
Coordination

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The Russian physiologist Bernstein (1967) defined coordination as a problem of mastering the very many degrees of freedom involved in a particular movement—of reducing the number of independent variables to be controlled. The initial theorizing and experimentation on “Bernstein’s problem” was conducted largely in terms of how a device of very many independent variables might be regulated without ascribing excessive responsibility to an executive subsystem. A second round of theory and research on Bernstein’s problem is now under way. This second round is motivated by similarities between coordination and physical processes in which multiple components become collectively self-organized; it is directed at an explanation of coordination in terms of very general laws and principles. The major achievements of the first round of efforts to address Bernstein’s problem are summarized, and six examples of the theory and research typifying the second round are presented.

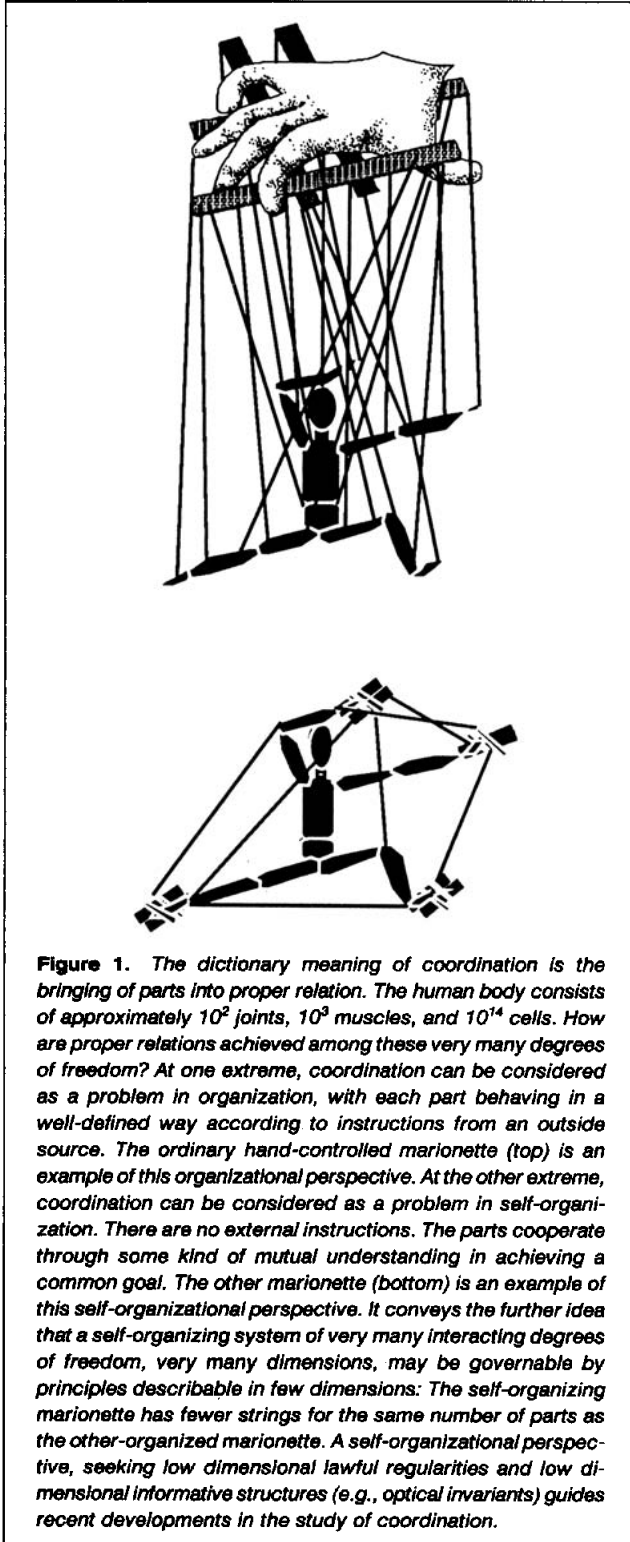
In satisfying everyday demands, an animal routinely coordinates segments of its body with one another and with the surrounding layout of surfaces. Coordinations may be relatively uncomplicated, as in rhythmically flexing and extending a limb, fin, or wing in locomotion, or relatively complicated, as in playing the piano, returning a tennis serve, or executing a triple in ice skating. Coordinations can be described macroscopically, in terms of the patterning of body and limb motions relative to the patterning of environmental objects and events, or they can be described more microscopically, for example, in terms of configurations of tensile states or the patternings of cellular and vascular activities.

As characteristic expressions of biological systems, coordinations necessarily involve bringing into proper relation multiple and different component parts (e.g., 10^{14} cellular units in 10^3 varieties), defined over multiple scales of space and time. The challenge of properly relating many different components is readily illustrated. Muscles act to generate and degenerate kinetic energy in body segments. There are about 792 muscles in the human body that combine to bring about energetic changes at the skeletal joints. Suppose we conceptualize the human body as an aggregate of just hinge joints like the elbow. It would

then comprise about 100 mechanical degrees of freedom, each characterizable by two states, position and velocity, to yield a *state space* of, minimally, 200 dimensions. In the 1960s and early 1970s a number of scholars—most notably, Gelfand, Tsetlin, Gurfinkel, Fomin, Shik, and Feldman in the Soviet Union (e.g., Gelfand, Gurfinkel, Tsetlin, & Shik, 1971), and Greene, Easton, Boylls, and Arbib in the United States (e.g., Greene, 1972)—sought to catalogue the special problems and to identify the general principles behind the resolution of coordination in systems of such complexity. Their efforts in this regard were shaped primarily by the pioneering studies of a Russian physiologist, Nikolai Aleksandrovich Bernstein (1896–1966). English translations of Bernstein’s major papers appeared in a volume published in 1967.

Early in his career Bernstein had argued that the kinematic and dynamic aspects of movements, and the functional expediencies of these aspects, were grossly undervalued in accounts of coordination. For him, the problem in studying movement was one of understanding the control of a complex kinematic system. Recognizing that inertia, reactive forces, and initial postural conditions combine with active muscle forces in producing movements, Bernstein ruled out any straightforward, unambiguous relation between the nervous impulses innervating movements and the movements themselves. In so doing, he underscored the essential formative and steering roles of the information available to perceptual systems. More specifically, he saw the basic problem of coordination as that of mastering the many degrees of freedom involved in a particular movement—of reducing the number of independent variables to be controlled. Coordination, as Bernstein expressed it succinctly, is the organization of the control of the motor apparatus. Resolutions of the problem couched in terms of arranging fixed movement elements were dismissed by Bernstein. Reflexes, for example, were not elements of coordinated actions for Bernstein but, rather, elementary coordinated actions and, therefore, part of the problem of coordination rather than contributors to its solution. Because of certain contemporary developments in the analysis of complex systems, it is especially useful (as I hope to show) to express Bernstein’s statement of the problem in the following manner: Each and every movement comprises a state

space of many dimensions; the problem of coordination, therefore, is that of compressing such high-dimensional state spaces into state spaces of very few dimensions (see Figure 1).



Bernstein's Problem: Round 1

By the end of the 1970s, an inventory of core issues and basic principles of organization of relevance to Bernstein's (1967) problem of degrees of freedom could be distilled from the work of the aforementioned scientists and of others pursuing a similar tack. I made a stab at detailing some of the items in this inventory (Turvey, 1980). These items are reviewed here with some additions and modifications. They summarize what I regard as the first round of investigations of Bernstein's problem. A second round is now in progress, and it is the major focus of the present article.

1. *Distributed construction of movements.* The kinematic (spatiotemporal) details of any coordinated state are not determined at the outset, in a single step by a single subsystem. The details are contributed gradually, by many subsystems working together.

2. *Indefiniteness of action plans.* It is possible to configure (a) different degrees of freedom (e.g., body segments and joints) in the same way to achieve the same purpose and (b) the same degrees of freedom in different ways to achieve different purposes. These abilities, in conjunction with distributed construction, imply that a "plan" for a coordinated act is probably defined functionally in an abstract manner that refers neither to body segments nor to actual motions. The referents appear to be relations among properties that are relatively few in number, realizable in all body segments, and capable of generating many different motions.

3. *Local expedencies.* The subsystems that compose a biological movement system are relatively autonomous; each relates to the "external medium" of surrounding subsystems according to a locally defined and simple expedient, for example, minimal interaction. With each subsystem satisfying its own local and particular expedient, multiple subsystems cooperate to generate "desired" states of affairs at the system level without "knowing" that they are doing so. There may well be a method of cooperation that is independent of the particular bodily coordination to be achieved. That is, cooperation among autonomous subsystems may be solved once and for all by very general principles common to all biological movement systems.

4. *Separation of activation and tuning.* Subsystems of a biological movement system have standard behaviors or generate standard functions. When a subsystem is active a "ballpark" of states, a family of functions, is established. In order to produce a variant of the coordination

This manuscript is dedicated to Delos D. Wickens who died in the spring of 1988. Professor Wickens made it possible for me to assume a career in psychology, and supervised my doctoral studies from 1964 to 1967. I will always be grateful to him.

The preparation of this article was supported by a James McKeen Cattell Fellowship and Grant BNS-8811510 from the National Science Foundation. Many thanks to Claudia Carello for her invaluable assistance in creating the figures.

