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CHAPTER 19

Has Ecological Psychology Delivered What It Promised?

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It has been 20 years since the publication of the landmark chapter by Micha Turvey entitled "Preliminaries to a Theory of Action with Reference to Vision" Shaw and Bransford's (1977) volume *Perceiving, Acting, and Knowing: Towa an Ecological Psychology*. In the motor control and learning field, the ecologic or "action systems" approach (Meijer and Roth 1988) offered a radically differe view of movement behavior from that of the more established artifactual or "mot systems" approach. In particular, ecological psychologists emphasized anim environment reciprocity (e.g., Michaels and Carello 1981) as the foundation of t overriding principle of ecological realism. To this end:

> The ecological strategy observes two rules of thumb: (1) resist taking out loans of intelligence; and (2) regard with skepticism, and be prepared to jettison, any assumption, concept, interpretation, fact, theory, strategy etc., that undercuts or threatens to undercut the principle of ecological realism. (Turvey and Carello 1981, 314)

The marrying of the views of Bernstein on movement coordination (e.g Bernstein 1967) and Gibson on direct perception (e.g., Gibson 1979), as well the application of concepts in nonequilibrium thermodynamics to self-organizatic in biological systems (e.g., Kugler 1986; Kugler and Turvey 1987) and concepts synergetics to the problem of pattern formation in complex systems (e.g., Hake Kelso, and Bunz 1985; Schöner and Kelso 1988a, 1988b) posed a clear challen to the establishment view of movement control.

In addition to the promise of a unified theoretical framework, the early writin of proponents of the ecological approach offered a set of fascinating and intuitive appealing metaphorical images to illustrate the ecological realism of pattern formation in nonequilibrium systems and perception-action coupling, including termites building arches (Kugler 1986), horses changing gaits (Tuller, Turvey, and Fitch 1982), gannets diving for fish (Lee and Reddish 1981), electricity-detecting sharks, egg laying by parasitic wasps, tree climbing by arboreal vines (Turvey et al. 1981), and fish schooling (Kelso 1982). Furthermore, the view that the principles of self-organization (e.g., developmental transitions from random to ordered phases of organization) apply equally to insect architectural development and to infant motor development (Kugler 1986) provided a very powerful and radical approach to understanding motor behavior.

The wide philosophical differences between the ecological and information-processing/cognitive approaches have spawned much debate (e.g., Abernethy and Sparrow 1992; Cutting 1982; Meijer and Roth 1988; Summers 1992) and, for some, have placed the motor control and learning field in the "midst of a true paradigm crisis" (Abernethy and Sparrow 1992, 27). Whether the crisis will be resolved by the emergence of one view as dominant (Abernethy and Sparrow 1992; Beek and Meijer 1988) or by a reconciliation between the two perspectives (Davids, Handford, and Williams 1994; Pressing in this volume; Summers 1992) remains to be seen. At the present time, the debate seems to be over, with both sides agreeing to disagree. This may be due to the acceptance that there are no critical experiments to distinguish the two approaches. In fact, a recent trend in motor learning research from the computational perspective is to concern itself even less with movement execution processes and more with the knowledge structures and cognitive architecture underlying skilled performance (Glencross, Whiting, and Abernethy 1994).

In this chapter, I do not wish to resurrect the debate but rather to critically examine the progress of the ecological approach toward its laudable goals. The viewpoint expressed is that of a movement scientist with a background in the cognitive approach who has recently been using the tools of nonlinear dynamics to investigate bimanual coordination (e.g., Semjen, Summers, and Cattaert 1995; Summers et al. 1995; Wuyts et al. 1996). During the preparation of this chapter my task has been made much easier by the publication of an excellent critical review entitled "The State of Ecological Psychology" by Clare Michaels and Peter Beek.

Divergence of Views

From the start, the goal/agenda of ecological psychology appeared to be much wider and all-encompassing than that of the information-processing perspective:

> The ecological approach to perception and action incorporates psychology as a companion endeavor to physics and biology for the purpose of studying the epistemological relationship between an animal, as agent and perceiver, and its environment. The goal of a theory of action and perception is to explicate the organizational principles relating animal and environment on the basis of energy and informational transactions. (Kugler, Kelso, and Turvey 1982, 69)

The ultimate aim of this approach is "to formulate laws or law-like statemen about perception and action that express regularities among observable quantitie (Michaels and Beek 1996, 263). In recent years, however, there appears to ha been a divergence among the chief proponents of the ecological approach abo how the relation between perception and action should be conceptualized and e amined. This has led to the emergence of three closely related but distinct perspe tives within the field of ecological psychology: the direct perception, nonequilibriu thermodynamics, and dynamical systems approaches.

