

102
In N.I. Badler, B.A. Barsky, + D. Zeltzer, (Eds.).
(1991). Making Them move: Mechanics, control,
and animation of articulated figures.
San Mateo, CA: Morgan Kaufmann. Pp.157-170

Dynamics and Task-specific Coordinations

M. T. Turvey

Center for the Ecological Study of Perception and Action
University of Connecticut, Storrs, Connecticut
Haskins Laboratories, New Haven, Connecticut

Elliot Saltzman

Haskins Laboratories, New Haven, Connecticut
Center for the Ecological Study of Perception and Action
University of Connecticut, Storrs, Connecticut

R. C. Schmidt

Center for the Ecological Study of Perception and Action
University of Connecticut, Storrs, Connecticut
Haskins Laboratories, New Haven, Connecticut

ABSTRACT

A strategy for addressing task-specific movement coordinations is described, motivated by the broad issue of how control is achieved in a system of very many degrees of freedom at multiple scales. The strategy incorporates the sub-disciplines of physical biology and ecological psychology as companion endeavors in an effort to understand coordination in very general terms. Several lines of research pursuing this strategy are described. They demonstrate the reduction of high-dimensional articulatory spaces to low-dimensional task spaces, the mutual influences between these spaces, the variety of means (optic, haptic, mechanical) available for coupling dynamic degrees of freedom and reducing dimensionality, and the rule of intention in harnessing dynamics.

7.1 Introduction

The dictionary defines *coordination* as “the bringing of parts into proper relation.” Routinely in the course of ordinary everyday activity, an animal coordinates parts of its body with one another and with the objects and events that populate its environment. These coordinations involve bringing into “proper relation” multiple and different component parts (for example, 10^{14} cellular units in 10^3 varieties), at various scales of space and time. Consider the coarse scale of the skeletal system. About 792 muscles in the human body combine to bring about energetic changes at the skeletal joints. If the human body was only an aggregate of hinge joints (which it is not), then it would comprise nearly 100 mechanical degrees of freedom. Starting about 15 to 20 years ago a number of people—most notably, Gelfand, Tsetlin, Gurfinkel, Fomin, Shik, Orlovskii, and Feldman (see Gelfand et al., 1971) in the Soviet Union and Greene, Easton, Boylls, and Arbib (see Greene, 1972) in the United States—attempted to identify the special problems facing coordination in systems of such complexity, and the means of their resolution.

The ideas of Nikolai Bernstein (1967), a Soviet physiologist, played a significant role in instigating and shaping this endeavor. Bernstein argued that the kinematic and dynamic aspects of movements had been undervalued in popular accounts of coordination. He saw the basic problem of coordination as that of mastering the very many degrees of freedom involved in a particular movement—of reducing the number of independent variables to be controlled. Specifically, coordination entailed the control of a complex biomechanical system in which inertia, reactive forces, and postural conditions combined with active muscle forces in producing movements. Such complexity meant that there could be no straightforward relation between outflow or efferentation (e.g., motoneuronal activity) and the resultant movement patterns. Given efferentation’s equivocality, essential formative and steering roles must be played by inflow or afferentation (e.g., haptic, optical information).

A modern paraphrase of Bernstein’s statement of the problem of coordination reads: The multiple neural, muscular, and skeletal components of movements define a state space of many dimensions. Understanding coordination, therefore, is understanding how such high-dimensional state spaces condense into task-specific state spaces of very few dimensions. However, it would not suffice to focus our attention strictly on the outflow of the movement system in attempting to discover the principles behind coordination. The crucial roles of afferentation, noted above, require that inflow be organized in a way that is suited to the outflow. Thus, attention should be focused equally on the contributions of afferentation to task-specific processes of condensing degrees of freedom. In other words, the problem of coordination holds equally for afference as well as efference or, in more general terms, for perceiving as well as acting. Its resolution must be sought in the examination of perceiving-acting cycles.

7.2 Physical Biology and Ecological Psychology

We approach Bernstein's problem, as do a number of our contemporaries (Beek, 1989; Kay, 1989; Kelso, Delcolle, and Schöner, in press; Kugler, Kelso, and Turvey, 1980; 1982), through the subdisciplines of physical biology and ecological psychology. These are companion endeavors in our attempts to understand perceiving-acting cycles in ordinary and extraordinary skilled activities. Both endeavors 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.

