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Human Movement Science 19 (2000) 407–423

HUMAN  
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## Debates in dynamics: A dynamical systems perspective on action and perception

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### Abstract

Since the seminal publication by Kugler, Kelso and Turvey (1980), which formulated an agenda for understanding movement coordination based on the merging of Bernstein's insights and modern nonlinear dynamics, and since the classic results on phase transitions in rhythmic bimanual coordination the dynamical systems approach to action and perception has made considerable progress. The special issue collects research presented in a 3-day workshop "Debates in Dynamics" that portrays recent advances in the dynamical systems account to perception and action. As reflected in the wide spectrum of themes, the dynamical systems account has clearly diverged in the issues it addresses, in the levels of analysis, and in the formal concepts and tools it applies, without losing its common thread of convergent assumptions and language. © 2000 Elsevier Science B.V. All rights reserved.

*PsycINFO classification:* 2330; 2326

*Keywords:* Dynamical systems; Perception and action; Motor control

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It is now more than 20 years ago that a group of researchers was formed at Haskins Laboratories and the University of Connecticut that led to the

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development of a new paradigm in the field of motor control. Looking back to this period, the word *paradigm* indeed appears appropriate, even when used in the strict Kuhnian sense, as these early studies which initiated the “dynamical systems approach to action” clearly broke with mainstream research and formulated new theoretical and experimental problems. It began with the rebellious rejection of the “computer metaphor”, the too literal translation of concepts from the theory of information processing to perceptual, cognitive, and motor processes in the biological nervous system (Turvey, 1975). The signs for an alternative approach to the control of action were set as early as 1977, when Turvey integrated and adapted a host of thus far unappreciated literature and prepared the scene for a new formulation of the problem of perceptual-motor control (Turvey, 1977a,b; Turvey, Shaw & Mace, 1979). The notion of synergies figured as a pivotal concept to address Bernstein’s problem of the degrees of freedom (Bernstein, 1967). Another early example of an extensive re-interpretation of coordination and skill can be found in Fowler and Turvey (1978). I use the word *extensive* because most of these concepts have become almost mainstream by now and a reference to Bernstein in publications on movement coordination has since become almost obligatory or redundant.

After having laid out the problem and questions, it was experiments and formalization that were needed to further substantiate these ideas. A theoretical language was found almost simultaneously in the burgeoning field of nonlinear dynamics which experienced a rapid development since the 1970s, extending from its early foundations laid by Poincaré (1899) and a large body of work done during the first half of the century. Early inspirations for researchers in movement coordination came from the theoretical subfields of homeokinetics by Yates and Iberall, of nonequilibrium thermodynamics by Prigogine, of synergetics by Haken, and of catastrophe theory by Thom (Haken, 1977; Iberall, 1972; Prigogine, 1976; Prigogine & Nicolis, 1972; Thom, 1970, 1972; Yates, 1978, 1982; Yates, Marsh & Iberall, 1972). In 1980, the seminal publication by Kugler, Kelso and Turvey appeared that set the agenda for the dynamical systems approach to action which was based on the merging of Bernstein’s insights and the emerging field of nonlinear dynamics (Kugler, Kelso & Turvey, 1980). With a tutorial-like covering of the main concepts the authors argued that phenomena in biological systems, which thus far could only be attributed to intentional control, should be interpreted as regularities of nonlinear dynamical systems. The stage was set for the following experimental work: the involuntary transitions in the rhythmic coordination of two fingers from

antiphase to in-phase have become the textbook example for the dynamical systems approach to action by now (Kelso, 1984). The modeling of this empirical observation as nonlinear coupled oscillations and, specifically, the rendering of the transition in terms of order parameter dynamics has brought Haken's synergetics to the forefront in movement science (Haken, 1977, 1983). Since the classical work by Haken, Kelso and Bunz (1985), the collective variable relative phase between two or more limbs has become a widely used dependent measure for rhythmic coordination. A host of studies on rhythmic interlimb behavior followed and the theory of coupled nonlinear oscillators has shown to provide a robust framework for modeling transitions and steady states in rhythmic interlimb coordination (for overviews see Amazeen, Amazeen & Turvey, 1998; Beek, Peper & Stegeman, 1995; Haken, 1995; Kelso, 1995).