Michaels and Beek (1996) have argued that the three perspectives can be disti guished and evaluated in terms of the way they deal with four basic probler confronting the mutuality of perception and action. The first relates to the identi cation of the essential variables of perception and action to be entered into law-lil statements. That is, what are the appropriate metrics for the description of tl organism-environment interface? The second problem concerns the process aı the criteria to be used in proving or disproving the law-like statements. A lon standing criticism of ecological psychology is that the models are not easi falsifiable and that proponents have been reluctant to subject them to rigoroı testing (e.g., Schmidt 1988). The third general problem identified by Michaels aı Beek (1996) relates to how variability of any sort (i.e., within-subject/task, b tween subjects/tasks) is handled by the three perspectives. That is, should variabi ity be minimized or accepted and exploited? The direct perception perspective, f example, with its emphasis on attunement to higher-order invariants in the prox mal stimulus, expects minimal variability within an individual over time and b tween individuals. The dynamical systems approach, in contrast, regards variabili as an essential feature of behavior and behavior change, and its tools are designe to deal with variability of all sorts (see Newell and Corcos 1993; Newell and Slifk in this volume for review). The final problem that must be addressed by any a proach to motor behavior relates to how change of any sort (i.e., through evolutio development, or learning) is incorporated into the theoretical framework.

In the remainder of the chapter a brief overview of the three perspectives will t presented, focusing on how each approach deals with or fails to deal with the foı general problem areas listed. Particular attention, however, will be given to tl dynamical systems approach, which arguably has been of greatest relevance motor functioning.

Direct Perception

In theorizing about the information support for coordinated motor behavior, tl writings of James Gibson still remain paramount. Central to ecological psycholo gy's attempt to explain motor behavior, without recourse to notions of memory (knowledge structures involving symbolic representation, have been the concep of *invariants* and *affordances* (Michaels and Carello 1981). Invariants refer to highe order properties of the optic array that remain constant during changes associate with the observer, the environment, or both. However, these invariant optical pa terns are not perceived directly; rather we perceive the affordances of objects an events around us. Affordances represent possibilities for action in the environme (Gibson 1979). As such, affordances are strictly a property neither of the organis nor of the environment but reflect the interaction between the particular capabilities of the organism (termed "effectivities") and the particular properties of the environment/object in question. Because affordances can be directly perceived, there is no need to refer to stored representations. In this perspective, *information* refers to the energy patterns specifying affordances that are detectable by the perceptual systems and, as such, serves as the substrate for the coupling of actions to objects and events (Michaels 1993). Thus, perception involves the pickup of such information through a process of active exploration of the perceptual-motor work space.

Although affordance is a key concept in ecological psychology's organism-environment mutuality, the nebulosity of the term has been an impediment to the wider acceptance of Gibsonian ideas. In many respects, the concept of affordance appears to share many of the problems associated with definitional imprecision that the concept of schema enjoys in cognitive psychology. As van Wieringen (1988) notes, most of the work on affordances has dealt with the "environmental aspect," that is, the analysis of the higher-order invariants available in the optic array. However, the crucial issue of how the organism becomes "sensitive" to these higher-order invariants, including the relevant contributions of genetic endowment and learning, has until fairly recently (e.g., Adolph 1995; van Leeuwen, Smitsman, and van Leeuwen 1994) been largely neglected. Clearly a great deal more work is needed to enhance the efficacy of the concept of affordance and counter such views as expressed by Fodor (1980), who wrote, "The category of 'affordance' seems to me a pure cheat: an attempt to have all the goodness of intentionality without paying any of the price" (107).

In an attempt to deal with the question of the development of expertise without invoking the notion of sophisticated knowledge structures, direct perceptionists have proposed that expertise is associated with the development of smart perceptual devices that are attuned to the higher-order invariants specific to a particular context or task (Runeson 1977). Once again, however, how these devices are acquired and how they relate to the affordance concept are unclear. As Michaels and Beek (1996) note, proposing innate smart perceptual devices does not solve the problem. Rather, they suggest, perceptual learning may be best conceived as initially involving the exploitation of lower-order (nonspecific) perceptual variables that may guide the search for and/or become parts of a higher-order informational complex, the smart perceptual device.