7.2.1 Physical Biology

A physical approach to biology—as expressed by homeokinetics (Iberall and Soodak, 1987) and synergetics (Haken, 1983), for example—regards living systems as ordinary physical systems that happen to be very complex and are extraordinary in their means of using the principles and laws of physics (Yates, 1982; 1987). Identifying this use is a major challenge. Physical laws and principles are few in number. In contrast, patterns of coordination exhibit great diversity. New methods of observation and measurement, coupled with novel applications of traditional experimental strategies, are needed to disclose the lawful underpinnings of such patterns (Beek, 1989; Kugler and Turvey, 1987; Schöner and Kelso, 1988a). Exacerbating the challenge of identifying what laws are involved and how they are used is the fact that intentions (goals, plans) function as exceptional boundary conditions, either constant or varying in time, that harness physical laws and principles (Kugler and Turvey, 1987). Understanding how intentions play this role is an important challenge in its own right, but it is not outside the purview of experimental investigation (Schöner and Kelso, 1988b). In the most general of terms, understanding this role amounts to understanding the relation between the discrete mode and the continuous mode of functioning characteristic of biological systems—that is, the relation of symbols to dynamics (Kugler and Turvey, 1987; Pattee, 1972).

In our view, three essential and related properties of the symbols constraining movement dynamics are that (1) the relation between these symbols and their referents cannot be merely definitional or associative; (2) what these symbols stand for cannot be other symbols; and (3) how they exert their control cannot be by instructing explicitly all the details of a coordinated movement (in other words, the detail of an intention can only be a small fraction of the detail that would be necessary for a completely formal and explicit specification of a coordinated movement pattern, and yet it must suffice to produce the pattern in full). The implications of these properties considered jointly can be stated as follows. First, the relation between such symbols and their referents must be established

on natural grounds, that is, through natural laws and the local constraints of physical (including neural) structures. Second, this relation must have an explicit embodiment in the form of constraints that cannot be an inherent property of either the symbol vehicle or its referent (Pattee, 1980). And third, the control must be exercised through an implicit harnessing of natural laws and structures that themselves need no instructions (Kugler et al., 1980; Kugler and Turvey, 1987; Pattee, 1980; Turvey and Kugler, 1984).

The conceptual tools and experimental methods of nonlinear (dissipative) dynamics seem especially relevant to addressing coordination in general terms. In particular, one promising way of addressing the role of symbols in a dynamic account of skilled activities is through the concept of *attractor*. An attractor is a set of points S such that, for almost any point in the neighborhood of S , the dynamics approaches S as time approaches infinity. For example, the attractor may be a point, or a closed curve (a limit cycle), or a torus (the surface of a doughnut). In contrast with the preceding attractors that have simple geometries with integral dimensions, another class of attractors exist that have peculiar geometries and may have nonintegral dimensions. These attractors are called "strange."

An attractor can function as a controlling symbol. This concept is appealing since the relation between an attractor as a controlling symbol and the dynamics to which it refers is lawful rather than merely definitional or associative. As noted, an attractor defines a system's asymptotic behavior, and the low dimensional set of equations of motion that describes motion along this attractor can be derived from the higher dimensional equation set describing the original system (Haken, 1983; Thompson and Stewart, 1986). Relatedly, an attractor as a controlling symbol is, by definition, far less detailed than the output to which it refers.

7.2.2 An Ecological Approach to Perception

The essentials of the ecological approach to perception as developed by James J. Gibson (1959; 1966; 1979; Reed and Jones, 1982), 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 and to one's movements. In more expanded terms, the ecological approach advanced by Gibson comprises a program of research and theory having three parts relating, in turn, to the nature of information, the basis of perception, and the development of perception.