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suiting to current circumstances, the activated subsystems must be adjusted or tuned. The tuning is done by other relatively autonomous subsystems, for example, feedback from receptors signaling current limb positions.

5. *Executive ignorance and equivalence classes.* In a biological movement system with its distributed control, any subsystem (or set of subsystems) in the executive role will not know the actual outputs of the subordinate subsystems from which it composes an act. This follows, in part, from the ballpark/tuning distinction. To achieve a given end, the executive might always activate a given subsystem, even though the subsystem's actual behavior cannot be anticipated by the executive because of the subsystem's tuning, which varies from one occasion to the next. Moreover, the subsystem activated by the executive might not be the actual subsystem that does the job. Different subsystems can satisfy a piece of an executive specified function and will be interconverted by low-level automatic processes according to a local expediency of which subsystem gets the job done most simply. Executive knowledge is, therefore, only approximate, referring to large classes of tunings, subsystems, and low-level processes in general, that seem equivalent because they can be used to achieve the same purpose. On the positive side, these equivalence classes may identify systematically behaving units of very few degrees of freedom in terms of which intentions (goals, plans) can be framed for coordinating the behaviors of very many degrees of freedom.

6. *Reducing mechanical degrees of freedom through muscle linkages (or synergies, or coordinative structures).* A group of muscles spanning several different joints, and capable of contracting independently of each other, can become functionally linked so as to behave as a single task-specific unit. Such linkages may comprise the most primitive independently governable actuators of movement. They are characterized by a pronounced standardization that lessens the degrees of freedom requiring executive control. During movements that vary in speed and power, the internal mechanical degrees of freedom of a muscle linkage relate among themselves and with respect to the time frame in a fixed fashion. Muscle linkages are also characterized by task-specific flexibility. If perturbed temporarily, all of the internal mechanical degrees of freedom—and not just those at the site of the perturbation—readjust immediately in such a way that the task goal is preserved.

7. *Spring model of control.* Ballistic limb movements (e.g., an arm rotating by its own momentum) are put to considerable use. Such movements can be achieved by setting the muscle linkage to behave like a spring whose equilibrium position is the intended limb position. This springlike organization simplifies control. To set the spring, one needs only to know the final position; knowledge of the initial position is not needed. With proper damping, the limb moves by itself without monitoring and with a speed dependent on the spring constant. By varying the damping and stiffness, movement patterns can be repetitive or discrete.

8. *Special purpose, task-specific solutions capitalizing on the features of real-world complexity.* A biological movement system does not have to do everything; the contexts for coordination are restricted, not universal. In consequence, movement coordinations are probably the product of a system that is special purpose rather than general purpose in its design. The generality that a biological movement system exhibits is the result of task-specific solutions to actual recurrent problems gathered into a coherent style of organization. By capitalizing on peculiarities (e.g., invariants and lawful regularities) of the tasks, and their real-world circumstances, surprisingly simple solutions can be obtained for high-dimensional problems.

9. *Complementation of a movement system by its environmental context of constraint.* The organizing principles underwriting coordination cannot be understood solely through reference to the biological movement system. If the environment to which the movement system relates is interpreted as just another large set of variables, then the juxtaposition of an animal and its environment would amplify the problem of degrees of freedom. An attenuation rather than an amplification of dimensionality would occur, however, if the multivariable movement system and its multivariable environment complemented each other, thereby constraining mutually their respective degrees of freedom.

10. *Simultaneous organization of afferentation and efferentation.* Reinforcing the feature just noted, it would not suffice if the principles behind coordination were restricted to the outflow of the movement system. The formative and steering roles of inflow require that it be organized in a way that is suited to the outflow. In other words, the problem of coordination holds equally for afference as well as for efference or, in more general terms, for perceiving as well as acting. Its resolution, in the sense of condensing degrees of freedom, must occur simultaneously in both.

As noted, the 10 properties just listed can be viewed as the results of the first major round of theorizing and experimentation on the problem of coordination as formulated by Bernstein (1967). This first round was conducted largely, but not exclusively, within the context of understanding how one would go about regulating an artifact of very many independent variables without ascribing to any one subsystem (an executive) excessive responsibility. If the regulation is to be achieved through sequential computation, then the problem is especially acute. Many degrees of freedom is a curse. If the regulation is to be achieved through parallel and distributed computation, then the problem is potentially more manageable. As noted by Geoffrey Hinton (1984), a computer scientist and psychologist currently at the University of Toronto, the availability of many degrees of freedom might aid rather than hinder the task of networking local processors to do the job. The rigorous pursuit of such ideas would continue the thrust of the first round (e.g., Bullock & Grossberg, 1988). But a second major round of theorizing and experimentation is now under way,

building on the results of the first, yet departing from it in important respects. My primary goal in this article is to convey something of its direction and content.

Bernstein's Problem: Round 2

Why a *second* round? In terms of strategy, of how to proceed, Round 1 achieved three major things. It highlighted the infeasibility of explaining coordination in piecemeal fashion through models specific to individual phenomena and tailored to arbitrary variables. It directed attention to a number of appealing but vague ideas—for example, “regularity without regulation,” and “patterned outputs from unpatterned inputs.” And it emphasized the need for more theory, so that we would know which of the indefinitely many measurable things are relevant and, therefore, what to look for in the effort to get beyond uncertain conclusions. In sum, it might be said that the ultimate legacy of the first round was the call for a new strategy, one characterized by a search for general explanation and an appreciation of the similarities between coordination and other natural phenomena in which multiple components become collectively organized.

In a nutshell, the foundations of this second round of theorizing and experimentation are the subdisciplines of physical biology and ecological psychology. A physical approach to biology regards living systems as ordinary physical systems that happen to be (a) very complex and (b) extraordinary in their means of using the principles and laws of physics. It would attempt an account of coordination in terms of laws and circumstances. (Laws identify real possibilities. When circumstances—boundary conditions, constraints—are appended, actual events result.) Such an account is challenging in two respects. First, there is the challenge of the laws themselves. Physical laws and principles may be few in number and operate very generally. Nature, however, is not very economical with respect to patterns of coordination. There is great diversity, with each pattern giving expression to the general laws and principles in very specific ways. As a consequence, the application of the general laws and principles to coordination can be obscured. Novel methods of observation and measurement, together with creative applications of established strategies, are required to reveal them. Furthermore, in the province of coordinated movements, the circumstances appended to laws include intentions, plans, goals, and so on. Intentions function as exceptional boundary conditions on natural law, and understanding how they do so is the second challenge. If one had to identify the kinds of contemporary physics most suited to understanding coordination, they would be the nonlinear dissipative branches of thermodynamics and dynamics, the physics that addresses the self-organizing capabilities of systems in nonequilibrium, systems that are subject to gains and losses in energy and matter (e.g., Nicolis, 1989). That coordination might be usefully addressed in these terms was suggested 10 years ago by Peter Kugler (Kugler, Kelso, & Turvey, 1980), then a graduate student in psychology at the University of Connecticut, and now at the University of Illinois.

An ecological approach to psychology, as developed by the late James Gibson of Cornell University, emphasizes the mutuality of an animal and its environment (Gibson, 1966, 1979). In this approach, perceiving is defined as the means by which an individual maintains contact with his or her environment and, in kindred spirit with physical biology, as a phenomenon understandable in terms of lawful regularities and symmetry principles defined at the ecological scale of animals and environments. The essentials of the approach can be expressed succinctly: Perception is specific to information and information is specific to the environment and to one's movements; hence, perception is specific to the environment (extero-perception) and to one's movements (proprio-perception). *Information* in the ecological approach refers to specificity between the structured energy distributions available to a perceptual system and the environmental and movement properties causally responsible for that structure. The specificity is sought at a macroscopic level of description and is expected to be revealed in terms of variables of low dimension that, in general, have not yet been identified in physical theory. The proposed specificity of perception to information implies that for every property perceived there is a property of the structured energy distribution to which the perceived property corresponds (see Figure 2).

In the second round of theorizing and research, physical biology and ecological psychology are companion endeavors. Both are directed at understanding coordination in terms of very general principles. Physical biology focuses on general principles having to do with transformations of energy and the time evolution of observable quantities; ecological psychology focuses on general principles having to do with the generating and pick-up of information. I will provide examples of the kinds of research typifying this second round, but first let me identify the methodological features that shape it.

The first feature is the recognition of rhythmic movement as the cornerstone of a theory of coordination. Rhythmic movements are ubiquitous in animal behavior, a fact that by itself makes the study of rhythmic movement phenomena intrinsically important. In addition, because coordinated activities are essentially patterns evolving nonmonotonically in time, they are analyzable, in principle, as a sum of periodic contributions. These facts combine to make periodic movement the basis of any theory constructed to account for patterns of coordination. More specifically, the pragmatic belief is that, in order to develop the analytic ideas indispensable to understanding coordination—whether it be the coordination of parallel rhythmic movements or serially discrete movements—a thoroughgoing investigation of elementary oscillatory movements must be conducted. The rigorous study of rhythmicity, therefore, is not arbitrary but imposed by the nature of the general problem that encompasses biological coordination, namely, understanding nonmonotonic temporal behavior or pattern evolution.

