Hot Topics in Motor Control and Learning

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A Dynamic Systems Perspective to Perception and Action

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Theoretical Lines of Convergence

In 1980 Kugler, Kelso, and Turvey published the seminal article "On the Concept of Coordinative Structures as Dissipative Structures. I. Theoretical Lines of Convergence." As suggested in the subtitle, the authors laid out how Bernstein's insights into movement coordination have converged with progress in the theory of nonlinear dynamics. The concept of "coordinative structures" which had been the key term coined for the reconceptualization of coordination, as proposed by Turvey and colleagues, was therefore programmatically changed into "dissipative structures" (Tuller, Fitch, & Turvey, 1980; Turvey, Shaw, & Mace, 1978). This term, borrowed from nonequilibrium thermodynamics, refers to systems in which energy is not conserved (i.e., energy is dissipated and, unless the system comes to rest, nonlinearities within the system give rise to continuous energy in- and outflow).

The motivation to interpret perception-action systems as dissipative systems has arisen from an integration of Gibson's ecological psychology and Bernstein's work on coordination, promoted by Turvey, Shaw, and Kugler (Kugler, Kelso, & Turvey, 1982; Shaw & Turvey, 1981; Turvey, 1977). The major tenet of ecological psychology is the irreducible mutuality between perceiving and acting, and between the actor and environment (Gibson, 1979). In his rejection of cognitive processing of information, Gibson postulated that biological systems directly perceive information that is functionally specific to their actions. Kugler and Turvey continued to develop the concept of information as specified by a low-energy force field which directly shapes the actions of a biological system. Similarly, movement coordination should not to be understood as governed by a "homunculus," commanding the musculoskeletal links. Coordination is a complex but orderly system in which energy flows and rate-dependent processes lead to form and function (i.e., coordinated behavior). Evidently, this view rejects an anthropocentric world view in exchange for one in which physical laws determine orderly behavior. With nonlinear dynamics emerging as the new discipline for understanding such laws in complex systems, the undertaking transgresses the boundary between living and nonliving systems. Spiral waves in chemical systems and convection rolls in viscous fluids are taken as the paradigmatic examples revealing the essential phenomena that nonlinear systems can display: stable, attractive behavior that is resistant to perturbations, discontinuous phase transitions resulting from continuous change in parameters, hysteresis, and many other features (Haken, 1977). What was formerly deemed unpredictable or purely cognitively controlled behavior now promised to be understood by an entirely deterministic, albeit nonlinear system.

A First Empirical and Theoretical Focus: Rhythmic Interlimb Coordination

In adopting this approach, the study of behavioral phenomena has become part of the physical sciences. Behavioral phenomena can now be cast into mathemati-
cral language that offers a precise approach and allows unambiguous and testable predictions. The first seminal study establishing a direct link between empirical data and a formal model derived from synergetics was the rhythmic two-finger coordination task that displays phase transitions (Kelso, 1984). The spontaneously occurring transition from antiphase to inphase coordination mode as a function of movement frequency provided the first example demonstrating that movements can be understood in terms of coupled nonlinear oscillations (Haken, Kelso, & Bunz, 1985). Subsequent studies expanded on this approach, showing that these transitions were accompanied by enhanced fluctuations prior to transition and that switching time between modes is a function of relative attractor strength (Kelso, Scholz, & Schöner, 1988). Many more investigations followed, published not only in the journals of movement science but also in physics demonstrating the impact these findings also have to the physics community. Since these first path-breaking steps, many studies continued to focus on the phenomenon of synchronization between two or more limbs. Coupled oscillator models were developed to demonstrate that stable rhythmic performance can be interpreted as a stable limit cycle regime (e.g., Kay, Kelso, Saltzman, & Schöner, 1987). The paradigm of single- and two-handed wristpendulum oscillations explored issues of asymmetry in the coordinated limbs (e.g., Sternad, Turvey, & Schmidt, 1992). Even synchronization between people only coupled by visual contact obeyed the same laws as synchronization between physically coupled limbs (Schmidt, Carello, & Turvey, 1990).