With respect to the first part, it attempts to identify the specificity between the structured energy distributions available to a perceptual system and the environmental and movement properties causally responsible for that structure. This latter specificity is what is meant by "information" in the ecological approach. The specificity is sought at a macroscopic level of description and is expected to be revealed in terms of observables that, in general, will not have been identified in physical theory. One characteristic of these macroscopic observables is their

low dimensionality (meaning, roughly, that very few quantities are needed to describe them). In state spaces of minimal dimensions, these observables wrap up or condense the order present in surrounding energy distributions that are described molecularly in state spaces of very many dimensions.

With respect to the second part, the ecological approach asserts the directness of perception, in the sense that the specificity of perception to information dispenses with any intervening special process, like inference. Integral to this second part is the hypothesis that, for every property perceived, there is a corresponding macroscopic property of the structured energy distribution. This generalized hypothesis of information-perception specificity directs investigation to the uncovering of one-to-one mappings between information and perception. A particular perception results if and only if a particular informative structure is detected. In reference to perception-action cycles, this second part aims at understanding how specificity is preserved over the components of an animal-environment system.

With respect to the third part of the program, it suggests that improvement in perceiving in any given situation follows from the discovery of, and attunement to, information. In any given situation, the lawful regularities between aspects of surface layout and macroscopic properties of structured energy distributions specify a wide range of environmental properties, including the property of interest. In learning to perceive, the perceiver progresses from under- or overdifferentiating the ambient energy distribution to differentiating it precisely (Epstein et al., 1989; Gibson and Gibson, 1955; 1972).

7.3 Task-specific Coordinations

One preliminary way to think about a task-specific coordination is in terms of an attractor layout—attractors and their surrounding basins of attraction (Saltzman, 1986; Saltzman and Kelso, 1987; Saltzman and Munhall, 1989). Task-specific coordinations can follow from the simple control of initial conditions that put the system into the basin of a given attractor. The act will then (self) organize by converging onto the attractor. 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. In dynamic 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 spatially defined point attractor. If reaching is a task whose dynamics are those of such a point attractor, then the challenge is to understand the embodiment of this invariant task dynamic in variable movement patterns. Our strategy has been to conceptualize the point attractor dynamics as a description of the task in a small number of functionally defined coordinates (defining a so-called *task space*) and then to pursue an understanding of the transformation of coordinates that maps these *intended*, low dimensional task dynamics into the higher dimensional articula-

tory (skeletal, muscular, neural) subspace. Effectively, this mapping defines a task-specific pattern of coupling or coordination among the articulators that acts to convert the articulator subset into a special-purpose device tailored to the intended task.

Planar reaching movements have been shown experimentally to display quasi-straight line path shapes en route to the target object (Flash, 1987; Morasso, 1981). It has been demonstrated (Saltzman and Kelso, 1987) that such reachable objects can be simulated as points in task space that are capable of attracting a multiplicity of different limb trajectories displaying straight-line hand paths. However, quasi-straight lines are not straight lines, and it is important for a dynamic account of reaching to address this discrepancy. In a recent paper, Flash (1987) has suggested on empirical and theoretical grounds that deviations from straight-line hand paths are systematic and may be interpreted as the results of a "competition" between the controlling influences of a straight-line *reference trajectory* in the task space and the inherent biomechanics of the musculo-skeletal apparatus (for example, the posture-dependent stiffness field due to the elastic properties of muscles and tendons, and reactive torques due to inertial, coriolis, and centripetal coupling among joints). In the following sections, we explore more closely the relations between task space and articulatory dynamics in the context of rhythmic biological movements.

7.3.1 *Coordinative Structures as Cooperative States*

Many years ago, the German behavioral physiologist von Holst noted that coordinated rhythmic states entail cooperation among units that, roughly speaking, prefer to be doing something else. Investigating the rhythmic fin movements of Labrus, a fish that swims with its longitudinal axis immobile, von Holst (1938; 1973) observed that each rhythmic unit had a preferred tempo—exhibited when the unit oscillated freely and in isolation from other fin rhythmic units—that had to be compromised when its behavior was coordinated with that of one or more other fin rhythmic units. Von Holst referred to the tendency of a unit to revert, when released from the demands of coordination, to its preferred or inherent dynamics as the "maintenance tendency." The cooperative process that bound together units with different intrinsic dynamics was termed the "magnet effect." He underscored that, even when fins were perfectly synchronized—that is, all oscillating at the same frequency in what he called absolute coordination—the maintenance tendency remained latent. For von Holst, the gathering of components into a single functional organization, a coordinative structure, involved cooperation and competition.