The second methodological feature is a radical ex-

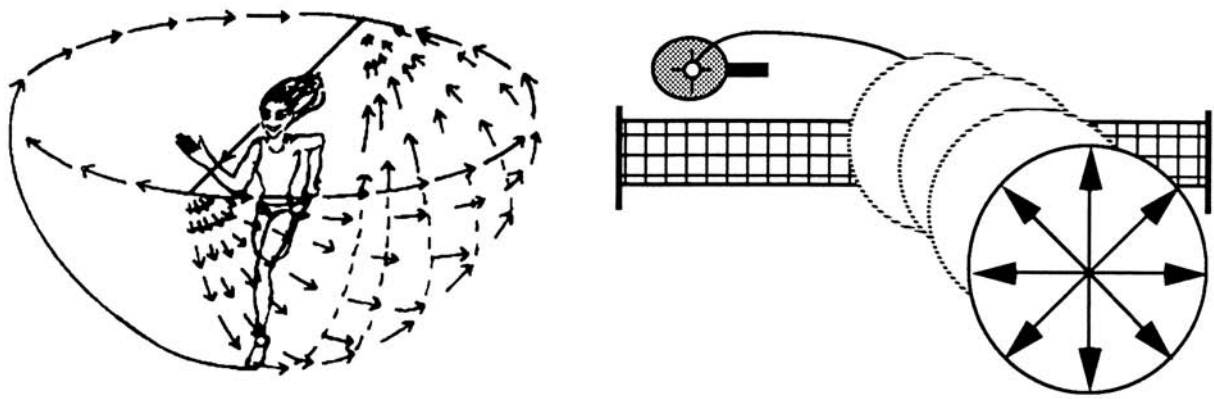


Figure 2. The notion of information advanced by J. J. Gibson is well suited to a lawful perspective on coordinated activity. The notion applies quite generally to all energy distributions and their respective perceptual systems. Consider one example that is of significance to the visual guidance of action. A person is immersed in light. Microscopically and quantitatively, light's properties are intensity, wavelength, and phase. Macroscopically and qualitatively, its properties are unbounded. Large scale distributions of light energy are patterned by surrounding surfaces, events, and by movements of the point at which the patterning is defined. The patterning is lawful, and gives rise to geometric, kinematic, and temporal optical field properties that are of low dimension, meaning that one can describe them through very few quantities (usually one). These low-dimensional macroscopic patterns, or morphologies, are specific to their sources—the animal–environment circumstances that generated them. An Olympic sprinter is shown moving forward (left). A global optical outflow is generated by her rectilinear forward motion in a transparent medium (air) filled with light. This form of optical flow at her point of observation specifies her forward motion and the direction in which she is heading (as demonstrated experimentally by William Warren [Warren & Hannon, 1988], a psychologist at Brown University). Also shown is an object, such as a ball, approaching a point of observation (right). Synchronizing one's actions with respect to a projectile—for example, hitting it—is made possible by a variable called tau, described as the inverse of the relative rate of dilation of a closed optical contour. This particular macroscopic optical patterning is generated by an approaching object and specifies when it will be at the point of observation. Tau is a temporal property of the large scale patterning of light by events. Its role in coordination has been investigated most extensively by David Lee (1980), a mathematician and psychologist at Edinburgh University. Recently, Reinoud Bootsma (1988), a movement scientist at the Free University, Amsterdam, has shown that top-class table-tennis players amend their drives during execution on the basis of the changes in tau resulting from the coordinate motions of ball and player.

tension of the set of observables (roughly, measurable quantities) in terms of which coordinated movements are described and, thereby, understood. Customary measures in psychology, such as reaction times and errors, fail to make contact with the full richness of movement dynamics and, as a result, underconstrain accounts of coordination. The nonlinear dynamics of physical biology and the informational analyses of ecological psychology enrich and extend the range of relevant observables.

Six Examples From Round 2

Searching for the building blocks of movement oscillators. It has been customary to think of coordination in terms of the fitting together of things—neuroanatomical entities like reflexes and neural pacemakers have been prime examples. The metaphor is of units *in* coordination. An alternative metaphor is of units *of* coordination (Reed, 1982). That is, rather than thinking about a coordinated act as a thing made up of things, we ought, perhaps, to be thinking about it as a relation analyzable in terms of relations. *Action plans*, as understood in the first round of reactions to Bernstein's (1967) problem, are indefinite because they refer to relations and not to particular things. In this spirit we expect that rhythmic movements are composed from a small repertoire of relations among properties, regardless of the fact that they can involve

large numbers of body segments of many different kinds. The opening question, therefore, is what kinds of relations among what kinds of properties comprise the rhythmic movement patterns so characteristic of human and animal behavior?

If a person so chooses, a limb can be maintained for a reasonable amount of time in continuous oscillation. The sustained oscillation is achieved by an energy source (the chemical fuel contained within the muscles) that has no oscillatory properties (more exactly, it does not oscillate at anything like the space and time scales of the limb). Wherever a source of nonoscillatory excitation is converted within a system to oscillatory excitation, the system is designated a self-induced or self-sustained oscillator. It is appropriate, therefore, to consider rhythmic movements as self-sustained oscillators. Such oscillators consist essentially of four components (see Figure 3, top): (a) an oscillatory component, comprising an elastic property (the system's stiffness or spring) that guarantees a return to equilibrium and an inertial property that guarantees overshoot; (b) an energy source that makes up for the loss of energy through friction; (c) a gate that admits energy to the oscillatory component in the right amounts and at the right instants; and (d) a feedback component that controls the gate, using the properties of the oscillatory system itself.

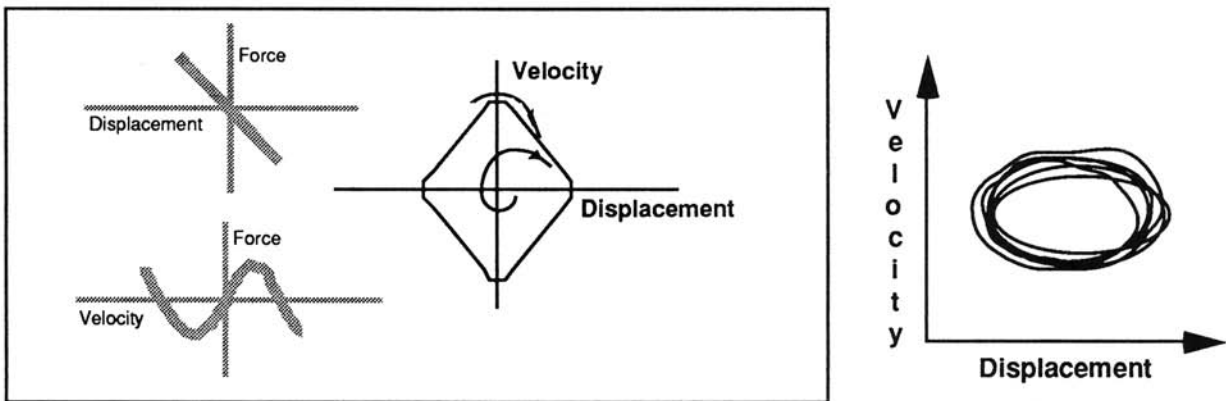
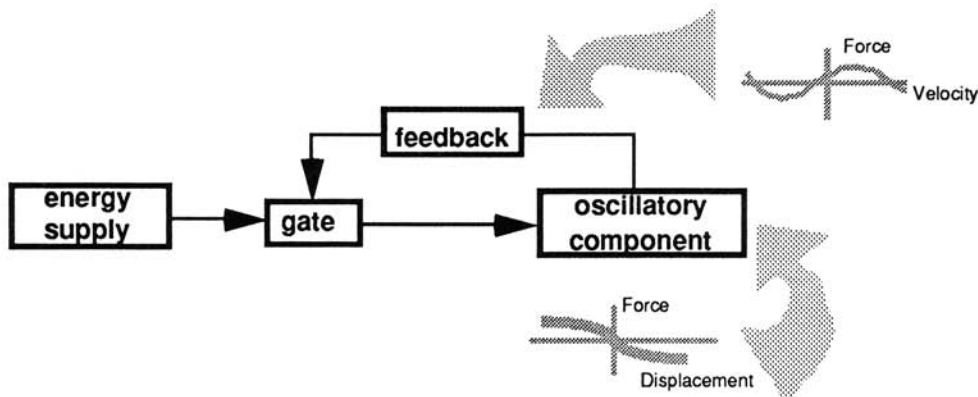


Figure 3. A self-sustained oscillator consists of four components as identified by the four boxes (top). A nonlinear stiffness function (force vs. displacement) of the kind that might go into the make up of the oscillatory component is shown. Also shown is a nonlinear friction function (force vs. velocity) of the kind that might govern the dissipation of energy (negative sloping parts of the function) and the restoration of energy (positive sloping part). Such a function would make up the feedback loop. An example is given of how an oscillator looks in the phase plane description (velocity by displacement), when assembled from a linear stiffness and a particular nonlinear friction function (lower left panel). The closed orbit is called a limit cycle, and it is characteristic of self-sustained behavior. When perturbed, the system returns to the orbit from either inside or outside. A further example of a phase portrait is given (lower right panel). This one is of the sort found in the study of human rhythmic movement. It is not a single closed orbit but a band of orbits. Does it represent an attractor state, like a limit cycle? How many degrees of freedom are actually needed to describe it? Questions such as these concerning the dimensionality of coordination patterns can be addressed, in principle, through contemporary methods of nonlinear dynamics.