A crucial issue for proponents of the direct perception perspective, therefore, has been the identification of the "higher-order" invariants, available in the structured energy gradients of perceptual flow fields (optical, acoustical, haptical) that act as information for the coordination of movement in units scaled to the dimensions of the perceiver (e.g., Lee 1976; Turvey and Carello 1988; Warren 1984). Although there have been vigorous attempts to identify candidate variables in ecological acoustics (e.g., Shaw, McGowan, and Turvey 1991) and haptics (e.g., the inertial tensor, Pagano and Turvey 1995), most of the work has concerned the visual sense, with variables such as optical expansion patterns, texture gradients, and motion perspective being suggested as links between perception and action.

Within the optic flow field, researchers have been somewhat preoccupied with the optical invariant *tau* specifying directly the time-to-contact between an observer and object or surface in the environment (e.g., Lee 1976, 1980). Time-to-contact information has been implicated in the control of interceptive actions in a variety of everyday activities (e.g., car braking, Lee 1976) and sport activities involving catching, hitting, and jumping (see Davids, Handford, and Williams 1994 for review). A problem with the overdependence on tau to provide support for direct perception is that criticisms of the variable (e.g., Tresilian 1991, 1993; Wann, Edgar, and Blair 1993) tend to undermine the whole approach in the eyes of the skeptics. In fact, a recent reexamination of some of the studies regarded as providing strong support for the use of tau has shown that the data actually argue against its use (Michaels and Beek 1996; Wann 1996). For example, a reanalysis of the frequently cited deflating-ball experiment by Savelsbergh, Whiting, and Bootsma (1991) suggested that, rather than providing support for the causal role of tau in interceptive timing, the data indicate that other optic variable(s) may be more important in such actions. A further problem with the time-to-contact concept is that, despite its elegance, the role of tau in predictive timing has never been directly verified and there seems to have been some reluctance by proponents of tau to submit the concept to critical evaluation. Rather the evidence in support of the use of tau in interceptive actions has been largely circumstantial. As Michaels and Beek (1996) remark:

> Demonstrations that judgments and actions are consistent with the use of tau do not constitute proof of that use, especially when a blind eye is turned to the limitations of tau and to the predictions that tau might make. (268)

In summary, the direct perception perspective, through its attempts to identify the key perceptual invariants for the control of movement, has contributed a great deal to the understanding of the perceptual aspect of the circular relationship between perception and action. Unfortunately, there has been an overdependence on the tau variable, and there is an urgent need for the identification of other higher-order variables that subserve the coupling of perception and action. The organization of action relative to the information in the environment, however, has not received much attention in this perspective (Michaels and Beek 1996). Of particular importance is the determination of those aspects of optical flow that are involved in the prospective control of behavior. Furthermore, the dual concepts of affordance and effectivity to account for the coupling aspect are still ill defined and as such remain unconvincing to many critics of the ecological approach. Finally, Michaels and Beek (1996) express concern that the direct perception perspective lacks a clear theoretically based research program and is in danger of "diverging into a potpourri of arbitrarily derived perceptual quantities, particularly if it continues to ignore the problem of coordination" (267).

Nonequilibrium Thermodynamics

A second perspective developed out of the general goals of ecological psychology through application of the principles of thermodynamics to the study of movement control (see Kugler and Turvey 1987). Kinetic theory, as it has been termed (Michaels and Beek 1996), was motivated as a response to Bernstein's (1967) famous question of how the many degrees of freedom of the body can "be regulated systematically in varying contexts by a minimally intelligent executive intervening minimally" (Tuller, Turvey, and Fitch 1982, 253). To solve the degrees of freedom problem, proponents of the ecological approach introduced the concept of muscle linkage or coordinative structure, defined "as a group of muscles often spanning several joints that is constrained to act as a single functional unit" (Tuller, Turvey, and Fitch 1982, 253). Further, to deal with the problem of how order in complex systems can be achieved without the influence of an external agent, in a now classic paper Kugler, Kelso, and Turvey (1980) proposed that biological systems can be modeled as thermodynamic engines and coordinative structures as nonequilibrium dissipative structures. The beauty of open thermodynamic systems is that they can exchange energy with the environment and as such manifest spatiotemporal self-organization. That is, pattern formation occurs spontaneously when one or more control parameters (e.g., energy, in the form of various physical variables) change and guide the system through its various stable states. Of particular importance in the adoption of this approach is that the general principles governing the emergence of order in complex systems do not require a "material (symbolic) representation within the system itself" (Beek, Peper, and van Wieringen 1992, 600). In a wonderful example of such a self-organizing information system, Kugler (1986) describes insect nest-building behavior in graphic detail.