A cooperative state in physical systems can be regarded as three tiered. For example, the vortex arising in a fluid flowing through a pipe may be regarded as an in-between level of organization that is supported by the interplay between the dynamics of the molecular processes "below" and the boundary conditions of the walls of the conduit "above" (Iberall and Soodak, 1987). By analogy, a

coordination may be regarded as three tiered: The lower level comprises the autonomous units with their inherent dynamic preferences; the upper level comprises the intention (goal, plan, schema); and the middle level is the coordination (Kugler and Turvey, 1987; Turvey et al., 1986). A simple coordination of rhythmic movements can be used to express this analogy and its usefulness.

7.3.2 Absolute Coordination of Pendulumlike Rhythmic Movements

Imagine a person seated, holding a pendulum in each hand. The pendulums can vary physically in shaft length and/or the mass of the attached bob. Because of these physical magnitudes, a person's comfortable swinging of a hand-held pendulum about an axis in the wrist (with other joints essentially immobile) will exhibit a preferred dynamic. That is, the pendular motions will tend to a particular frequency and a particular amplitude (Kugler and Turvey, 1987). The exhibited intrinsic dynamic is not strictly that of a gravitational pendulum, however. In particular, the person must use chemical energy in the muscles to sustain the rhythmic movement and must establish a pattern of muscular co-contractions to maintain fairly even periods and amplitudes from cycle to cycle. For bimanual tasks, if the pendulums held in each hand differ in physical dimensions (length, mass), then their intrinsic dynamics—their maintenance tendencies—will not correspond. Consider bringing to bear the following task demands on these rhythmic units: That they oscillate together comfortably at the same frequency in phase (with a 0° phase difference); that they oscillate together comfortably at the same frequency out of phase (with a 180° phase difference); that they oscillate at the most comfortable phase relation, whatever it may be; that they oscillate with the same amplitude, and so on. Each of these task demands, by analogy with ordinary physical cooperativities, results in a different boundary condition or constraint on the same inherent dynamics. Each task demand can be satisfied only by the component rhythmic units departing from their preferred states in particular ways; and each coordination, resulting from the interplay of the task demand and the intrinsic dynamics of the component units, ought to exhibit dynamic idiosyncracies of its own.

Let us focus first on the fate of the component units. Experiments have shown that when a hand-held pendulum is made to depart from its preferred state by the demands of coordination, fluctuations in the period and amplitude of the rhythmic movement increase (Rosenblum and Turvey, 1988). Or, conversely, when a hand-held pendulum oscillates in coordination with another hand-held pendulum at a tempo close to its preferred tempo, then its fluctuations are least. This outcome is consistent with von Holst's maintenance tendency. Another outcome is also consistent. In the experiments just referred to, a person was asked on each trial to swing two pendulums comfortably at the same frequency out of phase.

Across trials the physical dimensions of the pendulums varied, as did the differences between members of a bimanual pair. It turned out that although the person's intent was to have one pendulum swinging forward exactly as the other was swinging backward—that is, a 180° phase difference—the actual phase difference depended systematically on the size of the difference between the dimensions of the two hand-held pendulums and, thereby, the size of the difference between their characteristic frequencies (Rosenblum and Turvey, 1988). Two conclusions follow from this result. One is that the intrinsic dynamics of the component units penetrates the modal coordination state. The phase difference reflects the fact that the intrinsically faster unit leads the intrinsically slower unit (a fact that had been observed by von Holst (1937; 1973), with fish fins, and by Stein, 1977, in the crayfish swimmeret system). The other conclusion is that the intentions to achieve comfortable absolute coordination and a 180° phase relation cannot both be satisfied simultaneously. This latter conclusion nicely underscores how it is that achieving a task-specific coordination (the state “in between”) depends on the compatibility of one's goals (the constraints “above”) and the characteristic preferences of the component units (the intrinsic dynamics “below”).