Comments on the first and fourth components are in order. The first component's elastic element generates a force pulling the moving part back to its resting position. (Think of gravity acting on the pendulum of a grandfather clock.) This elastic element, however, will rarely exhibit a restoring force that increases linearly with displacement from equilibrium. More likely is a restoring force that increases greater than linearly or less than linearly. Pioneering investigations of mechanical oscillators with nonlinear stiffness (e.g., restoring force growing as the cube of displacement) were conducted by Duffing (1918), a German physicist, in the early decades of the 20th century. The fourth component is an indispensable part of all self-sustained oscillators and one that is often difficult

to identify. The complexity of the feedback function—how the feedback is phased relative to the oscillatory motion—is readily appreciated, however. A force acting in the same direction as the oscillatory component's velocity does positive work (imparting energy, overcoming damping); a force opposed to velocity does negative work (withdrawing energy, increasing damping). Because negative feedback acts like normal friction to stop oscillations and because positive feedback acts like the opposite of friction to excite oscillations, the feedback function is described most usefully as a friction function (see Figure 3).

Rayleigh (an English physicist) in the 19th century and Van der Pol (a Dutch radio engineer) in the early

decades of the 20th century pioneered the investigation of such functions in musical instruments and electrical circuits, respectively. Instruments that sustain notes, such as bowed and wind instruments, involve positive feedback (inverse friction) at low velocities and negative feedback (normal friction) at high velocities. Rayleigh (1877/1945) found that, in the simplest case, the oscillatory property used by the feedback component to control the gate in the preceding fashion was a sum of velocity and cubed velocity. In electronic oscillators based on vacuum tubes, Van der Pol (1934) noted that the resistance encourages flow through the circuit when the square of the current is small and impedes flow when the square of the current is large. Expressed in the language of mass-spring systems, he found the relevant oscillatory property to be a combination of a velocity term and the product of this velocity term with the square of a displacement term. One can think of these pioneering studies of Rayleigh and Van der Pol as discovering that nature engages rather special kinds of properties (cubed velocity and velocity times squared displacement) in governing the patterning of energy gains and losses behind persistent function.

The properties associated with Duffing, Rayleigh, and Van der Pol refer to elementary nonlinear components for the construction of self-sustained oscillators. With respect to the opening question, we can expect rhythmic movements to be built from them (Kay, Kelso, Saltzman, & Schönner, 1987). On the other hand, there may be additional elementary building blocks of potential significance to movement that are as yet unrevealed in the study of spring pendulums, musical instruments, and electrical circuits. Analyses of human rhythmic movements by Peter Beek, a movement scientist at the Free University of Amsterdam, and Wiero Beek, a physicist at the Technical University of Delft, suggest that biology may have much to teach us about how nature builds her oscillatory phenomena. Two new properties have surfaced (Beek & Beek, 1988). One new property is the product of displacement and squared velocity, a new nonlinear elastic term. The other new property is the product of squared displacement and cubed velocity, a new nonlinear friction term.

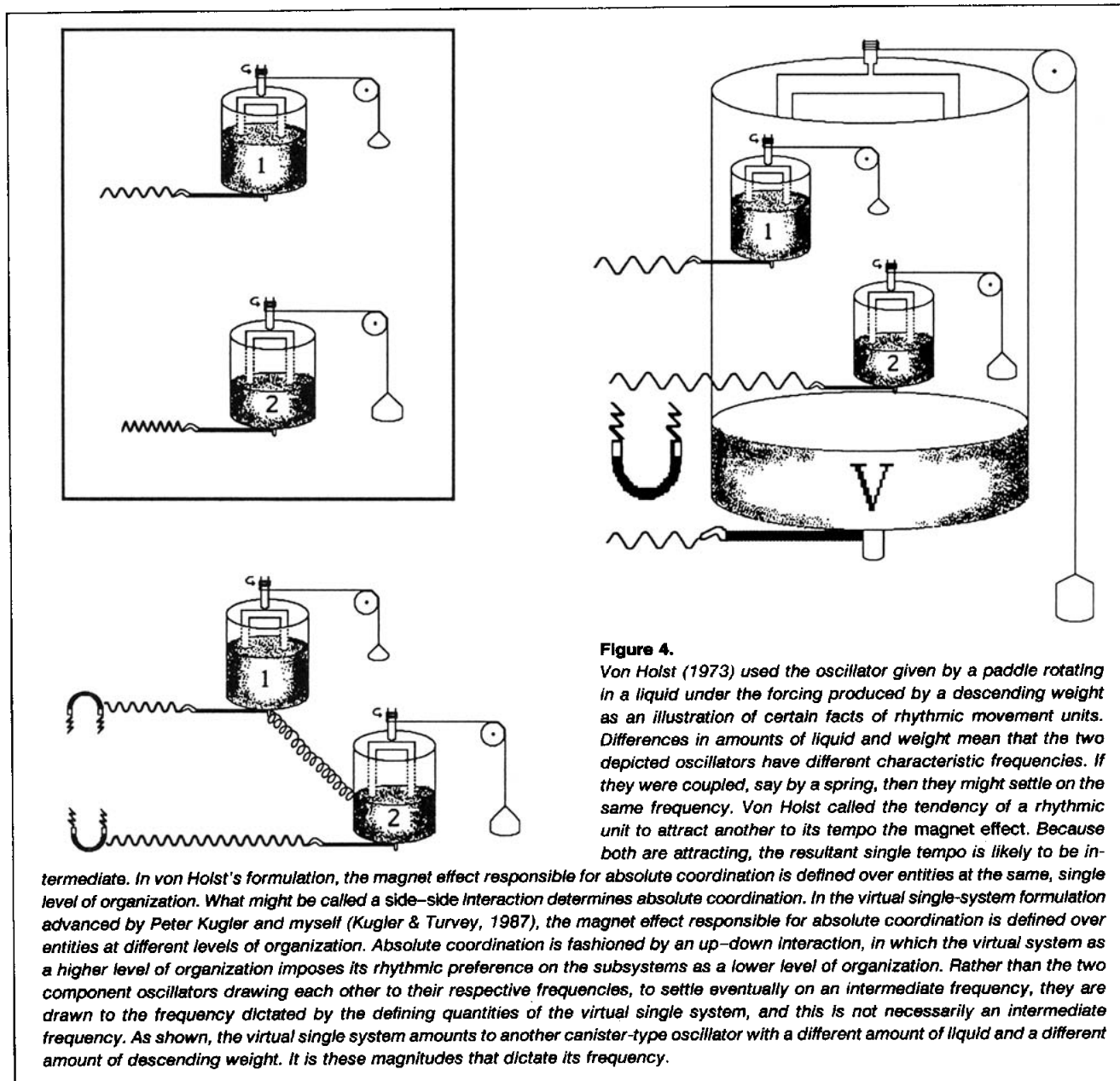
Dimensionality of simple rhythmic movements. The elementary elastic and friction functions limit the ways in which the body's many varied microcomponents can be assembled into a rhythmic unit of far fewer degrees of freedom. If we now proceed to identify a rhythmic unit with a dynamical system, then we can make note of a further source of constraint. A dynamical system is a system that evolves in time—it starts up, passes through some behavioral variations, and settles eventually into a regular pattern. If a friction function is involved, as is typically the case, then the degrees of freedom needed to describe a dynamical system's eventual behavior are less than those needed to describe the system itself. The evolutionary process provides a further constraining of dimensionality. This is an important result of the study of dynamical systems, and it introduces us to the significant notion of an attractor, a preferred state or sequence of

states that a system gravitates to from arbitrary starting conditions and following arbitrary disturbances.

Consider the behavior of an oscillator in terms of its velocity plotted for each point or phase in its cycle. The plot is called a *phase portrait* (see Figure 3, lower left). For an oscillator with balanced energy losses and gains, the phase portrait after transients have died out is a closed orbit. The orbital attractor has one degree of freedom; phase position completely determines the system's velocity, and vice versa. When the oscillator is not on its attractor, however, but on some trajectory that will converge eventually on the attractor, then both position and velocity are needed to describe the behavior. In short, *off* the attractor the oscillatory behavior comprises two degrees of freedom; *on* the attractor it comprises just one. The dimensionality shrinks as the system evolves.

It will come as no surprise, I am sure, to learn that a sustained rhythmic movement is not quite like the sustained mechanical oscillator I have just been discussing. Most significantly for present purposes, rhythmic movement does not produce a clean, single orbit in the phase by velocity plot. Rather, the successive cycles of movement produce a reasonably thick band of closely similar but nonidentical orbits (see Figure 3, lower right). Consequently, a pertinent question arises as to the dimensionality of the rhythmic behavior: How many degrees of freedom does it involve? What is the nature of its attractor? What makes these questions especially challenging is the fact that rhythmic movement is patterned at both large (e.g., limb motion) and small (e.g., neural process) scales of observation. Bruce Kay, a psychologist at MIT, has looked at the dimensionality of simple rhythmic movements of the index finger. Using methods in nonlinear dynamics for computing the dimensionality of observable behavior (e.g., Grassberger & Procaccia, 1983), Kay (1988) found evidence for two processes, one at the large scale and one at the small scale. The process at the large scale could be described by an attractor with a single degree of freedom, characteristic of a system that balanced energy losses and gains; the process at the small scale had an infinite number of degrees of freedom. In the simplest terms, the rhythmic behavior studied by Kay was best understood as the behavior of a dynamical system governed by an orbital attractor with noise. The significance of this pioneering work is the promise of being able to address the central question of how many degrees of freedom define a given coordination at the behavioral level, a question that cannot be answered on a priori grounds.