A key aspect of this perspective has been the successful modeling of coordinative structures as nonlinear, limit-cycle oscillators. Not only do limit-cycle oscillators exhibit self-sustaining properties, but they are also mutually synchronizing or entraining. Subsequent demonstrations of entrainment as a property of neuromuscular systems (e.g., Kelso et al. 1981) provided a mechanism for the coordination of coordinative structures "for free," that is, without requiring the intervention of some high-level executive system (Tuller, Turvey, and Fitch 1982).

The kinetic perspective differs from the direct perception approach in a number of ways. First, it emphasizes the reciprocal relationships between the pickup of perceptual information (flow field) and muscular forces (force field). That is, there is a circular causality whereby action (e.g., muscular forces) produces changes in perceptual flow fields (e.g., optic flow) that in turn affect future action force fields and so on (Kugler and Turvey 1988). In this sense, the kinetic perspective has emphasized Gibson's (1979) suggestion that "we must perceive in order to move, but we must also move in order to perceive" (223). Second, by viewing biological systems as thermodynamic engines, and coordinative structures as dissipative mechanisms, this perspective has provided an "explanation" of how order emerges from randomness in physical and biological systems. That is, such systems are able to use energy from a number of dynamic sources in the environment (e.g., gravity, friction, inertia, reactive forces) to coordinate component parts and produce flexible, goal-directed behavior with minimal input from a high-level executive system (Davids, Handford, and Williams 1994; Turvey 1990). Third, this perspective explicitly assumes that a particular perception-action cycle is initiated to realize a specific intention on the part of the individual. This has led to a concern with how intentionality can be mapped onto the general physical laws that underlie coordinated movements, termed intentional dynamics (e.g., Shaw et al. 1992). Cognitive functions (intentions, plans, goals, etc.) are viewed as a set of extraordinary circumstances (boundary conditions, constraints) that harness the physical laws in specific ways to produce specific behavior (Turvey 1990).

The main agenda of kinetic theory is to identify information-force transactions. Michaels and Beek (1996), however, argue that while this perspective appears to offer a more formal approach than the direct perception perspective, with the

exception of Kugler and Turvey's work on dynamic touch (see Kugler and Turve 1987; Turvey 1994) there have been few attempts to explicitly connect force vari ables to perceptual variables. As the authors remark:

> Talking about forces per se is not sufficient; without some account of the principles by which neuromuscular machinery might create a particular force vector, the kinetic approach must arbitrarily project kinetics that are merely consistent with kinematic shadows. (Michaels and Beek 1996, 266)

As with the direct perception perspective, the kinetic perspective has lacked comprehensive theory of learning and development. Skill acquisition is seen as th process of searching for the optimal motor solutions to accomplish the task i question. Thus, "Learning is the coordination of the perceptual environment wit the action environment in a way consistent with the task constraints" (Newell 1991 225). Such coordination involves the mapping of certain informational variable onto certain motor execution variables (e.g., speed, direction) with a consequentia change in the state of the informational variables (Bootsma 1993). Developmenta change in the kinetic perspective is conceived as a series of states of stabilit instability, and phase shifts in an attractor landscape through which an initial ran dom phase of organization is transformed into progressively more ordered phase (Kugler 1986; Thelen 1995). Such change is brought about through processes o exploration and selection by which the infant finds solutions to new task demands Even "phylogenetic skills" such as crawling, reaching, and walking are regarde as emerging via "a process of modulating current dynamics to fit a new task throug exploration and selection of a wider space of possible configurations" (Thele 1995, 86). Although this view offers a radically different alternative to traditiona stage models of development (e.g., McGraw 1943), to date it has been largel supported by a set of metaphorical images (e.g., termite nest building) and purel descriptive studies rather than a rigorous program of research. However, a promis ing future direction suggested by Thelen (1995) may be the linking of these new behavioral perspectives with current perspectives on brain development and plasticity, in particular Edelman's (1987) theory of neuronal group selection, whicl provides a specific neural mechanism for the dynamic processes of exploratior and selection.