It has been hypothesized (Wing, 1980; Wing and Kristofferson, 1973) that the temporal variance in a rhythmic movement is decomposable into two independent variances—the variance in a dynamic organization that functions as a timekeeper and the variance in the activation of the muscular components that implement the rhythmic movement. In particular, it was predicted that the correlation between adjacent cycles should be negative (between 0 and -0.5 on the average), and the correlations between nonadjacent cycles should be nonsignificant. The closer the lag 1 autocorrelation approximates -0.5 , the larger is the relative contribution of motor variance and the smaller the relative contribution of clock variance to the overall fluctuations in periodicity. Empirically, when people swing two hand-held pendulums in absolute coordination, the lag 1 autocorrelations are significant and in the 0 to -0.5 range, whereas the autocorrelations at higher lags are insignificant—the pattern of results that is required by the assumption of independent “clock” and “motor” processes (Turvey, Schmidt, and Rosenblum, 1989).

This analysis of “clock” and “motor” variance permits further understandings about the relation between the coordinated state and the component units from which it is composed. First, motor variance but not clock variance is found to increase when a rhythmic unit is forced to depart from its preferred tempo by the task demands of absolute coordination (Turvey et al., 1989). These demands serve to increase the proportion of active muscular forces relative to the contributions of the mechanical forces associated with the hand-held pendulum. Second, whereas clock variances are highly correlated across the two (left and right) units in absolute coordination, motor variances are not (Turvey et al., 1989). Third, clock variances of both units are larger when absolute coordination approximates a 180° phase relation than when absolute coordination approxi-

mates a 0° phase relation; the motor variances, in contrast, are unaffected by the mode of coordination (Turvey et al., 1986). These results suggest that, in satisfying the task demands of absolute coordination, the component units (1) are organized according to a modal task space attractor that acts implicitly as a timekeeping function and is more stable when the coordination mode is in phase than when it is out of phase, and (2) the component units become increasingly irregular in the patterning of muscular activity with increasing displacements from their preferred tempos. More generally, we see that it is possible to identify the dynamic properties of the lower level (the component units) and the middle level (the cooperative state) of a coordinative structure and to hypothesize that the notion of preferential or intrinsic dynamics can be extended to the middle level. Thus, two or more rhythmic units may couple better in some ways than in others, and the maintenance tendency may apply, therefore, to combinations of units as well as to isolated units. Before pursuing this idea, let us take a look at the same kind of coordinative structures just examined, but now with the rhythmic units belonging to different people and linked visually.

7.3.3 *Optically Based Coordinations*

Imagine two people sitting side by side, each holding a pendulum. One person holds a pendulum in the right hand and one person holds a pendulum in the left hand. The pendulums, as before, are swung about an axis in the wrist. The free hand and arm, which is the arm closest to the other person, rests on the thigh. The task of the two people is to watch each other closely and coordinate the swinging of the two pendulums such that they oscillate at the same frequency and out of phase. Paralleling the experiments described above, the physical dimensions of the pendulums can be the same or different, and the pairings of pendulum dimensions change from trial to trial. Results from an experiment conducted in the preceding fashion (Schmidt, 1988) reveal the same pattern in two-person, visually based coordination as is found in the more familiar one-person, haptically based coordination (where *haptic* refers to the perceptual system by which one knows about relations among body segments and properties of adjacent surfaces by means of the body). First, the two oscillating units can achieve and maintain absolute coordination (1:1 frequency locking). Second, the maintenance tendency is in evidence, in that fluctuations in frequency and amplitude tend to increase as a unit is forced to oscillate, by the demands of absolute coordination, at a nonpreferred frequency. Third, the phase relation between the two units is exactly 180° out of phase only when the inherent frequencies of the two units are identical. Otherwise the phase relation increases systematically with the difference between the characteristic frequencies of the two units.

The latter result is especially important. As far as we can tell, each of the following conditions exhibit phase relations in absolute coordination with one and the same dependency on the intrinsic frequencies of the component rhythmic units: spontaneous rhythmic fin movements of decapitated fish; oscillations of

crayfish swimmerets induced by stimulating "command neurons"; voluntary rhythmic movements of pendulums held in a person's left and right hands; and voluntary rhythmic movements of a pendulum held in the right hand of one person and a pendulum held in the left hand of another person. One reading of this convergence is that common dynamic principles are at work. If that is a correct reading, then recognition must be given to the possibility that these principles apply when the coupling is informational (Kugler and Turvey, 1987; Schmidt, 1988). Presumably, between-person visual coordination is based on optical information specific to the dynamics of the component rhythmic units. The observed convergence of phase-locking phenomena might then suggest that coordination instanced in other ways is similarly based on information specific to dynamics.