Moving different segments of the body at a common tempo. The most pervasive coordination pattern is that of absolute coordination in which two or more limbs or limb segments move rhythmically together at the same frequency (1:1 frequency locking), as in walking. An interpretation fashioned 30 years ago by von Holst, a German behavioral physiologist, anticipated the dynamics perspective. In one of his articles (1973), von Holst presented a simple mechanical model of independent, biological rhythm generators of the kind thought to underlie fin movements in fish. I will use it to illustrate his ideas.



Imagine two oscillatory mechanisms, both consisting of canisters containing a liquid in which a paddle is caused to rotate by a descending weight linked to the paddle by a pulley system (see Figure 4). The two oscillators differ only in the size of the descending weight and in the amount of liquid resisting the paddle's rotations. Consequently, their resultant cyclic motions differ in frequency and each oscillator has a preferred frequency dictated by its defining quantities. A connecting spring conducts the rhythmic motions of one oscillator to the other. Each oscillator would prefer to stay at its own tempo, thereby satisfying its intrinsic dynamics—a preference von Holst (1973) called the *maintenance tendency*—but because of the connecting spring neither may be able to

do so. Each oscillator tries to pull or attract the other to its frequency. As a result of this magnet effect, von Holst assumed that the coupled tempo is the preferred tempo of one oscillator (if one oscillator can dominate completely the other) or, more generally, a tempo that lies between the preferred tempos of the two oscillators. In the coordination of rhythmically moving fins or limbs, von Holst saw the maintenance tendency (to move at one's own pace) and the magnet effect (to move at the pace of another) as working in direct opposition. If the maintenance tendency dominates, then the coordination is relative (multiple rhythms and wandering phase relations); if the magnet effect dominates, then the coordination is absolute (one rhythm, one phase relation). Von Holst appreciated

the flavor of the cooperative-competitive dynamics at work: Even when absolute coordination was achieved, he saw a continuing, though latent, struggle between the maintenance tendency (the intrinsic dynamics of the component rhythmic units) and the magnet effect (an extrinsic dynamics).

Von Holst (1973) conducted his studies with fish, in which spine and brain were surgically separated. In this preparation, the fins exhibit their pure metronomic character, oscillating autonomously for hours after the surgery. Peter Kugler and I (Kugler & Turvey, 1987) have investigated absolute coordination in intact humans with a procedure that permits wide variation in the characteristic frequencies of the component limb oscillators and that requires an intentional contribution on the part of the subject. A pendulum is held in each hand and oscillated by rhythmic motions of the hand. The frequency of comfortable oscillation can be varied by varying the pendulum's dimensions. Questions that can be addressed with this paradigm include the following: What determines the frequency that a person settles on when asked to swing two pendulums comfortably in absolute coordination? Does achieving a 1:1 frequency relation depend on the comparative magnitudes and, therefore, the comparative characteristic frequencies of the two hand-held pendulums? Is there evidence of a struggle between the maintenance tendency and the magnet effect?

The answers to the first two questions point to a somewhat different characterization of absolute coordination from von Holst's (1973; see Figure 4) and seem to follow from certain facts that would be true if the two pendulums were constrained by a rigid connection that made them behave as one pendulum. Any rigidly connected pair of pendulums is equivalent mechanically to a pendulum whose mass is equal to the total mass of the pair and concentrated at a single point a certain distance from the axis of rotation. This point is called the *center of oscillation*. Its distance defines the length of a pendulum whose characteristic frequency is the same as that of the rigidly connected pair. Taking the tack that two hand-held pendulums in absolute coordination compose a virtual single pendulum, a center of oscillation can be calculated. Frequency of absolute coordination was found experimentally to vary in accordance with variation in center of oscillation, that is, with variation in the magnitude of a virtual single system and not as a function of the characteristic frequencies of the two pendulums so coordinated (see Figure 4).

Absolute coordination is achieved, with apparent equal facility, for any pair of hand-held pendulums. Experiments conducted with Lawrence Rosenblum (Rosenblum & Turvey, 1988), a psychologist now at the University of California, Riverside, used left- and right-hand-held pendulums, whose ratios of characteristic frequencies ranged between 0.5 and 2.6. Subjects achieved 1:1 frequency coordination in all cases. The implication is that not all instances of two or more limbs moving at a common tempo are going to be understandable as entrainment, a process of achieving absolute coordination when

the oscillators in question have closely similar characteristic frequencies. Achievement of common timing in violation of the requirements for entrainment implies one or more constraints. In the experiments with hand-held pendulums, the major constraint is the person's intention to move two pendulums rhythmically at the most comfortable, common tempo. Although obviously soft and temporary (rather than hard and permanent), this constraint appears to harness neural processes in a way that simulates certain aspects of solid matter: Two pendulums connected rigidly would always oscillate together at one frequency, regardless of wide differences in their individual preferences, and if allowed to oscillate freely, they would always do so at the frequency dictated by their center of oscillation.

Despite the successful attainment of absolute coordination in these varied cases, the evidence for a latent struggle is strong and, surprisingly, of the same form as that observed by von Holst (1973) with decapitated fish. Given two hand-held pendulums of different lengths and masses in absolute coordination, the one of higher characteristic frequency reaches the peak of its cycle ahead of the one of lower characteristic frequency. An intended absolute coordination of 180° (pendulums moving together in opposite directions) or 0° (pendulums moving together in the same direction) is achieved only when the two pendulums are of identical size; the actual phase relation varies systematically with the magnitude of the difference between the characteristic frequencies (Rosenblum & Turvey, 1988). The implication is that in the absolutely coordinated state, a component rhythmic unit compromises, but does not lose, its intrinsic dynamics. The same conclusion is reached from a consideration of the variance in a rhythmic unit's timing, amplitude, and energy. The further a component rhythmic unit is forced away from its preferred state by the demands of absolute coordination, the greater the variance in its behavior (Rosenblum & Turvey, 1988).

I have been talking for convenience as if the characteristic frequency of a hand-held pendulum is given by the free, undamped motion of the pendulum. I must now be more exact. The characteristic frequency is that of the free undamped motion of the pendulum with a spring attached some small distance from the axis of rotation. Muscular and other tissues function as the spring that elastically stores and releases mechanical energy. This revision is important to connecting certain facts of absolute coordination observed in laboratories in Connecticut with certain facts of absolute coordination observed on the plains of the Serengeti in Kenya. Peter Kugler and I (Kugler & Turvey, 1987) found that the periodic times produced by our subjects were scaled in a particular way to pendulum mass and length; the times varied as mass to the 0.06 power and as length to the 0.47 power. Think of it this way: On a trial we gave to the subject a mass and a length, and the subject gave us, in return, a time; over trials and, therefore, over variations in the masses and lengths of the pendulums, the times the subject gave us were proportional to mass^{0.06} and length^{0.47}. Originally,

we thought that these time scales—the power relations between period and mass and period and length—were biological in origin, in the sense that they depended somehow on particular features of the body's tissues. Further investigation showed, however, that our original interpretation was quite wrong. Working with Richard C. Schmidt (a psychologist at the University of Connecticut's Center for the Ecological Study of Perception and Action) and Lawrence Rosenblum (Turvey, Schmidt, Rosenblum, & Kugler, 1988), we fed different mass and length values into the equation defining the oscillatory behavior of a pendulum-with-spring for different values of the spring's stiffness and received, in return, the corresponding periodic times. In the range in which the spring's stiffness in the equation was similar to that of our subjects, the power formulas relating time and mass and time and length matched those produced by our subjects. The match-up of time scales corroborated modeling the high-dimensional process of absolute coordination (it involves very many neurons and very many muscles) by the low-dimensional resonance equation of a pendulum-with-spring system. We applied this understanding to quadruped locomotion.

There is a wonderful body of data available on the limb frequencies of creatures, large and small, walking, trotting, and cantering in the Serengeti (Pennycuik, 1975). The amazing feature of these data from my perspective is that the frequencies of all of the observed four-legged animals fall on three straight lines when plotted against limb length or limb mass. There is one line for walking, one for trotting, and one for cantering. Despite differences in body size (from 20 kg to 6,000 kg) and body form (e.g., gazelle vs. elephant), there is a sameness. Each quadruped in walking, trotting, and cantering is essentially like every other quadruped. What is the invariant? The pendulum-with-spring model of absolute coordination provides the answer. It is the ratio of the spring's stiffness or restoring torque to gravity's restoring torque. Gravity's tendency to return the pendulum (the limb) to its equilibrium position is given by the product of limb mass, limb length, and the constant acceleration due to gravity. It appears that for each of the four-legged animals roaming the Serengeti, the spring's restoring torque—the elastic recoil defined on the animal's tissues—is so assembled as to be equal to gravity's restoring torque in walking, six times larger in trotting and nine times larger in cantering. There is a universality to locomotion's design, a particular exploitation of nature's laws, and it is heartening to know that simple laboratory experiments with humans can provide insight into its major features.