Where is the dynamical systems approach to action and perception 20 years later? Since these classical studies of the 1980s, the experimental and theoretical work has progressed a long way. Many lines of research have arisen that pursue the thesis that the properties of high-dimensional multi-level nonlinear systems are functionally important and that their recognition is necessary for the understanding of control of voluntary goal-directed movements. In parallel, nonlinear science has also grown rapidly, both in the basic disciplines as well as in their applications, and developed more tools and techniques to capture properties of nonlinear systems. While many studies of the 1990s on rhythmic interlimb coordination followed in the footsteps of the pioneering work which was inspired by synergetics (Haken, 1977, 1983), other lines of research have developed since that have come from different backgrounds and addressed other movement phenomena and consequently employed other modeling techniques. Nonlinear time series analysis has become a frequently used tool to reveal regularities in time series (e.g., Dingwell, Cusumano, Sternad & Cavanagh, 2000; Kay, 1988; Newell, Slobounov, Slobounova & Molenaar, 1997), group theory has been invoked to understand the different locomotory patterns (Collins & Stewart, 1993; Schöner, Jiang & Kelso, 1990), and nonlinear mechanical models have captured a perceptual-motor task (Sternad, Duarte, Katsumata & Schaal, 2000) – to name only a few. Given this diversification of questions and tools, the question arises what is comprised by “the” dynamical systems approach 20 years after its inception?

In August 1999, a small group of researchers came together in a four-day workshop “Debates in Dynamics” held at The Pennsylvania State University to discuss recent developments and challenges for a dynamical systems

account to perceptual motor control.<sup>1</sup> This special issue is the result of this workshop and it aims to portray some recent advances in the dynamical systems perspective, both in their convergent assumptions and in their divergent routes. Truly reflecting the interdisciplinary nature of this approach, the 10 participants came from a wide range of disciplinary backgrounds, including psychology, kinesiology, physics, computer science, physiology, music, and linguistics, both experimentalists and theorists. And yet, as the contributions of this issue reflect, the concepts and language of nonlinear science provide a common thread. As is evident from the contents of this issue, the research themes represented by the participants ranged from the nature of control schemes in postural control to the bridging between brain and behavioral phenomena, from spinal control modules governing multi-joint movements to the localization of bimanual coupling in the cortico-motoneuronal pathways, from the perception of metric structure in music to the modeling of temporal regularities and variability in speech utterances, from the interrelation of translatory and cyclic elements in complex behavioral sequences to intrinsic constraints that break the symmetry in bimanual actions. What in this broad spectrum has emerged as the convergent and divergent themes in the present selection of studies?

### **1. Extension of synergetic modeling: Identification of new control parameters**

In numerous studies on interlimb coordination, the so-called HKB model has served as the one representative example for the synergetic modeling approach (for overviews see Amazeen et al., 1998; Beek et al., 1995; Haken, 1995; Kelso, 1995). Essential for this formal approach is the distinction into order and control parameters, where relative phase between the oscillating units has served as the parameter capturing the order of the system. Thus far, the model has included two major control parameters: movement frequency has been mapped onto two parameters, the ratio of which acts as a bifurcation parameter and their modulation captures observed transitions from antiphase to in-phase, corresponding to the increase in oscillating frequency. Asymmetry in the eigenfrequency between the two oscillating units was the second, additive parameter for manipulating and modeling the dynamics of relative phase. More recently, Daffertshofer, van den Berg and Beek (1999)

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<sup>1</sup> The attendants of the workshop were: Richard Carson, Andreas Daffertshofer, Tjeerd Dijkstra, Armin Fuchs, Simon Giszter, Viktor Jirsa, Bruce Kay, Edward Large, Elliot Saltzman, and Dagmar Sternad. The workshop was organized by Dagmar Sternad, sponsored as a Fellow-at-Large of the Santa Fe Institute.

identified the ratio in amplitudes of two asymmetrical oscillators as another control parameter, and in the study of rhythmic visual tracking, Tass, Kurths, Rosenblum, Guasti and Hefter (1996) showed that the delay in the presentation of visual feedback acts as a control parameter inducing changes in the phasing of the tracking movement relative to the target signal.