Dynamical Systems

The dynamical systems perspective is concerned primarily with the application of the concepts and tools of nonlinear dynamics and synergetics to movement coordination (Beek, Peper, and Stegeman 1995). This line of research, initially developed by Haken, Kelso, Schöner, and colleagues (e.g., Haken 1983; Kelso 1984; Schöner and Kelso 1988a, 1988b), aims to mathematically model the stability and loss of stability (phase transitions) evident in the formation of patterns in movement systems. In this sense, the dynamical perspective differs from the kinetic and thermodynamics perspectives in that it is concerned with spatial, temporal, and functional patterns of organization in natural systems (Michaels and Beek 1996). The dynamical systems perspective has focused on the phenomenon of phase transitions as the key to understanding coordinated movement. Phase transitions refer to situations in which a system's behavior changes qualitatively, and they represent the simplest form of self-organization known in physics (Turvey 1990). Analyzing pattern change in terms of phase transitions allows the identification of a macroscopic quantity called an order parameter, or collective variable corresponding to the defining characteristic of a particular pattern by which qualitative changes in that pattern are indexed, and one or more nonspecific control parameters that are responsible for pattern changes. The discovery of phase transitions in bimanual coordination (i.e., anti-phase to in-phase transitions during two-finger oscillations) provided strong support for the application of dynamic pattern theory to human motor behavior (e.g., Haken, Kelso, and Bunz 1985). Research on interlimb coordination suggested relative phase among the limbs as a collective variable and frequency as a control parameter that moves the system through its various collective states. Further predictions of dynamic pattern theory and synergetics with regard to the phase transition phenomenon have been supported in the bimanual paradigm, including enhancement of fluctuations and critical slowing down around transition points and differences in switching times between patterns of coordination (see Jeka and Kelso 1989). Phase transitions have also been shown to apply to other interlimb coordinations, such as arms and legs (e.g., Kelso and Jeka 1992) and hands and feet (e.g., Carson et al. 1995), to coordinations between two people (Schmidt, Carello, and Turvey 1990), and to coordination between an arm and a visual stimulus (Byblow, Chua, and Goodman 1995).

The dynamics perspective has specifically attempted to deal with the issue of how coordination dynamics can change as a function of learning by distinguishing between intrinsic dynamics, which refer to existing movement patterns, and extrinsic dynamics, which are to-be-learned movement patterns. The learning of movement patterns is seen as the extrinsic dynamics acting on (cooperating or competing with) the intrinsic dynamics (see Schöner, Zanone, and Kelso 1992). The extrinsic dynamics are specified by *behavioral information* that is expressed in the same "language" (e.g., relative phase) as the intrinsic dynamics. That is:

> Information is meaningful and specific to the biological system only to the extent that it contributes to the order parameter dynamics attracting the system to the required (e.g., perceived, learned, memorized, intended) behavioral pattern. (Jeka and Kelso 1989, 29)

This concept of behavioral information bears no obvious relation to the term information as used by proponents of the direct perception perspective to refer to variables in the perceptual flow fields.

Whereas the direct perception perspective can be criticized for failing to satisfactorily address how perceptual variables map onto motor variables, the dynamical systems perspective has concentrated on the action side of the perception-action cycle; the mapping of coordination dynamics onto perceptual variables, with the exception of the work of Warren and colleagues (e.g., Warren 1984, 1988; Warren, Kay, and Yilmaz 1996), has to a large extent been neglected. This may have been a deliberate strategy, because as indicated in the definition given earlier, coordination dynamics are inherently informational in character, and distinguishing between information in terms of properties of the perceptual flow fields and the dynamics of movement is unnecessary (Kelso 1994). Schöner (1994b), however,

has argued that an important development in the dynamic pattern approach mu be to determine how action-specific perceptual variables such as tau map on (inform) the coordination dynamics. A further consequence of the neglect of tl perceptual side of the equation has been that issues such as perceptual learning ar the relationship between the concepts of affordance and behavioral informatic are yet to be discussed. This lack of communication between the direct perceptic and pattern dynamics perspectives may also reflect the different styles of inqui adopted in the two perspectives. The dynamicists have opted for laboratory-base research using contrived movement tasks, such as finger oscillations, wrist rot tions, and pendulum swinging. Perception-action coupling in such tasks has usı ally involved synchronizing oscillatory movements to an auditory metronome scale in frequency. As such, there has been little attempt to link coordination dynamic to concepts like tau.