Sudden jumps in coordinated rhythmic movement. Especially interesting insights into the dynamics of absolute coordination and locomotion generally are to be gained by looking at the transition between the two dominant synchronies of in-phase and out-of-phase. Characteristic of locomotion in horses, dogs, cats, and the like, is the presence of relatively sharp transitions between one gait and another as the speed of locomotion increases.

About a decade ago it was suggested that gait transitions, and perhaps rapid spontaneous shifts in movement organizations more generally, might be analogous to the simplest form of self-organization known in physics, namely, *the phase transition* (Haken, 1977; Kugler et al., 1980). Scott Kelso, a psychologist, physical educator, and Director of the Center for Complex Systems at Florida Atlantic University—in collaboration with two German physicists from the University of Stuttgart, Hermann Haken and Gregor Schöner (who is now at the Ruhr University, Bochum)—has put this suggestion on a sound empirical and theoretical footing. In introducing their work, I will outline two related aspects of the general physical strategy for understanding discontinuities in a system's behavior. One aspect is the identification of the basic variable in the description of a transition; the other aspect is an inventory of properties that universally characterizes a transition that results from loss of stability.

The basic variable takes the form of a macroscopic quantity called an *order parameter*. This variable does two things: It simplifies the description of the transition because it is assembled from the most relevant quantities that tend to be few in number, and it expresses the extent of the system's order during the transition. Let me introduce a time-honored example from physics to express the idea of an order parameter in its most basic form. When ordered perfectly, copper-zinc alloy (brass) is a lattice of cubes with the zinc atoms at the vertices, say, and the copper atoms at the centers of the cubic cells. If the copper and zinc atoms change places, as they will do with heating, then the alloy becomes less well ordered, with some probability of finding either atom type at every lattice site. A second-order phase transition is said to have occurred when the alloy becomes completely disordered, with equal probabilities of finding zinc at the vertices and copper at the centers. A quantity can be defined that is a function of the probabilities P of finding a copper (Cu) atom and a zinc (Zn) atom, respectively, at any given lattice site: $\mu = (P_{Cu} - P_{Zn}) / (P_{Cu} + P_{Zn})$. This quantity μ is 1 when the atoms are in the right place and 0 when the spatial distribution is 50/50. μ is the copper-zinc system's order parameter; it wraps up in a one-dimensional space the very many degrees of freedom composing the alloy's microstructure.

With respect to movement patterns like walking and running, Hermann Haken and his colleagues (Haken, Kelso, & Bunz, 1985) have hypothesized that the phase relation among the limbs is analogous to μ , the brass alloy's order parameter, and locomotion frequency is analogous to temperature, the variable that controls the brass alloy's order-disorder transition. Phase relation provides a simple and efficient description of the spatial order of the locomotory system.

If the phase relation between two limbs is the order parameter, and if the change in absolute coordination is a phase transition of the kind typifying nonequilibrium systems, then the phase relation quantity must exhibit the following properties: *modality*, meaning that the quantity has two or more distinct values in which it may

occur; *inaccessibility*, meaning that values outside of the distinct states cannot be maintained reliably; *sudden jumps*, meaning that a slow change in the control parameter may lead to a relatively rapid change in the order parameter; *hysteresis*, meaning that a sudden jump and its reverse do not occur at the same values of the control parameter; *critical slowing down*, meaning that the time taken by the order parameter to return after a perturbation to its value before a perturbation increases as the transition point is approached; and *critical fluctuations*, meaning that the variance in the order parameter may become large as the transition point is approached.

All of the preceding criteria have been observed in experiments by Scott Kelso, John Scholz (a psychologist and physical therapist currently at the University of Delaware), and Gregor Schöner, using a paradigm in which a person is required to oscillate the two index fingers (or two hands) at a common frequency (Kelso, Scholz, & Schöner, 1986; Scholz, Kelso, & Schöner, 1987; Schöner & Kelso, 1988). The phase relation, as noted earlier, is the order parameter, frequency is the control parameter varied by a metronome that the person tracks. Results show that there are only two steady states: in-phase and out-of-phase. With increasing frequency, out-of-phase coordination switches rapidly to in-phase. In-phase, however, does not switch to out-of-phase, and the out-of-phase to in-phase transition is not reversed by a reduction in frequency. Most significantly, the order parameter exhibits critical slowing down and critical fluctuations.

Recently, Richard C. Schmidt, working in collaboration with myself and Claudia Carello (a psychologist, and Director of the University of Connecticut's Center for the Ecological Study of Perception and Action), studied spontaneous jumps in coordination when two limbs are connected optically between two people rather than anatomically within a person (Schmidt, Carello, & Turvey, 1990; see Figure 5). In these experiments, two seated people each oscillated a leg, with the goal of coordinating the two legs out-of-phase or in-phase as the frequency of the movement was increased. To satisfy the goal, the two people watched each other closely. As with the within-person case, the between-person case exhibited a sudden behavioral transition from out-of-phase coordination to in-phase, but not vice versa; it showed divergence, hysteresis, and critical fluctuations (critical slowing down was not investigated). If the two people began their movements out-of-phase, and increased limb frequency simultaneously at the same rate without watching each other, then no transition occurred. The phase transition depended on looking.

The two cases of phase transition differ in many ways, most notably in the populations of neurons involved (the nervous systems of two people vs. the nervous system of one person) and the perceptual systems involved (the visual perceptual system in between-person coordination vs. the haptic perceptual system in within-person coordination). That these differences did not affect the major qualitative features of the phase-transition phenomenon suggests the possibility of an order-parameter dynamics

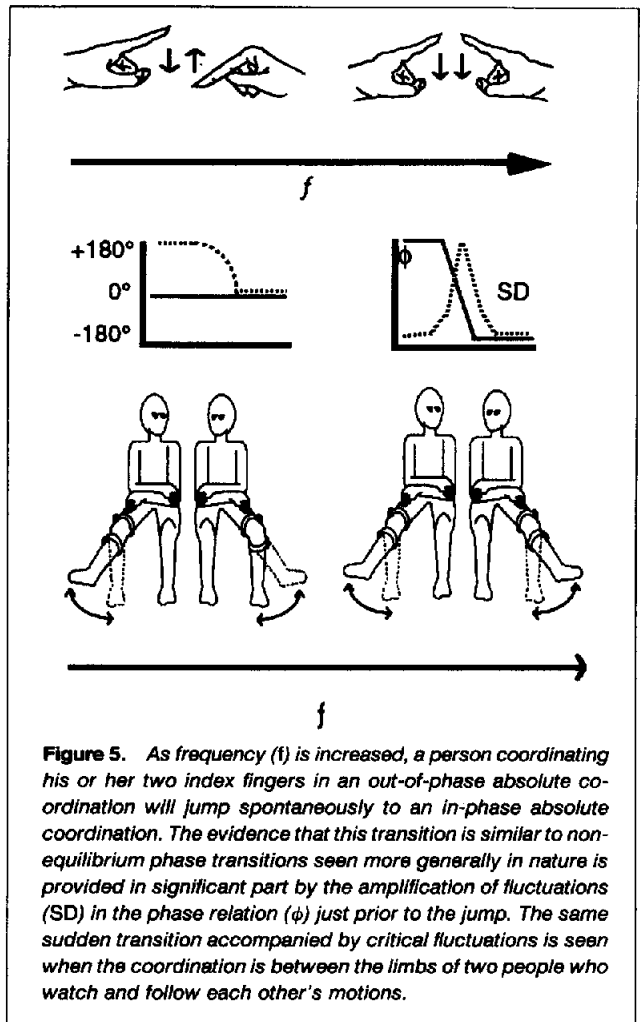


Figure 5. As frequency (f) is increased, a person coordinating his or her two index fingers in an out-of-phase absolute coordination will jump spontaneously to an in-phase absolute coordination. The evidence that this transition is similar to non-equilibrium phase transitions seen more generally in nature is provided in significant part by the amplification of fluctuations (SD) in the phase relation (ϕ) just prior to the jump. The same sudden transition accompanied by critical fluctuations is seen when the coordination is between the limbs of two people who watch and follow each other's motions.

that applies equally to the two kinds of neural and perceptual settings because, presumably, the interactions in these settings are only superficially different. The within-person case and the between-person case involve the same observable quantities related dynamically in the same way. As such, one and the same dynamics can be used to model the differential stability of the two coordination modes and the phase transition between them (see Figure 6). In abstract but quantifiable dynamical terms, anatomical and optical connectives between rhythmic movements appear to be identical.