A direct extension from the work on the HKB model for interlimb coordination is represented by the contribution of Fuchs and Jirsa. Their work was stimulated by challenging findings of Carson and colleagues, who manipulated neuro-musculo-skeletal constraints for two pronating and supinating hands and created scenarios where the classic antiphase to in-phase transition was reversed (Carson, 1996; Carson, Riek, Smethurst, Lison & Byblow, 2000). To account for these observations, Fuchs and Jirsa extended the HKB model to include a new control parameter that captured the symmetry of the two rhythmic units in the difference of their respective rotational axes. This theoretical extension not only accounted for Carson's observations but also provided a list of new qualitative and quantitative predictions that are experimentally testable and will, in turn, evaluate the correctness of their modeling assumptions. This linking of theory and experiment is an exemplary demonstration of how experimental and theoretical work go hand in hand to further explore principles of movement coordination.

## **2. Bridging levels of analysis: Neurophysiological underpinnings of bimanual coupling**

Carson's work that was initially a direct continuation of Kelso's behavioral account of bimanual coordination is now branching into other levels of analysis. An explicit concern in Carson's more recent work is to integrate the study of phenomenological principles, as primarily addressed by the pioneering work using dynamical modeling, with the biological and physiological sciences that traditionally have had a more reductionist strategy, and focused on revealing structures and mechanisms responsible for certain functions. Using the same pronation/supination wrist and forearm movements as in their previous behavioral work, Carson and Riek now ask whether such ongoing movements and their biomechanical configurations influence the excitability of descending pathways via their changing effect on peripheral afferent input. Motor potentials evoked in the stationary hand by transcranial magnetic stimulation exhibit amplitude modulations that are directly proportional to the mechanical context of the simultaneously rhythmically moving hand. The

location of the external axis of rotation is also manipulated as in a previous study (Carson et al., 2000). The excitability of the descending pathways from higher motor centers to spinal motoneurons depends in part on the level of activation of the contralateral limb. This result is interpreted as an expression of the degree of coupling between limbs. This work is an example of how an existent experimental task can become a platform for asking further-reaching questions: the well-documented oscillatory movements become a window to understanding neuronal mechanisms underlying the behavioral level.

The bridging of levels of analysis has become a theme that also pervades a number of other lines of research (Fuchs, Kelso & Haken, 1992; Kelso, Fuchs & Jirsa, 1999). The article by Daffertshofer et al. (1999) represents a series of studies performed at the Free University of Amsterdam that continues previous work on polyrhythmic tapping (e.g., Peper, Beek & van Wieringen, 1995a,b,c) but furthermore attempts to merge behavioral observations with magneto-encephalographic data of brain activity. Constraints evident in the coupling of two hands when tapping at two different frequencies have already been addressed with an extension of the original HKB model (Haken, Peper, Beek & Daffertshofer, 1996; Peper & Beek 1988; Sternad, Turvey & Saltzman, 1999). Now, Daffertshofer et al. (1999) attempt to specify the explicit functional form of the coupling and to seek parallel signatures in the concomitant cortical signals, analyzing the spatio-temporal activity patterns found in both hemispheres in parallel with behavioral data. However, in the pursuit to extract significant features in the MEG signal that are indicative of cortical interactions, new methodological problems arose that required the development of new measures. Consequently, Daffertshofer et al. (1999) propose a new cross-spectral measure that allows for the determination of frequency-locked areas in spatio-temporal MEG signals in the presence of rather complicated spectral distributions. In addition, a closed mathematical description is sought that combines the macroscopic pattern formation at the behavioral and the cortical level. In resolving such methodological and theoretical problems, this study demonstrates the challenges in relating mathematical model, behavioral data, and brain data and, specifically, how new questions in coordination necessitate the development of new analysis techniques.