7.3.4 Sudden Jumps in Haptically Based and Optically Based Coordinations

Let us now turn, as promised, to the inherent dynamics of the cooperative, modal level of organization sustained by the interplay of the intentional constraints "above" and the dynamics of the rhythmic units "below." We shall consider these cooperative or modal dynamics in the context of an analogy with the simplest type of self-organization in physics, the phase transition. Under certain conditions, one type of interlimb coordination gives way suddenly and spontaneously to another. The phenomenon in question can be observed in a paradigm in which a person is required to oscillate the two index fingers (or two hands) at the same frequency (Kelso, Scholz, and Schöner, 1986; Scholz, 1986). Frequency is varied by a metronome that the person tracks; it acts as a control parameter. The phase relation between the body segments is interpreted as an order parameter. A parameter of the latter kind does very much what its name suggests—it quantifies the order present in a collection of things. Such parameters are essential in cases where there is a lot of detail and one needs a simple measure to keep track of all this detail, especially if it is undergoing a fairly abrupt change. Results show that the order parameter for interlimb coordination is more stable at some values than others. With increasing frequency, an out-of-phase interlimb coordination switches abruptly to an in-phase coordination. 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. The in-between level of organization has an inherent dynamics marked by a preference for limbs moving together in the same direction.

Of particular importance with respect to the drawing of parallels with physical phase transitions is the fact that the order parameter exhibits critical slowing down (if perturbed, it takes longer to recover closer to the transition point) and, under certain conditions, the order parameter exhibits critical fluctuations (the standard deviation grows significantly as the transition point gets closer). These conditions are that the fast time scale associated with the relaxation back to out of phase is notably less than the time scale of change in the control parameter,

which is notably less, in turn, than the slow time scale associated with the passage from out of phase to in phase. Order parameter fluctuations do not increase prior to the sudden behavioral change when the slow time scale is less than the time scale of the control parameter.

The same phenomenon of a sudden transition in coordination, exhibiting many of the same criterial properties, has been observed when two limbs are connected optically between two people (Schmidt, 1988; Schmidt, Carello, and Turvey, 1990). In the experiments in question, two seated people each oscillated a leg with the goal of coordinating the two legs out of phase (180°) or in phase (0°) as the frequency of the movement was increased. To satisfy the goal, the two people watched each other's lower leg. The between-person visual coordination case matches the within-person haptic coordination case: A transition occurs, it occurs in only one direction (180° to 0°), and it is accompanied, under certain conditions, by critical fluctuations. The between- and within-person cases involve the same relations among the same observable quantities despite the obvious differences between the two cases (e.g., the nervous systems of two people vs. the nervous system of one person; using the visual perceptual system in between-person coordination vs. using the haptic perceptual system in within-person coordination).

The sudden changes in haptic and visual instances of interlimb coordination may be taken as examples of a process in which the attractor layout in task space evolves during the execution of the activity. The implication is that very general dynamic and informational principles are at work and that a comparison of behavioral discontinuities in movement systems with phase transitions in physical systems may prove to be more than mere analogy. In both of the above cases, the differential stability of the two phase relations and the transition between them can be accommodated under the assumption that the system of coordinated limbs is governed by a smooth potential function whose shape depends on both phase (order parameter) and frequency (control parameter). The function can be so defined that the minima of the potential (attractors) are located at 180° and 0° , the function's global minimum is at 0° and the 180° local minimum is annihilated at some critical control parameter value (Haken, Kelso, and Bunz, 1985).