While this body of empirical research has had considerable impact, critics have increasingly raised concerns that perceptual control of movements embraces more than just interlimb coordination. Objections were raised that nonlinear dynamics can only account for stable rhythmic behavior and is unable to address equally fundamental issues such as discrete movements, the sequencing of movements, intentional aspects and, in general, more complex movement skills. Often overlooked is the fact that besides the overwhelming number of studies on bimanual coordination in the laboratories of Kelso and Turvey, many other lines of research have started to develop. By now, the potential of nonlinear dynamics has been recognized outside the ecological community, and many other branches in the psychology and life sciences have utilized the tools as well as adopted the arguments. Table 1 gives an overview of major research lines addressing questions in the perceptual control of movements other than 1:1 rhythmic interlimb coordination. A primary criterion for selection was that studies should include and explicitly develop the formal tools from nonlinear dynamics in conjunction with empirical data.

In the following, I will address two more fundamental concepts in motor control research and highlight how such old themes may be understood in the new light of a dynamic systems account. I will address the two topics of motor equivalence and interindividual differences and show how topological orbital equivalence offers a formal tool to: (1) examine different movement realizations for their underlying equivalence and, (2) show how interindividual differences may be understood as realizations of the same underlying dynamic regime. Results on dynamic stability in the performance will precede it, as they are prerequisite information for the topic in focus. In doing so, emphasis is also given to laying out the methodological strategy that a dynamic modeling account provides.

**Rhythmic Bouncing of a Ball on a Racket**

The model task is to bounce a ball rhythmically with a racket, as can be done with a tennis racket (see Figure 1). Participants were instructed to keep the ball’s amplitude as invariant as possible. This motor task poses an archetypal perception-action problem in that the hand’s movement has to be synchronized with the ball’s trajectory. To achieve a specific ball amplitude, the racket has to impact the ball with the right velocity. To control the hand’s or racket’s movement, the actor requires perceptual information about the ball trajectory as well as his or her own hand and arm movements, which will again lead to the next perceived ball trajectory. This task is essentially rhythmic and stable, and, as such, lends itself to modeling as a dynamic system at equilibrium. In the chosen modeling strategy, the task is reduced to its central component: a planar surface performing periodic vertical motions bouncing a ball vertically in a rhythmic fashion (see Figure 1). The movement of the surface is the resultant of the effector-racket movements. Ball and racket’s trajectories are confined to one vertical dimension, and the impact position is specified neither in model nor experiment.

Assuming arbitrary periodic motion of the surface together with the laws of ballistic flight and elastic impact for the ball, a discrete impact map for ball and racket movements is derived (Schaal, Sternad, & Atkeson, 1996; Sternad, Schaal, & Atkeson 1995):

\[
\begin{align*}
\dot{x}_{n+1} &= -\sqrt{1 - \alpha^2} \left( x_n + \alpha x_{n+1} \right) + 2g (x_n - x_{n+1}) \\
\dot{x}_{R,n} &= x_{R,n+1}
\end{align*}
\]

(1)

where \( t_n \) results from:

\[
-\frac{1}{2} \dot{x}_{n+1}^2 + \left( (1 + \alpha) \dot{x}_{n+1} - \alpha \dot{x}_n \right) t_n + \left( x_n - x_{n+1} \right) = 0
\]

\( t_n \) denotes the times at successive impacts \( x_R, x_{R+1}, \dot{x}_R, \dot{x}_{R+1} \); \( x_R, x_{R+1} \) are the vertical positions and velocities of racket and ball at the \( n \)th ball contact, \( \alpha \) is the coefficient of restitution, and \( g \) is the gravitational constant.
Stability and Variability of Performance $\dot{x}_R \in [-g, 0]$

The model system is dissipative due to the energy loss expressed by the coefficient of restitution $\alpha$, and it is highly nonlinear mainly due to the square root function. Hence, it is expected that it displays stable attractive regimes, and stability analyses can be performed. Applying a local linear stability analysis identifies that the acceleration of the racket at impact $\dot{x}_R$ completely determines the stability characteristics of the ball’s trajectory. Importantly, stable solutions with invariant ball amplitudes can be limited to the condition where $\dot{x}_R \in [-g, 0]$. Figure 2 shows a set of three simulations using Equation (1). Panel 2a shows a set of 15 slightly different initial conditions for a positive $\dot{x}_R$ whose ball trajectories increasingly diverge over the course of the 13 impacts. The system is sensitive to initial conditions and therefore unstable. Panel 2b displays the same simulation, but $\dot{x}_R$ was set to zero. Initial differences are maintained and the system is said to be neutrally stable. Finally, panel 2c illustrates stable behavior where different initial conditions converge to the one stable periodic ball trajectory. This kind of performance implies that the system is resistant to small perturbations which die out by themselves.