### **3. Temporal patterning and variability in rhythmic coordination**

The issue of multi-frequency coordination is further pursued in the contribution by Saltzman and Byrd who address the theoretical problem of  $n:m$

coordination together with another predominant theme in the nonlinear dynamics literature: the modeling of variability (Newell & Corcos, 1994). Two coupled rhythmic units not only have the tendency to produce an isochronous pattern (1:1), they also exhibit more complex harmonic (1: $n$ ) or polyrhythmic ( $n$ : $m$ ) relationships. Saltzman and Byrd's system of interest is the articulatory coordination in speech production, but the principles and modeling technique are germane to both speech and manual tasks. The temporal patterning of speech is understood as the creation of temporal order over increasingly extended and nested time spans: speech gestures are nested within syllable cycles, and in turn, syllable cycles are nested within cycles defined according to stress groups. This nesting into repetitive groups yields stable isochronous and poly-rhythms with various frequency ratios and relative phases, that is stable patterns that are characteristic for coupled nonlinear oscillations. The second empirical observation is that relative phase across articulatory gestures is not punctate, i.e., fixed to single target values, but variability is constrained to fall within an admissible range or *phase window* (Byrd, 1996). Both phenomena are addressed in Saltzman's task dynamical approach which consists of a two-layered modeling, where a set of two coordinate systems (component and task coordinates) are linked (Saltzman & Kelso, 1987; Saltzman & Munhall, 1989). Specifically, the authors model variability by means of a "flat" potential function, such that relative phase values can have a continuous, but not uniform distribution within a specified range. Simulations exemplify how final phase relationships can reside within a range of values but how they also depend on initial conditions and start-up transients. This approach provides an alternative to previous mathematical treatments in the motor control literature that have applied nonlinear dynamical systems theory and that are restricted to the production of punctate relative phasing patterns (e.g., Schöner, Haken & Kelso, 1986). Uniformity of results across manual and speech tasks suggests that a common dynamical structure underlies the production of these temporal patterns and thereby demonstrates the generality of this modeling approach.

#### **4. Networks of oscillators for the perceptual and motor synchronization to complex musical rhythms**

From the very inception of the dynamical systems approach the issue of how movement coordination is constrained by perceptual information was at the core of theorizing (Turvey, 1977b). A major driving force in formulating

the problem of the organization of goal-directed actions was, next to Bernstein's insights into coordination, Gibson's postulate that information must be meaningful and must specify action *directly* without mediating complex cognitive computations (Gibson, 1966, 1979). What therefore needs to be uncovered in the study of perception are parameters that encapsulate information from the complex perceptual array in a low-dimensional fashion. Perceptual information should be *functionally* specific and not necessarily isomorphic with physiological or first-order physical properties of the perceptual array (for a recent discussion of specificity see Stoffregen & Bardy, 2001). Adopting this point of view such perceptual parameters have been equated with behavioral information formulated in the same type of variables as the action variables such that they can modify the order parameter dynamics (e.g., Schöner & Kelso, 1988). While these Gibsonian postulates have been successfully explored for many domains of perception, ranging from perception of pictorial information to passable width, these studies all too often still remain within their traditional disciplinary boundaries of a psychology of perception. The explicit and quantitative link to measured action variables is often missing. Given the centrality of the original tenets, more studies are needed that relate perception with action data. The contribution of Large in this issue takes up this challenge.

How do we perceive and synchronize our movements to complex musical rhythms? Large proposes that the perceiver is endowed with a network of coupled oscillators representing the range of periods that humans can discriminate and entrain with. Metric structure in the musical score induces activation of oscillators of matching periods. Mutual inhibition and weighting amongst the array of oscillators ensures that only the most salient beats are accentuated. Given that psychological processes, such as differential attention to strong and weak beats are of interest, the individual oscillators explicitly refrain from capturing physiological or mechanical processes, but are formulated in so-called normal form. This mathematical description of Hopf oscillators constitutes the most generic level of description of an oscillation. Its advantage is that, apart from its analytical tractability, it keeps the number of parameters within reasonable limits. To test the model's performance, a musical score is presented as stimulus to both the model and musician subjects who are asked to tap to the beat. Various degrees of informational complexity are presented and performances of the model's beat induction and of musicians tapping to a complex musical score are compared. Performance and degradation of performance of the model with increasing complexity is indeed comparable to real tapping data. By making the

explicit link with experimental results on human performance, that work constitutes an example of how perceptual work can be bridged to empirical data on action. Using a dynamical model that explicitly instantiates the assumed perceptual and attentional processes, hypotheses on perceptuo-motor processes can be tested quantitatively by comparing simulated to real data.

