1980; Lee, 1976, 1980; Lee, Young, Reddish, Lough, & Clayton, 1983). Such studies are useful in identifying kinematically the types of coupling between perception and action that require further explanation in terms of the coupling between perceptual and kinetic movement variables. Thus far, this relation has seldom been investigated directly. A noticeable exception to this is provided by Warren, Young, and Lee (1986), who explicitly modeled the coupling between tau and vertical impulse in the control of running over irregular terrain.[4]

In their development of a synergetic theory of the coordination of rhythmic movement, Schöner and Kelso (1988a, 1988c, 1988d; Kelso, 1989; Schöner,

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[4] See also Warren (1988) for an attempt to model the relation between tau and the propelling kinetics of flying insects (including a discussion of the stable and unstable modes of flying), and Kugler (in press; Kugler & Turvey, 1987) for a model of termite nest building with interacting chemical flow fields and kinetic force fields.

1990) took a different approach to the problem. Their strategy illustrated how, even though not all behavioral changes take the form of phase transitions, the study of phase transitions can open a window into the different aspects of the informational guidance of behavior (i.e., perception, intention, and memory and recall).

After having mathematically identified the intrinsic dynamics of the relative phasing of rhythmic finger movements using a bifurcation paradigm (Haken et al., 1985; Schöner, Haken, & Kelso, 1986), Schöner and Kelso (1988c, 1988d) introduced the concept of behavioral information and defined it most generally as a required behavioral pattern (be it specified by perceptual information, memory, or intention). This definition allowed them to study the effect of behavioral information on the identified intrinsic dynamics. They endowed behavioral information itself with dynamics (i.e., they conceptualized it as a perturbation on the intrinsic dynamics of relative phase), so that they could incorporate it in the overall pattern dynamics and study the effect of the newly introduced dynamics accordingly. Two straightforward empirical predictions followed from their first modeling attempts and were confirmed by experimental results (Schöner & Kelso, 1988c): When intrinsic dynamics and behavioral information cooperate, the resulting state is close to the requirement and very stable, while in the case where they compete the resulting state is shifted from the requirement toward the intrinsic dynamics (inphase and antiphase), and is less stable (larger fluctuations; Scholz & Kelso, 1990).

Recently, both Kelso (1989) and Schöner (1990) discussed the value of the concept of behavioral information in deepening our understanding of perception-action couplings, as well as their intentional acquisition and recall. Although the goal of their efforts is not to identify the perceptual quantities that inform the action system, but rather to study its influence on the order parameters and their dynamics, their work surely addresses the dynamic coupling of perception and action. According to Kelso and Schöner, behavioral information is always meaningful and specific to biological functions or task, and, as such, it is reminiscent of Gibson's (1979/1986) notion of information as specification.

As intimated by others (Kugler & Turvey, 1987; Warren, 1989), the adaptation of action modes and the transitions between them are not deterministically driven by the dynamics of the system, but rather guided by information. The behavior of animals is not determined by physical laws, but by laws of perceiving and acting that can often be related to physical laws. An animal that is sensitive to its own dynamics and those of its interactions with the environment can exploit the system's stabilities and instabilities to control its behavior. This requires that there be information, in Gibson's (1979/1986) sense, that is specific to behaviorally relevant aspects of the system's dynamics—haptic patterns defined over skin, joint, and muscle receptors, optical patterns available at a moving point of observation, and so forth. In the high-dimensional space of possible postures and movements, only small regions are stable and functionally useful; an actor sensitive to those regions, their boundaries, and the transitions between them can control action reliably and efficiently.

Finally, we emphasize the point, made in the section on task-specific dynamics, that the concern with morphology in the dynamical systems approach is motivated by two related observations that bring together the work of Gibson and Bernstein. One is that human activity is continually productive, constantly creating new forms. The other is that such creation requires perception which, in turn, demands information in the form of qualitative properties. Thus, a preoccupation with morphology is part and parcel of a preoccupation with perceptual information.

SCALES OF ANALYSIS

Von Hofsten suggested that the role of the brain in organizing and controlling behavior is underestimated in the dynamic systems approach. There has indeed been a dearth of studies, within the dynamics approach, explicitly on the central nervous system. However, a large proportion of behavioral studies performed by psychologists do not purport to reveal specific properties of the central nervous system. A majority of those psychologists, nevertheless, believe the central nervous system to be relevant to the behaviors studied. Although a behavioral level of analysis has been pursued thus far, the definition of the boundaries of the system under study and the relevant scale of analysis is by no means intrinsically determined by the use of dynamics. On the contrary, an immediate advantage of a dynamical systems approach is that the descriptive apparatus is applicable to phenomena at multiple scales of analysis, for instance, starting at larger scales and working down, social organization, perception-action cycles, the brain, subsystems in the brain, or small groups of neurons, individual neurons, and chemical cycles (Abraham, 1985; Mittenthal, 1989; Mpitsos, Creech, Cohan, & Mendelson, 1988; Skarda & Freeman, 1987). The abstract nature of dynamics allows for scale independence and, therefore, for a tremendous generality of application (Haken, 1983, 1988; Schöner & Kelso, 1988b; Kugler & Shaw, 1989).[5]