7.4 Concluding Remarks

We have sketched an orientation to coordination that emphasizes (1) the formation of low-dimensional, task-space dynamical systems through the appropriate fashioning of coupling functions among the degrees of freedom of higher-dimensional articulatory spaces; (2) the mutual influences of these two dynamic levels on each level's behavior; (3) the wide range of sources of coupling influences (haptic, optic, mechanical) between dynamic degrees of freedom; and (4) the role of intention in constraining and harnessing the dynamics of the perception-action cycle.

Acknowledgments

Preparation of this manuscript has been supported by the following NIH grant NS-13617, NSF grant BNS-8520709, and NIH grant RR-05596, awarded to Haskins Laboratories, and NSF grant BNS-8811510 awarded to the first author.

References

- Beek, P.J. 1989. Timing and phase-locking in cascade juggling. *Ecological Psychology* 1:55-96.
- Bernstein, N.A. 1967. *The Coordination and Regulation of Movements*. London: Pergamon Press.
- Epstein, W., Hughes, B., Schneider, S.L., Bach-Y-Rita, P. 1989. Perceptual learning of spatial-temporal events: Evidence from an unfamiliar modality. *Journal of Experimental Psychology: Human Perception and Performance* 15:28-44.
- Flash, T. 1987. The control of hand equilibrium trajectories in multi-joint arm movements. *Biological Cybernetics* 57:257-274.
- Gelfand, I.M., Gurfinkel, V.S., Tsetlin, M.L., and Shik, M.L. 1971. Some problems in the analysis of movements. In I.M. Gurfinkel et al. (eds.), *Models of the Structural-Functional Organization of Certain Biological Systems*. Cambridge: MIT Press.
- Gibson, J.J. 1959. Perception as a function of stimulation. In S. Koch (Ed.), *Psychology: A Study of a Science* (Vol. 1). New York: McGraw-Hill.
- Gibson, J.J. 1966. *The Senses Considered as Perceptual Systems*. Boston: Houghton Mifflin.
- Gibson, J.J. 1979. *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.
- Gibson, J.J. and Gibson, E.J. 1955. Perceptual learning: Differentiation or enrichment? *Psychological Review* 62:32-41.
- Gibson, E.J. and Gibson, J.J. 1972. The senses as information-seeking. *The London Times Literary Supplement*, June 23, pp. 711-712.
- Greene, P.H. 1972. Problems of organization of motor systems. In R. Rosen and F.M. Snell (eds.), *Progress in Theoretical Biology* (Vol. 2). New York: Academic Press.
- Haken, H. 1983. *Advanced Synergetics*. Heidelberg: Springer-Verlag.
- Haken, H., Kelso, J.A.S., and Bunz, H. 1985. A theoretical model of phase transitions in human hand movements. *Biological Cybernetics* 51:347-356.
- Iberall, A., and Soodak, H. 1987. A physics for complex systems. In F.E. Yates (ed.), *Self Organizing Systems: The Emergence of Order*. New York: Plenum.