A second contribution in this issue exemplifies how the integration of perceptual variables into models on action can facilitate and improve our understanding of action. Dijkstra presents a dynamical set-point model in which he captures three phenomena typically found in postural control: (1) During upright posture a variety of studies agree that the migration of the center of pressure displays larger fluctuations without visual anchoring (e.g., Dijkstra, Gielen & Melis, 1992). (2) Perceptually perturbed stance is phase-locked to the perturbing frequency and shows systematic leads and lags as a function of the frequency (e.g., van Asten, Gielen & Denier van der Gon, 1988). (3) The migration of center of pressure happens at minimally two time scales (e.g., Gurfinkel, Ivanenko, Levik & Babakova, 1995). Dijkstra suggested a dynamical set-point model consisting of two components, the movements of the upright around an equilibrium point and an additional first-order dynamical equation for this equilibrium- or set-point. The set-point dynamics capitalize on deviations from the vertical coupled to positional information about the vertical. The model can predict a dependence between the natural frequency of the postural system and the position coupling of the damped spring model. Assuming strong coupling to static haptic information and weak coupling to visual information, the empirical data from visually and haptically perturbed stance indeed follow these predictions. Interestingly, including the second degree of freedom of a set-point dynamics, the perceived vertical effectively injects low-pass filtered noise into the dynamics of the upright and produces the second time scale in the observed fluctuations. The study thereby exemplifies how integrating sensory information into modeling action dynamics can provide further explanation for a phenomenon that has already given rise to different interpretations when only action was considered.

One further comment seems warranted: Dijkstra's model is called a *dynamical set-point model*, indicating its control theoretical influence. In fact, the deterministic part of the model is mathematically equivalent to a proportional integral derivative (PID) controller. This partial formal equivalence suggests that the dynamical systems approach and the control theoretical approach to motor control are not as distinct as has often been pictured in the motor control literature (for a recent contrast see Piek, 1998; Sternad, 1999). Indeed, some dynamical models allow for a control theoretical

interpretation, as exemplified in Dijkstra's postural modeling (Pressing, 1998, 1999; Schaal, Kotosaka & Sternad, 2000a,b).

### **5. Synergies as spinal modules or pattern generators with point attractor or limit cycle dynamics**

One pivotal theme in Turvey's *Preliminaries to a theory of action* was the assembly and the tuning of muscle synergies (Turvey, 1977a,b; see also Greene, 1972; Kugler & Turvey, 1987). While this concept is intuitively appealing, it has remained a challenge to identify such synergies and to specify the postulated low-dimensional tuning. An example that inspired further thinking were the classic studies by Feldman in which he laid the foundation for the equilibrium-point hypothesis (Feldman, 1966a,b). The control signal sets the equilibrium point by means of low-level neuromuscular mechanisms and kinematic and kinetic trajectories are the resultant consequences. In a similar vein, Shik and Orlovskii's early empirical findings on the locomotory patterns in the spinalized cat gave support to the existence of relatively autonomous synergies organized at the spinal level (Shik & Orlovsky, 1976; Shik, Severin & Orlovskii, 1966). While the concept and these findings are appealing and intuitive, further elaboration in terms of a structural or formal definition of the *tuning of synergies* has remained elusive. A reflection of its problematic nature is that several labels have been introduced to guide and clarify thinking about synergies: coordinative structures (Easton, 1972; Shik et al., 1966; Tuller, Turvey & Fitch, 1982), dissipative structures (Kugler et al., 1980) or dynamic patterns (Kelso, 1995) (for a discussion of the name synergy and its interpretations see also Latash, 1999).