Performing a different nonlocal, so-called Lyapunov analysis, the degree of stability can be differentiated across the wide range and maximal stability is identified for $\dot{x}_R \in [-3.5, -1.5]$ (for a more detailed account of the analyses see Schaal et al., 1996). The results on $\dot{x}_R$ of 6

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<td>Rhythmic bouncing of a ball</td>
<td>Kinematic modeling of basic nonlinear task mechanics, Lyapunov stability analyses</td>
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<td>Phase transitions formulated for field equations</td>
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<td>Finger tapping and long-range correlations reflecting memory and cognition</td>
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<td>Gilden, Thornton, &amp; Mallon, 1995</td>
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participants' performance gives evidence that participants indeed choose stable solutions. The average $\bar{x}_R$ of individual participants range between -0.54 m/s$^2$ to -8.94 m/s$^2$ but cluster around different preferred values. Importantly, adopting the stable strategy implies that small perturbations need no active corrections, as the coordinate regime is attractive and perturbations will converge back to the stable trajectory. This contrasts to dynamically unstable solutions where every deviation from the trajectory requires active correction, which is also possible, as some trials with $\bar{x}_R > 0$ show. The latter strategy is an “expensive” one which is also likely to lead to more variable solutions. Figure 3 shows mean $\bar{x}_R$ per trial for all 6 participants plotted against the standard deviations of $\bar{x}_R$. The standard deviations of $\bar{x}_R$ are used as an empirical analogue for the stability predictions from the Lyapunov analysis (denoted by the solid line). As predicted, participants cluster in the stable range of $\bar{x}_R$ and show least variability in the range of maximal stability.

**Motor Equivalence and Topological Orbital Equivalence**

A central concept in the theory of nonlinear dynamics is topological orbital equivalence which formalizes criteria for which one dynamical system can be continuously transformed into another. In other words, it determines transformations over an underlying invariant regime. As such, it is a close formal analogue to the empirical notion of motor equivalence which implies that an invariant and functionally equivalent outcome of a movement can be achieved by different neuromuscular or kinematical realizations. From Equation (1) a scaling relation can be extracted which formulates such a topological transformation identifying how the dynamical system of Equation (1) can be transformed into another with identical stability properties:

$$ x_{R,\text{amp}} / \tau^2 = \text{const} \tag{2} $$

$x_{R,\text{amp}}$ is the amplitude of the racket's trajectory, $\tau$, is the period between two successive impacts between ball and racket. In other words, Equation (2) expresses that if the racket's amplitude scales with the squared period, then different spatiotemporal solutions are variants of the same underlying dynamic regime.

To test whether the different solutions that participants chose to perform the task belong to one topologically equivalent family of solutions, the experimental task included the instruction to perform the rhythmic bouncing at three different amplitudes. Additionally, these trials were performed under two gravitational conditions.
one in which gravity was normal, $g_n$, and one in which gravity was effectively reduced by manipulating the ball suspension, $g_r$. Following Equation (2), $x_{\text{R,amp}}$ is regressed against $t^2$ to test for the predicted linear scaling relation (Figure 4 shows four exemplary participants). The linear regressions, performed separately for $g_n$ and $g_r$, obtained $r^2$ values between 92 and 99% and, therefore, provided evidence that different trials with different kinematic realizations obeyed the constant scaling. They can be regarded as topologically equivalent.

This analysis showed that racket trajectories from repeated performances which vary in their kinematic characteristics, specifically in their amplitudes and hence their periods, do not require a different underlying dynamic regimes. The advantage of this analysis is that it provides an explicit formulation of the nature of this equivalence lending itself to comparison with the data.

As long as racket amplitude and squared period scale proportionately, the systems are topologically equivalent and interpreted as satisfying motor equivalence.