- Kay, B.A. 1989. The dimensionality of movement trajectories and the degrees of freedom problem: A tutorial. *Human Movement Science* 7:343–364.
- Kelso, J.A.S., Delcolle, J.D., and Schöner, G. 1990. Action-perception as a pattern formation process. In M. Jeannerod (ed.), *Attention and Performance XIII*. Hillsdale, NJ: Erlbaum.
- Kelso, J.A.S., Scholz, J.P., and Schöner, G. 1986. Nonequilibrium phase transitions in coordinated biological motion: Critical fluctuations. *Physics Letters A* 118:279–284.
- Kugler, P.N., Kelso, J.A.S., and Turvey, M.T. 1980. On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In G.E. Stelmach and J. Requin (eds.), *Tutorials in Motor Behavior*, Amsterdam: North-Holland, pp. 3–47.
- Kugler, P.N., Kelso, J.A.S., and Turvey, M.T. 1982. On the control and coordination of naturally developing systems. In J.A.S. Kelso and J.E. Clark (eds.), *The Development of Movement Control and Coordination*. New York: Wiley, pp. 5–78.
- Kugler, P.N., and Turvey, M.T. 1987. *Information, Natural Law and the Self-Assembly of Rhythmic Movement*. Hillsdale, NJ: Erlbaum.
- Morasso, P. 1981. Spatial control of arm movements. *Experimental Brain Research* 42:223–227.
- Pattee, H.H. 1972. The nature of hierarchical controls in living matter. In R. Rosen (Ed.), *Foundations of Mathematical Biology*. New York: Academic Press.
- Pattee, H.H. 1980. Clues from molecular symbol systems. In U. Bellugi and M. Studdert-Kennedy (eds.), *Signed and Spoken Language: Biological Constraints on Linguistic Form*. Weinheim: Verlag-Chemie.
- Reed, E.S. and Jones, R. 1982. *Reasons for Realism: Selected Essays of James J. Gibson*. Hillsdale, NJ: Erlbaum.
- Rosenblum, L.D., and Turvey, M.T. 1988. Maintenance tendency in coordinated rhythmic movements: Relative fluctuation and phase. *Neuroscience*, 27:289–300.
- Saltzman, E. 1986. Task dynamic coordination of the speech articulators: A preliminary model. *Experimental Brain Research* Ser. 15:129–144.
- Saltzman, E. and Kelso, J.A.S. 1987. Skilled actions: A task dynamic approach. *Psychological Review* 94:84–106.
- Saltzman, E.L. and Munhall, K.G. 1989. A dynamical approach to gestural patterning in speech production. *Ecological Psychology* 1:333–382.
- Schmidt, R.C. 1988. *Dynamical Constraints on the Coordination of Rhythmic Limb Movements Between Two People*. Doctoral dissertation, University of Connecticut, Storrs.

- Schmidt, R.C., Carello, C. and Turvey, M.T. 1990. Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. *Journal of Experimental Psychology: Human Perception and Performance* 16:227-247.
- Scholz, J.P. 1986. *A Nonequilibrium Phase Transition in Human Bimanual Movement: Test of a Dynamical Model*. Doctoral dissertation, University of Connecticut, Storrs.
- Schöner, G., and Kelso, J.A.S. 1988a. Dynamic pattern generation in behavioral and neural systems. *Science* 239: 1513-1520.
- Schöner, G., and Kelso, J.A.S. 1988b. Dynamic patterns in biological coordination: Theoretical strategy and new results. In J.A.S. Kelso, A.J. Mandell, and M.F. Schlesinger (eds.), *Dynamic Patterns in Complex Systems*, Singapore: World Scientific, pp. 77-102.
- Stein, P.S.G. 1977. A comparative approach to the neural control of locomotion. In G. Hoyle (Ed.), *Identified Neurons and Behavior of Arthropods*, New York: Plenum Press, pp. 227-239.
- Thompson, J.M.T., and Stewart, H.B. 1986. *Nonlinear Dynamics and Chaos*. New York: Wiley.
- Turvey, M.T., and Kugler, P.N. 1984. An ecological approach to perception and action. In H.T.A. Whiting (ed.), *Human Motor Actions: Bernstein Reassessed*, Amsterdam: North-Holland, pp. 373-410.
- Turvey, M.T., Rosenblum, L.D., Schmidt, R.C., and Kugler, P.N. 1986. Fluctuations and phase symmetry in coordinated rhythmic movements. *Journal of Experimental Psychology: Human Perception and Performance* 12:564-583.
- Turvey, M.T., Schmidt, R.C., and Rosenblum, L.D. 1989. "Clock" and "motor" components in the absolute coordination of rhythmic movements. *Neuroscience* 33:1-10.
- von Holst, E. 1937/1938; 1973. *The Behavioral Physiology of Animal and Man: The Collected Papers of Erich Von Holst*. Coral Gables, FL: University of Miami Press.
- Wing, A.M. 1980. The long and short of timing in response sequences. In G.E. Stelmach and J. Requin (Eds.), *Tutorials in Motor Behavior*, Amsterdam: North-Holland, pp. 469-485.
- Wing, A.M. and Kristofferson, A.B. 1973. Response delays and the timing of discrete motor responses. *Perception and Psychophysics* 14:5-12.
- Yates, F.E. 1982. Outline of a physical theory of physiological systems. *Canadian Journal of Physiology and Pharmacology* 3: 217-248.
- Yates, F.E. (ed.) 1987. *Self Organizing Systems: The Emergence of Order*. New York: Plenum Press, 1987.