The ability of dynamical tools and concepts to provide a comprehensive d scription of developmental phenomena has also been recently questioned (Michae and Beek 1996; Vereijken 1995). Although this perspective has attempted to en pirically examine the general tenet that change, either through learning or deve opment, is heralded by the loss of stability, Vereijken (1995) has suggested som issues that need to be addressed in the application of the dynamical perspective t developmental data. One relates to the general problem of the incorporation c nonobservables such as motivation, memory, attention, and cognitive strategie into the theory. Another issue is that viewing development as a dynamic proces necessitates an understanding of not only why phase transitions occur but als why they occur at particular times in development. These issues and others le Michaels and Beek (1996) to comment, "As it stands now, the applicability c pattern dynamics to developmental phenomena may prove to be more limited tha widely suggested and hoped for" (276).

There are a number of other issues that the dynamical perspective will need t address in the future. The first relates to generalizability of the dynamical analysi of movements. The application of nonlinear dynamics to human motor behavic has been primarily to the coordination of oscillatory movements by the two hand and index fingers. A main goal of this work was to identify appropriate collectiv variable(s) and control parameter(s) that capture the behavior of the human moto system. Analysis of phase transitions during oscillatory movements provided sup port for the model proposed by Haken, Kelso, and Bunz (1985) that with subse quent extensions (see Fuchs and Kelso 1994) has dominated work on interliml coordination from the dynamical perspective (see, however, Schmidt and Turve 1995 for an alternative formulation). Although the model has been successfull applied to multifrequency bimanual coordination tasks (e.g., Haken et al. 1996 Peper, Beek, and van Wieringen 1995; Treffner and Turvey 1993), its extension t discrete movements (e.g., prehension movements) has proved to be more difficul (see Schöner 1994a, 1996 for a possible solution). The ability to account for discret movements within a dynamical framework is clearly an important issue for futur research. At present, a commonly expressed view is that the dynamical systems per spective may provide new insights mainly in activities involving rhythmical or con tinuous movements and a tight coupling between perception and action, such a locomotion, juggling, and steering a car (Davids, Handford, and Williams 1994).

A related problem is whether relative phase, to date the only order parameter iden tified, is the most appropriate collective variable for the description of movement other than continuous cyclical interlimb coordinations. In fact, it has recently been questioned whether measures of relative coordination efficiently characterize the performance of two-dimensional bimanual movements (Wuyts et al. 1996).

Other General Concerns

At the present time, therefore, the general field of ecological psychology encompasses three related but clearly distinct approaches to the undeniable mutuality of organism and environment. In terms of the four problems posed by Michaels and Beek (1996), all three perspectives exhibit limitations that need to be addressed. Although ecological psychology has become firmly established as a viable alternative to the traditional cognitive psychology approach to human behavior, the "battle lines" between the two approaches still exist. There appear to be a number of fundamental issues, maybe misconceptions, that are limiting the wider acceptance of the ecological approach:

1. *The continual denial by some ecological psychology theorists of any form of representation.* Certainly the outright rejection of internal representations by the early proponents of the ecological approach alienated computational theorists and became a central issue in the motor-action systems debate (see Meijer and Roth 1988). Although the strict assumption of organism-environment reciprocity removes the need for representations of the "mental copy" type, it seems that providing adequate alternatives to the notions of representation and memory are needed to explain more "cognitively mediated" skills involving complex sequences of movements, such as typing, handwriting, speech, and musical performance. Furthermore, van Ingen Schenau et al. (1995) have argued that the execution of tasks involving the coordination of multi-joint movements by necessity requires detailed internal representations of the properties of the effector system in relation to the environment. These representations refer to the structural properties of neurons and groups of neurons localized in circuits (pattern generators) with specific architecture and synaptic strengths that determine the accurate production of multi-joint movements. In the recent writings of some proponents of the ecological approach, the existence of some form of internal representation (broadly defined) appears to be accepted (e.g., Beek, Peper, and Stegeman 1995; Michaels and Beek 1996; Schöner 1996), and issues such as representation-action couplings are being discussed (e.g., Rieser 1995; Hofsten 1995).