**Interindividual Differences**

Despite the fact that participants display invariant spatiotemporal relationships across different bouncing heights, the individual participants visibly display differences in the actual slopes of the linear fits (i.e., the scaling constants of Equation 2). Do these differences finally reflect the unexplainable individual "choice," or can they be accounted for within the dynamic model? As reported above, the individual participants have individual "preferences" for $x_R$ values within the range of stable solutions. A simulation of Equation (2) shows that for different values of $x_R$, the linear scaling relationship results in lin-

![Figure 4](image.png)

**Figure 4.** Trial means of the racket's amplitudes $x_{\text{R,amp}}$ are regressed against the squared period $t^2$. The data were separated for the two gravity conditions, normal gravity $g_n$, and reduced gravity $g_r$. 

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ear relationships with different slopes (see Figure 5). Moreover, for each $\dot{x}_R$ the two gravity constants used in the experiment produces pairs of slopes that form different angles with each other. As shown in Figure 5, the difference in slope for a $\dot{x}_R = -1 \text{ m/s}^2$ for $g_\alpha$ and $g$ is progressively smaller than for $\dot{x}_R = -6 \text{ m/s}^2$. Comparing the individual participants’ $\dot{x}_R$ and their slope deviations between $g_\alpha$ and $g$ shows that, indeed, this individual instantiation of the scaling relation is directly constrained by the choice of $\dot{x}_R$. For instance, compare Participant 4 ($\dot{x}_R = -8.94 \text{ m/s}^2$) with Participant 2 ($\dot{x}_R = -1.91 \text{ m/s}^2$).

In summary, the dynamic model provides a basis that explains variations between individuals in their kinematic characteristics. An individual “choice” of the racket’s acceleration at impact, the critical variable $\dot{x}_R$, which is itself within the stable range as determined by the dynamic model, further determines variations over different instantiations. However, these variations are still highly constrained and can be shown to belong to the same underlying dynamic regime.

Conclusions and Outlook

The objective of the exemplary presentation of the study on rhythmic ball bouncing was to demonstrate that a nonlinear dynamic approach holds promise to shed some new light on old questions. Issues of stability and variability in performance are central in our basic and some new light on old questions. Issues of stability and predictions. Similarly, central issues in the domain of movement control are motor equivalence and interindividual differences—phenomena for which principled answers have been evasive. In the analysis of rhythmic ball bouncing, participants are shown to attune to the stability properties inherent in the dynamics of the task. The experimental results permit the conclusion that participants economize their active control of racket and hand movements by exploiting the physical properties of the task. Additionally, the variability of the racket’s movement follow the predictions of the stability analyses. Further analyses show that movement trajectories display topological invariance or, as suggested, motor equivalence across kinematic variations, which provides evidence that a common dynamic regime governs different variants of the movement. Last, differences between individuals’ solutions are variations that can be explained within the model’s scope.

As evident from the introductory overview, the first decade of empirical and theoretical work from the dynamical perspective revolved around interlimb coordination as a paradigm to understand locomotory activities in humans and animals. The central modeling framework was provided by synergetics, one branch of nonlinear dynamics, which formulates a potential equation on an abstract macroscopic level. Given the number and publicity of these studies it is often overlooked that the dynamic systems perspective is much broader and, indeed, has made considerable progress in other areas. More work is in progress, and the list of studies in Table 1 is by no means exhaustive. The ball bouncing study, for example, demonstrates a bottom-up modeling strategy which contrasts to the more abstract level of modeling pursued by synergetics. Importantly for the more applied branches of movement science, more perceptual-motor tasks have been and are being examined, ranging from postural control to as complex a task as juggling seven balls.

Nonlinear dynamics as a new theoretical framework to understand perceptual-motor coordination has only started, and we have only seen the tip of the iceberg. Nonlinear dynamics offers a vast field of tools which is growing in parallel with empirical problems. In fact, it is the responsibility of the experimenter to delve into and pose new problems to the theorist. The magnitude of these new challenges is conveyed by Abraham, one of the pioneers in the area, in his concluding remark (1987, p. 610): “There are miles to go before we sleep….”

References


**Author’s Notes**

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