

Neural networks and the first and second rounds of theorizing on Bernstein's problem *

Reaction to Bullock and Grossberg, 1991

R.C. Schmidt, P.J. Treffner, and M.T. Turvey

University of Connecticut, Storrs, USA

Introduction

The biological question addressed by Bullock and Grossberg is that of how a person, seated or standing, is able to reach an adjacent object from any initial posture, allowing only movement of an upper limb. The tack taken by these investigators is that of detailing the characteristics of, and interactions among, a modest number of information processing subsystems whose architectures (patterns of connectivities) are inspired by the structures of central and peripheral neural networks. The artistry with which Bullock and Grossberg apply their tools as neural network modelers is to be admired. The end product is an account of how one controls an arm that is wide in scope – accommodating more data, and more varied data (behavioral and neurophysiological), than any other account currently available – and generative – motivating reasons for the functions of a number of prominent neural components and predicting novel roles for others. Our comment focuses on placing their modeling efforts in the context of ideas developed to address the general nature of coordination in biological movement

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Correspondence address: R.C. Schmidt, CESP, U-20, 406 Babbidge Road, University of Connecticut, Storrs, CT 06269, USA.

systems. To be specific, we wish to position Bullock and Grossberg's account with respect to what we will term the first and second rounds of theorizing and experimentation on Bernstein's problem of degrees of freedom (Turvey 1990). In short, where the first round seeks resolution of this problem in mechanisms particular to nervous systems modeled as either von Neuman-like or connectionist-like devices, the second round seeks resolution in very general laws and principles.

Our comment has five parts, beginning with a review of Bernstein's problem. In the second part we emphasize the continuity between the major tenets of the first round and the tenets of Bullock and Grossberg, and suggest that Bullock and Grossberg's work may well represent the most sophisticated version of first round theorizing. In the third part we identify directions that first round theorizing could take which are not taken by Bullock and Grossberg, and we use these contrasts to highlight potential sources of arbitrariness in the kinds of analyses characterizing the first round. In the fourth part we sketch the second round and suggest why we think it is more likely to provide a nonarbitrary account of actions. In the final part we raise the issue of whether or not the two strategies, that advocated by Bullock and Grossberg and that characterizing the second round, may prove to be mutually beneficial; that is, we raise the question of the possibility of enhancing movement science through a careful braiding of both strategies.

Bernstein's problem

To an important degree, what makes an account of reaching so challenging is the number of components that it entails. An arm as a kinematic linkage consists of three joints and a hand, as an arrangement of kinematic linkages, consists of fourteen. In terms of joint motions there are many degrees of freedom whose values are to be specified. Thus, the upper arm is capable of motion on three axes and the lower arm and hand are each capable of motion on two axes; a joint of the hand permits motion on either one or two axes. Approximately twenty-four muscles actuate the arm, and close to twice as many actuate the digits. At scales finer than joints and muscles, one notes the very large numbers of motoneurons, receptors, neurons, and interneurons subserving muscle activation. In addition to these there are vast numbers of capillaries and lymphatic vessels engaged in the metabolic

processes promoting muscle activation. An act of reaching involves the management of these multiple components – these multiple degrees of freedom – at multiple length and time scales. Exactly how nervous systems, or nervous systems in environmental contexts, resolve this management question in the general case has become known as Bernstein's problem (Kugler et al. 1980; Turvey 1990). Following upon the intuitions of Bernstein's (1967), the idea, coarsely stated, is that the management must be achieved through a devolution of responsibility. The challenge for science is understanding the principled manner by which this devolution is achieved.

First round of theorizing on Bernstein's problem

Before the depth of Bernstein's problem was fully appreciated it was often implied that any given coordination was achieved through a single program of computation in which all the necessary details were specified by an executive subsystem in a single instance, including those needed to immunize against perturbing influences (e.g. Keele 1968). An idea carried over from the last century tended to permeate most of the literature on coordinated movements, viz., the spatio-temporal details of a movement, and the microactivities of the supporting neural substrate, were prescribed ahead of the movement. The metaphor was of an executive subsystem reading prepared scripts and instructing the individual neural players accordingly. If the variables to be controlled were few, then one can imagine that the foregoing strategy would be reasonably successful. On the other hand, if the total number of variables was very large, then one can imagine that the strategy of a single stage of exact computation would prove cumbersome and costly.