2. *Ability to account for "cognitive" processes such as strategic planning, decision making, attention, and instructional set within a dynamical framework.* To writers keen to apply the ecological approach to "real-world" activities such as sport performance, a major obstacle is seen as "the failure to designate an appropriate role for essential cognitive processes in strategical planning and decision making in unique sport environments" (Davids, Handford, and Williams 1994, 523). Schöner (1996) also argues that one of the needs or obligations of ecological psychology is "to open the approach toward cognition" (309). Perhaps a first step in that direction can be seen in recent research examining the effect(s) of "cognitive" variables such as attention (e.g., Amazeen et al. 1997; Byblow and Goodman 199[illegible] Wuyts et al. 1996) and instructional set (Lee, Blandin, and Proteau 1996) on th[illegible] dynamics of intrinsic coordination patterns. Whereas the initial thrust of the eco[illegible] logical approach has been to demonstrate that the human being functions accord[illegible] ing to the same relatively few, general physical principles as other biologic[illegible] organisms, it may now be time to examine those features that make humans dis[illegible] tinct from other species, such as the intentionality to follow one's will (Lee, Blandin and Proteau 1996). It has been suggested that higher levels of consciousness ma[illegible] intervene/modify/override the intrinsic dynamics of the movement system (e.g Davids, Handford, and Williams 1994; Summers 1989, 1992). This form of con trol may be particularly relevant in many sport actions (e.g., cricket bowling, gym nastics, race walking) and musical performance (e.g., polyrhythms) that appear t[illegible] require overriding the normal/natural functioning of the human biokinematic sys tem. Certainly all the ingredients now appear to be in place for the modeling [illegible] cognition as a subset of dynamics (Kelso 1996). The success of this enterprise i[illegible] vital for the future development of the dynamical systems approach.

3. *Equivalence of models.* Despite the great progress made by ecological psy chology over the last 20 years, it still cannot provide a complete alternative to th[illegible] cognitive approach. There have been few, if any, studies that have supported dynamical systems model to the exclusion of a cognitive interpretation (e.g., se[illegible] Heuer 1993; Pressing 1995; Rosenbaum 1991, for motor programming/cognitiv[illegible] interpretations of phase transitions in bimanual coordination). Given that the tw[illegible] approaches have very different aims, concepts, methods, and expected outcome[illegible] (e.g., the dynamical systems approach does not attempt to produce causal explana tions), it seems doubtful whether trying to distinguish empirically between the tw[illegible] approaches is possible or is even a worthwhile enterprise (Beek, Peper, an[illegible] Stegeman 1995). Perhaps a more promising approach would be to introduce con cepts and tools of dynamics, such as stability and loss of stability, to cognitiv[illegible] constructs such as the motor program (see Schöner 1996 for development of thi[illegible] approach).

4. *User-friendly language.* As if, for movement scientists outside the domain coming to grips with the language of dynamical systems theory, nonequilibrium thermodynamics, and so on is not hard enough, some proponents of the approach appear to adopt a writing style designed to obscure understanding even more. It is pleasing, therefore, to note a number of recent very readable accounts of the dynamical systems approach (Beek, Peper, and Stegeman 1995; Davids, Handford, and Williams 1994; Kelso 1995; Schöner 1996). Schöner (1996) also warns against the blind application of the languages of mathematics and physics within the ecological approach and emphasizes the need to develop a rigorous theoretical language commensurate with the goals of the approach. At present the approach suffers from a lack of clear definition and consistency in the use of some key terms/concepts. For example, the notion of "degrees of freedom" is central to Bernstein's problem, yet the term is ill defined, taking on different meanings depending on the context and level of analysis (e.g., neural, biomechanical, behavioral) (Broderick and Newell 1996). Without consensus on what a degree of freedom is, notions of freezing and releasing degrees of freedom as fundamental processes of learning and development have little meaning.

A related concept is "constraint"—a concept that is at the core of the dynamical approach but also suffers from definitional problems. A vast number of constraints are seen to influence movement production that have been variously labeled as temporal, spatial, informational, holonomic, organismic, environmental, nonholonomic, inherent, intrinsic, extrinsic, and incidental. There is a lack of clarity in identifying where these constraints come from, which ones are relevant (e.g., can "age" be usefully considered as a constraint), and how constraints interact (see Byblow, Carson, and Goodman 1994; Carson et al. 1996).

Future Directions

There are a number of ways in which ecological psychology, and the dynamical systems perspective in particular, can develop. In the short term, two areas appear to need to be addressed. The first is the relationship between knowledge, intentions, and the physical laws and principles that account for movement coordination. Mapping cognitive constraints onto intrinsic dynamics would seem to be a necessary next step in the development of the approach. Whether this can be done without the emergence of a hybrid model (e.g., Summers 1992) or the acceptance that the two approaches are not, at least mathematically, fundamentally different (see Pressing submitted; Pressing in this volume), is a matter for future research.