Von Hofsten failed to appreciate this expediency of task-specific dynamics when it comes to problems of perception and action, which, almost by definition, include the difficulties of linking events across and among scales of

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[5] It is the scale independence of nonlinear dynamics that allows for identification of organizational features (e.g., phase- and frequency-locking, subharmonic entrainment, stable and unstable modes, etc.) that neural patterns have in common with behavioral patterns. And it is the congruency of the resulting descriptions that is often used as a way to relate the macroscopic level of behavior to more microscopic, neurophysiological levels of analysis.

analysis. One problem, for instance, is how brain activity and organization interfaces with activity and organization in the perception-action cycle. The two reside at different scales of analysis. How are we to describe the linking of structure and organization at these different scales? The oft-made category mistake is to place nervous activity on a par with human activity. In contrast, task-specific dynamics pursues the following strategy already mentioned above. The high-dimensional activity at small scales is understood to produce low-dimensional activity at larger scales of observation, through coupling of local (subcomponent) processes with accompanying compression in the number of degrees of freedom.

Contrary to von Hofsten's apparent impression from the literature, the intent has not been to belittle the role of the brain in the organization of behavior, but rather to place its role in the proper and adequate context, namely, as coupled to the concurrent dynamics of other essential, and too often ignored, component systems including the musculo-tendon, circulatory, link-segment, and respiratory, and even nutritional subsystems.[6]

The realization that effective understanding of perception-action cycles requires consideration of all of these complex nonlinear subsystems and their nonlinear interactions motivates a behavioral level of analysis which captures the resulting low-dimensional coherence. This strategy holds the promise that, once an understanding of the global dynamics at this behavioral level of analysis has been achieved, one can begin to disentangle the local dynamics of the subsystems and their interactions, among which are the brain and its interacting subsystems. When used in isolation, a strategy that attempts to work in the opposite direction (i.e., from the complexities of small-scale events to the global dynamics of task-specific devices), will be as doomed to failure as an attempt to reconstruct the vortex in a whirlpool from an analysis of the local interactions among molecules. Behavior emerging from the interaction of nonlinear components cannot be predicted from a knowledge of individual component properties, especially when the components are numerous and inhomogeneous and the interactions complex. Of course, a knowledge of the local dynamics of the component properties is as essential to the enterprise as is a knowledge of the low-dimensional dynamics corresponding to the coherent behaviors produced by the system as a whole.

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[6] For studies recognizing and treating the subsystems and their interactions see, for instance, Bingham (1990), Bingham et al. (in press), Bramble (1983), Bramble and Carrier (1983); Carrier (1984), Falk (1990), and van Ingen Schenau (1989). Bramble (1983), for example, studied the coupling between respiration and locomotion in running humans using tools of nonlinear dynamics. He recorded breathing sounds and foot impacts and observed a number of different phase locked states between the frequencies of these oscillatory processes. The values (small integer ratios) of these phase locks proved dependent on the velocity of locomotion. Although a complete model of the mechanism underlying the entrainment is not available, dynamical methods were required to identify the global characteristics of the system in terms of entrainment and phase-locking.

COMMENSURATE DESCRIPTION OF HETEROGENEOUS ELEMENTS

A rather profound difficulty, in view of its history in the study of perception, is that of relating environmental and animal contributions to the organization of activity (Gibson, 1966, 1979/1986; Lombardo, 1987; Turvey, 1977; Turvey, Shaw, Reed, & Mace, 1981). Dynamics, in addition to being sufficient to the description of properties determining the forms of movement of the articulators in human behavior, is also indifferent to the origin of those properties. Contrary to von Hofsten's suggestion that dynamical systems models are restricted to phenomena composed of homogeneous elements, dynamics is popular as a particularly powerful modeling apparatus applicable to a wide variety of temporally evolving phenomena composed of heterogeneous components (Beltrami, 1987; Luenberger, 1979; Stein, 1989; Thompson & Stewart, 1986; Yates, 1987). For example, the terms within a differential equation representing the dynamics reflect all of the different types of determinants of movement at a given instant including inertial, dissipative, and conservative forces. The indefinite variety of functions and parameter values that can be used within each term to represent specific properties found in nature yield the requisite generality. This generality is expedient in its applicability to the heterogeneous components in any performance including the variety of subsystems inherent to the animal (e.g., nervous, circulatory, musculo-tendon, link-segment, etc.) as well as incidental environmental components (e.g., momentary surfaces of support, mass distribution in manipulated objects, the resistance of a bicycle pump, etc.).[7]