Two articles in this issue can be seen as directly taking up this challenge. Giszter's work on the spinalized frog is, in the broadest sense, in the tradition of the equilibrium point hypothesis. In a series of studies published over the past 10 years together with Bizzi and Mussa-Ivaldi, equilibrium-point properties have been identified in the leg movements of spinalized frogs (Bizzi, Accornero, Chapple & Hogan, 1984; Giszter, Mussa-Ivaldi & Bizzi, 1993). Microstimulation of the lumbar area of the frog's spinal cord or skin irritation produced (isometric) forces measured at the fixated ankle that suggested that there are few modules in the spinal cord used for such spinally elicited movements. Importantly, these force fields were only few and they were convergent such that they showed a single equilibrium point. Interesting for further speculation was the empirical and formal analysis that these few fields in superposition

were a viable way of decomposing and constructing new trajectories (Mussa-Ivaldi, Giszter & Bizzi, 1994). Even online adjustments could be understood as sums of force-field primitives (Kargo & Giszter, 2000). Clearly, this approach is one answer to the degree of freedom problem, in that such primitives may bootstrap the development of new behaviors. The present work extends this methodology: microstimulation is applied to the lumbar area of the spinal cord, which is topographically mapped in 3D. Forces and torques produced at the endpoint, hip and knee of the 4-DOF two-link system are measured in three-dimensional extrinsic space, in conjunction with measurements of the EMG activity of 11 muscles. In line with previous findings, there is evidence for the modularity of spinal cord function. The strongest forces measured at the endpoint are limited to only a few movement directions, and their distribution is clustered around a few magnitudes. Support for a spinally modularized organization of multi-joint synergies is found in torque patterns that comprise both pure hip torques and combined multi-joint knee/hip torque patterns including bi-articular muscles, but no pure knee torques. In sum, the guiding thought is that novel and adaptive behavior must be constrained by so-called *movement primitives* originating in the spinal motor apparatus.

Also the final study in this special issue by Sternad and colleagues proposes dynamical principles for synergy formation. The hypothesis is that single- and multi-joint movements can be understood in terms of two fundamental classes of synergies: discrete movements and rhythmic movements. These two *units of actions* are mapped onto fixed point and limit cycle dynamics as they constitute the two primary stable regimes in a nonlinear dynamical system. A model consisting of two separate pattern generators with fixed point and limit cycle dynamics is developed that produces rhythmic and discrete movement trajectories with features characteristic for human movement. It is assumed that these two regimes are two distinct patterns that can exist in isolation or in interaction in more complex behavioral tasks. In other words, it is principles of nonlinear dynamical systems that organize the musculo-skeletal system around the biomechanical degrees of freedom into stable synergies. The experiment that provides first empirical data for the modeling is a single-joint elbow movement consisting of a discrete angular displacement perturbing an ongoing rhythmic movement in the same joint. Perturbation analysis identifies the mutually constraining interactions between the two pattern generators which is captured by a reciprocally inhibitive coupling. In contrast to Large's work on perceptual oscillations, which opts for a more abstract rendering of oscillations, the authors chose a model with variables that are inspired by the half-center oscillator concept, originally proposed in the

neurophysiological literature (Brown, 1914) and modeled by (Matsuoka, 1985, 1987). This work also aims to bridge the gap between those lines of research that pursue either rhythmic or discrete movements, conveying the (misleading) impression that respective theorizing is limited to either one of the movement types. It also raises the challenge for dynamical modeling approaches that still predominantly address rhythmic phenomena, with a few exceptions (Schöner, 1990, 1994; Sternad, Saltzman & Turvey, 1998).

## 6. A paradigm developed

Having outlined the dominant themes in this array of studies, let's return to the initial question: what is *the dynamical system approach to action and perception* and where is this approach now, more than 20 years after its inception? The paradigm had a clear beginning marked by a set of fundamental theme papers. At its core were the postulates that an account of action has to be ineluctably coupled to perception, and that perceptual control of movements is governed by physical principles, specifically those of nonlinear dynamical systems. This framework was sharply contrasted against the then mainstream cognitive or information processing approaches in the perception and the motor behavior literature. In 2000, the delineation of the dynamical systems approach is no longer so straightforward, as may have become evident from the overview above.