Juggling and the "tiling" of time. As I remarked earlier, absolute coordination is pervasive. I will now consider an example of a highly skilled, learned activity involving an intricate coordination of the upper limbs that is close to absolute. The example is the cascade juggling of three balls in a figure-eight pattern (Figure 7) in which the juggler is catching a ball with one hand and tossing it to the other hand. The movements of the two hands mirror one another in the same time frame, but with a certain lag between their respective phases. Furthermore, the two hands move elliptically, through cyclical shoulder,

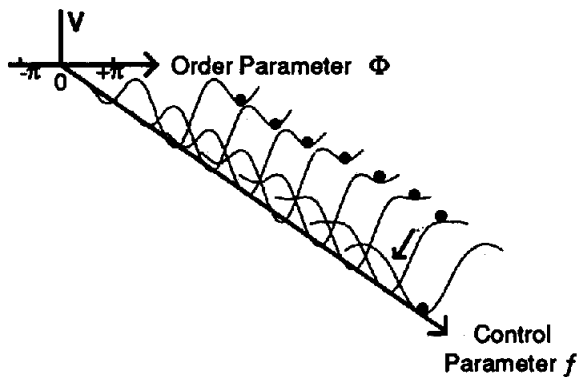


Figure 6. In nonequilibrium phase transitions, as a control parameter passes through a critical point, a previously stable organization becomes unstable, and the system jumps to a new organization that is stable beyond the critical point. The evidence for both the within-person and between-people situations suggests that the sudden change in the phase relation of two body segments is similarly due to loss of stability. In both situations, the differential stability of the two phase relations, $\Phi = 0$ and $\Phi = \pi$ (i.e., 180°), can be accommodated under the assumption that the system of coordinated limbs is governed by a smooth potential, V —a kind of unbroken energy landscape—that is a function of phase Φ (order parameter) and frequency f (control parameter). The physicist Hermann Haken and his colleagues (Haken, Kelso, & Bunz, 1985) have suggested that the function can be so defined that the minima of the potential are located at $\Phi = 0$, and $\Phi = \pm\pi$, the function's global minimum is located at $\Phi = 0$, and the $\Phi = \pm\pi$ local minima are annihilated at some critical control parameter value. In the figure, one can see how the potential changes in shape as the control parameter f increases. The system, represented by a marble, rests initially in the local well defined by a phase relation of $+\pi$. It stays there until the potential is so deformed that local minima desist. Then it falls precipitously into the global minimum—representing the stable organization beyond the critical point.

elbow, and wrist motions, and conform tightly to the parabolic motions of the balls in flight. In this instance of absolute coordination, optical information about the flights of the balls constrains the coordination of the limbs, in addition to haptic information about the limbs' motions and their loadings. The most significant source of optical information is the peak of an individual ball's trajectory. Successful juggling is achieved when all that can be seen of each ball's flight is approximately one third of the ball's diameter at the zenith of its parabola. In an ecological perspective, the understanding of this fact is to be sought in terms of a low-dimension optical quantity defined at the zenith that specifies the time to contact with the plane of the hands.

What must the juggler do to ensure smooth juggling without the balls colliding? In macroscopic terms, the answer is likely to be found in the relation among the various time quantities having to do with the hand movements and the motions of the balls in free fall. A hand loop is made up of two distinguishable times. One time is the duration in which the hand carries a ball; the other

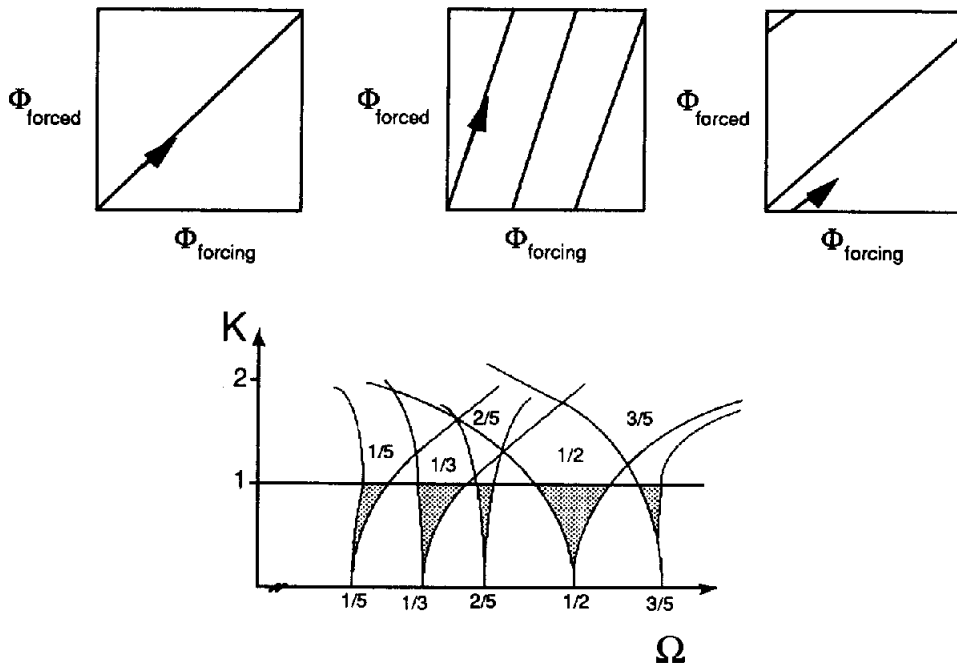
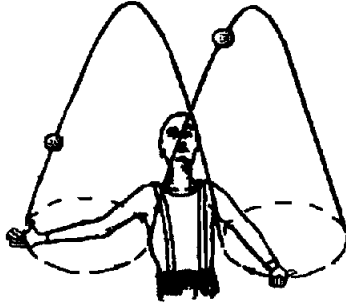
time is the duration in which the hand is empty and moving without a ball. A ball loop also comprises two distinguishable times: the duration in which the ball is in a hand and the duration in which the ball is in flight. Regardless of the exact values of these durations, in order to juggle in cascade fashion, the total of flight time and hand-loaded time per ball in a complete cycle must equal the total of hand-unloaded and hand-loaded time per hand in a complete cycle.

Focusing on the ratio of the time a given ball is in a hand to the time that this ball is in the air, one can raise the question of the juggler's options with regard to how these two times fill up the loop time of a ball. The question, metaphorically, is how many different ways can the juggler tile, that is, fill completely, the total loop time with component times? With respect to a fixed amount of two-dimensional space, it is well respected that filling the space completely through repetition of two-dimensional forms is achievable only with a limited number of types of forms. With respect to filling a fixed amount of time, there may well be similar limitations. The stable ratios that come into existence between two oscillatory processes, one that we will call the driven or forced oscillator and one that we will call the driving or forcing oscillator, hint at this possibility. These ratios are rational, with the two numbers composing the ratio limited to relatively prime integers (i.e., they do not have a common divisor). In short, there are only certain rational ratios, only certain *phase locks* as they are commonly called, accessible to two linked repetitive processes.

It has long been recognized that the stronger the forcing, the more likely that phase locking will occur. When the forcing is relatively weak, two coupled oscillatory systems will either coordinate at a fixed frequency ratio or they will drift, the latter being the phenomenon that von Holst (1973) called *relative coordination*. A very useful way of addressing these phase-locking phenomena is to examine the repeated application (iteration) of a simple equation that takes one point Θ_n on the circumference of a circle to a second point Θ_{n+1} (with $0 \leq \Theta < 1$). Such functions are called *circle maps*. A popular version is $\Theta_{n+1} = \Theta_n + [(K/2\pi)\sin 2\pi\Theta_n] + \Omega$, where K represents the amplitude of the periodic forcing and Ω represents the ratio of frequencies (frequency of forcing/natural frequency of forced oscillator). The sinusoidal term represents the effect of the forcing. If we create a diagram with the control parameters K on the vertical axis and Ω on the horizontal axis, and shade in the regions that produce phase locking (marked by recurring Ω values), then we see that when $K < 1$, these regions are quite distinct, with one region for each rational value of Ω (see Figure 7). The regions are known as Arnold horns or tongues, after the Russian mathematician who first investigated them. The significance of the diagram is that it tells us that when forcing is weak to moderate ($K < 1$), stable entrainment or phase locking will not necessarily occur for any randomly chosen set of parameter values. *Quasi-periodicity*, as it is called, is to be found in the regions outside the tongues.

Figure 7.

Juggling is an activity demanding temporal order. There are many movement segments that must be braided in time with the flight times of the balls. How is this temporal tiling achieved? What principles are at work? The theory of mode locking may provide insights. Two rhythmic systems, one forcing the other, may enter into fixed phase relations. We can look at this behavior in a plot of phase against phase. If the oscillators are in absolute coordination, or 1:1 phase lock, then the picture will be a straight line through the two corners of the plot. This same straight line will occur every time we cycle through the forcing oscillator's phases from 0 to 2π . If the phase lock is 1:3, then the forced oscillator will pass through its range of values three times for one passage by the forcing oscillator; the picture shows three lines, and these three lines will repeat every cycle of the forcing oscillator. If the oscillators are not phase locked, then every cycle of the forcing oscillator will result in a new line. The phase relation is said to wander, and the coupled systems are said to be quasiperiodic. In a space defined by the magnitude of forcing K and the ratio Ω of the frequency of the forcing oscillator to the frequency of the forced, the circle map reveals regions of phase locks as islands surrounded by regions of quasiperiodicity when $K \leq 1$. Beyond this value, phase locking becomes more probable, but chaotic. Timing relations in juggling appear to be quasiperiodic but on the borders of phase lock regions, or Arnold tongues as they are called.