A REMARK ABOUT INTENTIONALITY

We make no great concession in acknowledging that an account in terms of task-specific dynamics does not provide anything near a full account of the generative sources of intention, of purposes, goals, needs, drives, and so on. No

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[7] The use of the terms *inherent* and *incidental* in reference to the dynamical resources available for assembly into a task-specific dynamic is not happenstantial (Bingham, 1988) and contrasts with increasing usage, in parallel fashion, of the terms *intrinsic* and *extrinsic* (e.g., Schöner & Kelso, 1988c, 1988d). The latter terms invite distinction in terms of a boundary formed by the skin, akin to internal and external. This creates difficulties. For example, there is a ubiquitous dynamical element that plays a role in the interior and exterior alike, namely, gravity. Inherent refers to dynamical components that are inherently available and that tend to be employed across a variety of tasks. These are carried around as part of the animal. However, the problem of perceiving and organizing the dynamics of activity is indifferent to the skin boundary. For instance, perceiving the momentary inertial properties of the limbs is no different a problem in principle than perceiving the inertial properties of manipulated objects. What is important about the less consistently used dynamical components is not their location with respect to the skin boundary, in particular, but their incidental availability and relevance to the particular task at hand.

extant approach does. However, the problem of intentionality definitely has a place within the enterprise of task-specific dynamics—a place that, slowly but surely, becomes more pronounced. Promising new theoretical and empirical inroads into this elusive problem are being found and developed (Kelso, 1989; Schöner & Kelso, 1988c, 1988b; Shaw & Kinsella-Shaw, 1988; Shaw et al., 1990; Solomon & Turvey, 1988). The presupposition of task-specific dynamics is that by maintaining the focus of our analytical efforts on the plurality of tasks performed, and their underlying dynamics, we reveal, by parts, the topography of the functional landscape and the diverse roles that intentions can play in it.

CONCLUSION

On the basis of the arguments and facts presented in this article, we conclude that task-specific dynamics is uniquely efficacious in at least the following four respects.

First, the approach is uniquely able to assess the functional basis of behavior using the two predominant methods of dynamics, namely, perturbation and bifurcation. These methods refer to the mutually defining (and mathematically well documented) concepts of stable modes and transitions between modes accompanied by loss of stability. They have been successfully employed in uncovering dynamical organizations in behavior, that is, in revealing functional design.

Second, and most importantly, the approach is by no means restricted to easily measurable physical parameters with an implied exclusion of informational parameters. To the contrary, the use of qualitative dynamics provides a means of conceptualizing and actually measuring how perceptual access to the complex dynamical resources of the action system might be achieved and used to marshal those resources into coherent, controllable, and functionally effective organizations. Stability of movement and detectability of information are intimately (and dynamically) related in biological systems, and are therefore addressable by a single approach.

Third, the approach is not limited, in principle, to any single scale of analysis, but has the, thus far, unique ability to address phenomena at multiple scales of analysis with the concident advantage of being able to address the issue of relations among phenomena across levels. The brain resides at a different scale of analysis than the motor behavior to whose organization it contributes. Other components also contribute in a determinate fashion to the form of the observed behavior. The role of the brain must be viewed within the context of other components at the relevant scale of analysis before the question of the relation between scales of analysis can even be considered.

Fourth, despite an initial focus on homogeneous systems in the study of dynamical systems, the approach is not inherently restricted to such phenomena. To the contrary, the approach provides a potential means of relating components of the motor system that differ in kind, including neural, muscular, and circulatory components, among others. Furthermore, the approach provides a means of relating kinds heretofore understood as incommensurable, namely animal versus environmental. Without wishing to suggest that task-specific dynamics provides the only useful type of analysis that could be performed in the study of human behavior, we conclude that this approach is indispensable if one wishes to address the specific types of questions just discussed.

ACKNOWLEDGMENTS

P. J. Beek's participation in the writing of this article was enabled, in part, by National Science Foundation Grant (BSN–8811510) to the Center for the Ecological Study of Perception and Action at the University of Connecticut, Storrs, CT. G. P. Bingham was supported by a Summer Faculty Fellowship from Indiana University, Bloomington.

We thank Dragana Barac-Cikoja, Richard Schmidt, Bob Shaw, Esther Thelen, Bill Warren, and an anonymous reviewer for their time in commenting on an earlier draft of this manuscript.

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