The *Debates in Dynamics* workshop assembled a group of researchers who can be regarded as representatives of the dynamical systems approach. Yet, their themes and modeling approaches cover a wide spectrum. The selection of studies make obvious that the dynamical systems' perspective has drawn its roots from several traditions of research: (1) The neurophysiological work on *central pattern generators* has clearly provided a conceptual parallel and empirical support for the behavioral approach to rhythmic interlimb coordination. The parallels have become explicit when oscillator models were formulated to account for the rhythmic intersegmental coupling, as for instance seen in the undulations of the lamprey (Kopell, 1988; Kopell & Ermentrout, 1988). (2) Similarly, the *equilibrium point hypothesis* can be viewed as a related theoretical framework, as is most evident in Giszter's work. Clearly, an equilibrium point is a fixed point attractor, although the conceptualization and experimentation have been conducted at the neurophysiological level and the language of nonlinear dynamics and its modeling have not come to the forefront in this literature. (3) Even *control theory* should no

longer be viewed as entirely distinct from the dynamical approach to action. As recently argued by Pressing, and as hinted at in Dijkstra's work, the dynamical systems approach and control theory are formally close, although differences may still reside in the interpretation (Pressing, 1998, 1999).

A merging of the dynamical systems approach with other research traditions has also come about in the reverse direction. Researchers with clearly different theoretical and disciplinary histories have adopted concepts and proposed “dynamical interpretations” of their findings that were originally germane to proponents of the dynamical systems approach. This trend is visible in “cognitive psychology”, where for instance memory processes have been captured in the structure obtained from nonlinear time series analyses (Gilden, Thornton & Mallon, 1995). A long-studied “cognitive” phenomenon in infants, the so-called A-not-B error, has found a dynamical interpretation (Thelen, Schöner, Scheier & Smith, in press). For a discussion of the dynamical hypothesis in cognitive science see van Gelder (1998). In robotics, the archetypal area of control theory, researchers have started to explicitly adopt dynamical systems as part of their control mechanisms. Brooks (1991) has been a long-standing spokesman of dynamical principles for the control of autonomous artificial systems. A good example for how oscillators are used to generate rhythmic bimanual actions in artificial systems can be seen in Williamson (1998). Schaal et al. (2000a,b) include rhythmic pattern generators for the control of a humanoid robot performing bimanual drumming movements. Finally, neuronal interactions have been modeled with dynamical systems and the field of neural networks can be regarded as the high-dimensional parallel to the low-dimensional approach that has most frequently been adopted in the movement literature (Wang & Blum, 1995; Wang & Rinzal, 1995). Thus far, there are only a few examples, where network modeling has inspired the formalization of movement phenomena (Saltzman & Mitra, 1998; Zatsiorsky, Li & Latash, 1998).

In the light of all these converging and diverging streams of research, it appears that the paradigm has lost its contours. Yet, this is by no means a shortcoming – rather, it signals the appeal and success of these ideas. Concepts of nonlinear systems have penetrated almost every strand of science, as can be for instance seen in the *Science* issue of April 1999, which surveys recent empirical and theoretical approaches to complex systems, ranging from geographic, economical to biological signaling systems.

In movement science, similarly, the paradigm of the dynamical systems approach has spread. Following Kuhn, we may say that the paradigm has entered its mature stage.

In finishing, I would like to thank the reviewers who helped to make this special issue possible and who clearly improved the presented work by their constructive criticism: Fausto Baldissera, Daniel Bullock, Joseph Cusumano, Marcos Duarte, Anatol Feldman, Hermann Haken, Art Kuo, Mark Latash, Gottfried Meyer-Kress, David Ostry, Jeff Pressing, Bruno Repp, Gregor Schöner, Stefan Thurner, Ken Yoshida, and Vladimir Zatsiorsky.

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