Peter Beek (1989) has suggested that the logic of phase locking may apply very generally in biological coordination whenever and wherever there are different component motions consuming different times that must be combined to produce smooth, reproducible movements. Looking just at the hands, one can imagine that the temporal tiling problem reduces for the juggler to the problem of how long to hold onto a ball during a cycle of the hand. That is, what proportion of the hand's cycle time is to be taken up by holding or carrying a ball? Experiments conducted on expert jugglers revealed that, across four different jugglers (one of whom was a professional) and three different rates of juggling, the ratios of

time holding the ball to a hand's cycle time were always close to 3:4 without being exactly 3:4. All jugglers essentially tiled according to the same blueprint. Regarding 3:4 as an Arnold tongue for the task of cascade juggling, Beek computed a measure of the degree of quasiperiodicity or deviation from the Arnold tongue. The plot of the actual ratios against this measure was linear, with the values for the four jugglers at the three rates distributed on either side of the 3:4 value coinciding with zero deviation. The average deviation or quasiperiodicity was smallest for the professional juggler.

Juggling, apparently, does not entail perfect phase locking. In fact, one might argue that imperfect phase

locking is both inevitable and desirable. The circle map teaches us that if forcing is weak, then continued residence in an Arnold tongue demands precision with respect to forcing magnitude and forcing frequency (or their analogues) from cycle to cycle. Exact reproduction of parameters, however, is not characteristic of biological movement systems. Moreover, parameter flexibility rather than rigid phase locking is required to juggle adaptively and with flair. It remains true, nonetheless, that juggling success depends on a stable coordination. The variability–stability dilemma is resolved by the juggler operating close to, but not in, an Arnold tongue, and as we have seen, the more skilled the juggler, the closer to a tongue he or she gets. An intriguing and unanswered question is how the juggler perceives his or her proximity to an Arnold tongue; by what information is it specified?

Clearly, juggling is an activity that demands temporal order, and an activity that must be forged from a complex, high-dimensional neural basis. The preceding results suggest—in accordance with notions advanced some years ago by Arthur Iberall (1977, 1978), a physicist and a pioneer in physical biology—that the patterns of order and regularity evidenced among behavioral degrees of freedom might be understandable as the locking up of coupled nonlinear oscillators into stable modes defined by select phase and frequency relations. Insofar as these modes are universal and fashioned by very general principles, the juggling results and their analysis—together with recent interlimb coordination studies by Scott Kelso (Kelso & deGuzman, 1988)—hint at how one and the same method of cooperation among autonomous movement subsystems might be possible (see Round 1 of Bernstein’s problem), regardless of the movement pattern to be achieved.

Toward a dynamics perspective on each and every task. I will end my presentation of the second round of theorizing and experimentation on Bernstein’s (1967) problem by making note of an effort to bring the perspective of nonlinear dissipative dynamics to bear more generally. The effort is due primarily to Elliot Saltzman, a psychologist at Haskins Laboratories (Saltzman, 1986; Saltzman & Kelso, 1987). The key idea is to identify the functional aspects of a coordinated movement task with a dynamical system represented mathematically by an attractor. Some attractors possess a very simple geometric structure, for example, a point or a closed nonintersecting curve of the kind discussed earlier. We used these attractor notions to characterize the potential minima (point attractors) of the phase transition analysis and the asymptotic behavior (orbital attractors) of self-sustained oscillators. Some attractors possess more complicated geometric structures, for example, a torus (the surface of a doughnut) and others possess geometric structures of such complexity that they warrant being described as *strange*. These various attractors may be combined to create attractor layouts, comprising the attractors, their domains of attraction or basins, and the regions that separate them (see Figure 8).

It is fairly obvious to all of us that any given coordination will exhibit variations that depend on the con-

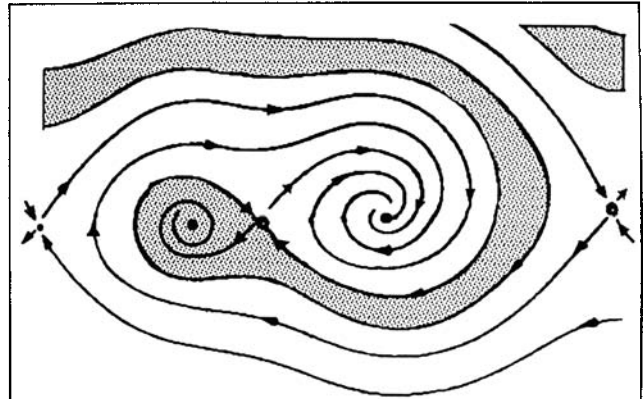


Figure 8. A noteworthy feature of ordinary everyday tasks is that the goal of the task is invariably attained even though the postural arrangement at the start of the task, and the movements used to execute it, are quite variable. There is an analogy here with dissipative dynamical systems. For these systems, independent trajectories, emanating from different initial conditions, approach each other eventually. They converge on a limiting set of end points that is called an attractor. There are a number of different attractors (the total number as yet, however, is not fully known). If the transient states are ignored, then all one needs to know about a dynamical system is its attractors. In principle, all dynamical systems can be represented by the same types of attractors in different clusters. Metaphorically, the attractors are atoms; the clusters are molecules. An example is given of the cluster or layout of attractors defining a comparatively simple dynamical system (a pendulum swinging back and forth between two magnets of different sizes). Trajectories can be seen to converge on two points. One has a small basin of attraction (shaded area) relative to the other. The boundaries of the two basins compose what is known as the separatrix. Three other points can be seen that attract some trajectories and repel others. These are called saddle points. Elliot Saltzman and his colleagues are exploring the analogy of tasks and dissipative systems. Can the structure of a given coordination be captured by an invariant attractor layout? For example, by what cluster of attractors can we define cascade juggling? In this enterprise, one can imagine discovering that tasks or coordinations that look to be very different on the surface are, in fact, governed by the same attractor cluster. A theory of tasks is possible.

text. Yet at the same time, it is clear that the coordination from context to context has a certain sameness about it. Consider reaching for an object on a table. Very many reaching movements, starting at very many different places within the vicinity of the object, can converge on the object. Any reachable object is like a point capable of attracting a multiplicity of different limb trajectories. In dynamical terms one would say that reaching—regardless of when, where, and with which parts of the body it is conducted—has the features of a system governed by a point attractor. If reaching is a task whose dynamics are those of a point attractor, then the challenge is to understand the embodiment of this invariant task dynamic in variable movement patterns. Clearly, reaching admits of several alternative descriptions, of which the point attractor dynamics is the most abstract, and a de-

scription in terms of the changes in joints and distance from the object is the most concrete.

There are two major challenges facing this style of analysis. One challenge, obviously, is mapping the functional descriptions of tasks onto qualitative dynamics, that is, identifying the attractor layouts. The other challenge is to identify the coordinate system in which the invariance of the dynamics is revealed. In Round 1, an effort was made to give accounts of coordination in terms of invariant parameters defined at the descriptive level of muscles and joints. For example, the achievement of lip closure in pronouncing the /b/ in *belief*, was presumed to follow from the speaker's pursuing a specified rest configuration of the involved articulators. Experiments showed, however, that if a speaker was perturbed by a brief tug at the jaw en route to closure, closure was still achieved, but with a very different configuration from that of unperturbed speaking (Kelso, Tuller, Bateson, & Fowler, 1985). The main implication of such research is that an invariant dynamics, if such exists, is not to be found in a coordinate space in which the coordinates are articulator variables. Saltzman (1986) has shown that the dynamics for the creation and release of any vocal tract constriction can be recovered in a space whose dimensions are simply location and degree of constriction, variables that are independent of any particular movement subsystem. This result, and others like it, set the stage for understanding how coordinations can emerge automatically in context-dependent fashion as the implicit consequences of invariant dissipative dynamics. One detects here a promise that we may yet understand the recalcitrant class of important phenomena known to generations of experimental psychologists as *response generalization*.

Matter and Mechanism: A Concluding Remark

According to the dictionary, *to coordinate* means "to bring parts into proper relation." In the study of coordination it has been traditional to hold the function of "bring . . . into proper relation" distinct ontologically from the "parts" so related. The tradition is rooted in 17th century definitions of matter and mechanism, namely, matter as passive and inert, and a mechanism or a machine as an instrument (like a lever or a pulley) for transmitting an outside action. Giovanni Borelli's treatise, *On Animal Motion*, published in 1680, was the first attempt at an explanation of movement phenomena in terms of physical laws. It was an attempt, however, of restricted scope. Borelli regarded the muscles as passive material instruments patterned spatially and temporally by an active soul. The 17th century view of matter fostered an enduring dualism in the study of coordination as it did in the study of psychology more generally.

Physical understanding of matter has broadened, of course, since Borelli's time. In recent decades we have learned that ordinary matter, under certain conditions, becomes lifelike, exhibiting self-organization, autonomy, and evolution of form. It is opportune, therefore, to take

a bold step beyond the tradition of Borelli and to look at coordination patterns, in addition to the trajectories of individual body segments, as governed by laws and principles. As I intimated at the outset, Bernstein (1967) recognized that the richly varied coordinated movements exhibited by animals possess a simplicity of control despite the enormous complexity of the nervous systems and environments involved. In the throes of the second round of reactions to Bernstein's observation, we are beginning to see that the simplicity can derive from low-dimensional dynamical laws and low-dimensional informative structures. And we are beginning, albeit very slowly, to appreciate the paradox that in the lawful restrictions on behavioral degrees of freedom lies the basis for the indefinitely many qualitative distinctions among coordination patterns.

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