The second issue relates to the need for theorists and researchers from the three perspectives to go beyond metaphorical descriptions. To some critics (e.g., Rosenbaum 1991), the aims of dynamical systems theory appear purely descriptive (see Beek, Peper, and Stegeman 1995 for a rebuttal of this characterization). For example, treating intention and intrinsic dynamics in similar ways does not tell us any more about psychological and/or neurological processes than earlier versions of dynamical systems models that ignored intentionality. As the primary aim of ecological psychology has been the identification of perceptual and coordination principles that apply across levels of description, little attempt has been made to link the observed variables to underlying physiological mechanisms. The real challenge facing ecological psychology is to map the dynamical descriptions onto neural correlates—that is, to show how the proposed organizations can be realized physiologically, and what variables are used by the central nervous system to control and coordinate movements. A major advance in this line of inquiry has been the recent work showing that dynamic phenomena, such as phase transitions, are also observed in brain activity (e.g., Fuchs, Kelso, and Haken 1992; Wallenstein, Nash, and Kelso 1995). Examination of changes at both the spinal and supraspinal levels during the development of coordination would seem to be a fruitful area for future research.

Finally, to achieve the aims outlined, it is clear that the future development of ecological psychology must be an interdisciplinary effort (Schöner 1996). As Beek, Peper, and Stegeman (1995) emphasize, the language of dynamics is ideally suited to the linking of phenomena at different levels of observation. That is, the abstract nature of dynamical descriptions makes them applicable across all levels of description including between-person coordination, perception-action coupling, intra- and interlimb coordination, and brain activity at various levels of description.

Conclusions

It is now some 20 years since ecological psychology offered a radically differ approach to the study of motor behavior. In this chapter I have tried to evaluate progress the approach has made toward an all-encompassing theory of percept and action. In this sense the review has been deliberately critical, and it is knowledged that many of the criticisms leveled at the ecological psychology proach apply equally well, if not more so, to motor programming approaches motor behavior (e.g., see Morris et al. 1994). Furthermore, it is clear that trem dous progress has been made by the ecological psychology approach in the development; and excellent recent reviews of some of these accomplishments c be found in Beek, Peper, and Stegeman (1995), Kelso (1995), and Turvey (199

As to the question posed in the title of this chapter, the answer must be that the approach is still very much in its infancy, it is too early to determine whetl ecological psychology will be able to provide the promised integrative view motor control and learning. Thus the present review may be seen as overcritical that some of the issues raised are being dealt with now or have yet to be systema cally addressed, while other issues are not seen as important within the theoreti framework. To their credit, leaders in the field have emphasized that the approa should not "try to run until it first understands clearly how to walk." The hon moon period, however, is now over, and it is time for theorists to advance beyo the metaphorical descriptions that have typified the approach to date. Finally, Michaels and Beek (1996) suggest, the direct perception, thermodynamics, a pattern dynamics perspectives must eventually come together. It is likely that t unification of the three perspectives into a single coherent account is necessary the original aims of the ecological psychology approach, as expressed by Kugl Kelso, and Turvey (1982), are to be realized.

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CHAPTER 20

Replies to J.J. Summers: Has Ecological Psychology Delivered What It Promised?

Commentary 1: Programming or Planning Conceptions Motor Control Speak to Different Phenomena Than Dynamical System Conceptions

Steven W. Keele

A considerable gulf separates those who think about motor control in terms "motor programs" or planning and those who think about motor control in ten of dynamical systems or in terms of somewhat correlated issues such as ecologic psychology. What is perhaps not frequently considered is that the gulf is due le to competing conceptions for the same phenomena than to the kinds of phenoı ena with which different groups of investigators are concerned.

Although not exclusively, investigators of a dynamical systems persuasion ve often are concerned with movement processes per se and most often with mov ments that repeat periodically. In the natural domain, locomotion may be consi ered a paradigm case. In the laboratory domain, back-and-forth movements fingers or arms may be studied. One presumes that the "finger-wagging" expeı ments are a model task intended to uncover principles that would apply to natur tasks like locomotion.

The focus in many of the studies that take a programming or process decomp sition view comes instead—at least for me—from a concern with a rather differeı class of skills and with skills that exhibit quite different phenomena. These skil include such things as keyboard skills, phoneme sequencing in speech, and th assembly of a set of actions as in woodworking. Some sequential skills occur even a higher level of organization, such as preparing for work by first turning o the coffee pot, brushing the teeth, showering, and dressing. A major aspect of suc skills is that although elementary motor acts may occur more than once in a strin of events, each event typically is different from the preceding, and when repeti tions occur they occur in nonperiodic forms. In typing the word "psychology," fc example, one finds that most of the letters are different from one another.