In the 1960s and 1970s a number of Soviet and American scholars (e.g., Gelfand, Tsetlin, Gurfinkel, Greene, Boylles), sensitized to the problems of controlling systems of many degrees of freedom, explored a different strategy. They emphasized the design principle of a limited number of autonomous subsystems created largely for the purpose of preserving stability of a system in a particular environment. And they posed the question: Given subsystems that perform according to local intrinsic criteria, how can they be suitably organized to perform according to some global extrinsic criteria encompassing the collection of

subsystems as a unitary system? More simply, the question posed was, given subdevices that do what they want, how do you get them all to do what you want? Obviously this strategy would be inelegant where few variables were involved since achieving any arbitrary configuration of the said variables could not be done directly (and, of course, this would be easiest), but only indirectly through the modulation and interaction of the autonomous subsystems. But such a strategy would be beneficial when very many variables were involved. Given the right organization, an approximation of a desired configuration of a very large number of degrees of freedom could, in principle, be achieved through the regulation of the relatively few degrees of freedom of the autonomous subsystems. Because the subsystems provide the movement details in the course of their activity, and because the role of any executive would be confined to setting up constraints to harness the natural tendencies of the subsystems, movement patterns under this second strategy are not performed but are emergent. The metaphor is that of morphogenesis, and a key analytic idea is that of autonomous subsystems as dynamical systems characterized by the time evolution of their defining observables.

Clearly, Bullock and Grossberg's account of reaching is in the spirit of this second strategy, which we refer to as the first round of theorizing and experimentation on Bernstein's problem (Turvey 1990). This first round takes as its major concerns (a) isolating and describing the autonomous subsystems, (b) identifying the manner of their interaction, and (c) detailing the methods by which the subsystems and their interactions can be modulated. Each of these concerns is taken up in earnest by Bullock and Grossberg. Although Bullock and Grossberg share a great many ideas (e.g., nonspecific central commands, muscle synergies) with others who have been engaged in the first round, they go beyond much of the previous work to give mathematically precise interpretations of a number of vague notions that appealed to first round scholarship – such as, for example, synergetic outputs from undifferentiated inputs and patterns of regularity without specific regulators.

Elaborating Round One theorizing in other directions

Bullock and Grossberg present in detail one direction that can be pursued in advancing Round One theorizing. But other directions are

possible. We briefly survey (a) another way to understand arm trajectories and (b) an alternative modeling style for neural processes. We conclude this subsection with (c) a query about the scope of neural network modeling. The latter provides an entry point into what can be termed the second round of theorizing on Bernstein's problem.

(a) Accounting for arm trajectories with minimal use of cybernetical components

Bullock and Grossberg posit two autonomous subsystems that produce the movement trajectory of a reaching arm under variable speed movements and force conditions. We review the components of these subsystems and then suggest other properties such subsystems could have in order to accomplish their goals.

The VITE module which produces trajectories that are invariant under speed rescaling consists principally of three components: a non-specific GO signal that controls the speed of the movement, a Target Position Command (TPC) that encodes the final position of the trajectory, and a Present Position Command (PPC) that controls the moment-to-moment outflow to the limb in the form of muscle lengths. The dynamics of the module consists of an efference copy loop that compares the PPC to the TPC and creates a Difference Vector (a set of DV_i , one for each muscle involved) that describes the next state that each muscle should attain in order to reach its final target position. The DV is organized into the outflow not by simply adding it to the PPC but by multiplying it first by the GO signal. This feature has the significant property of producing synchronous activity of the muscles involved; they all reach their final state at the same time.

While the VITE module has been presented by Bullock and Grossberg elsewhere (Bullock and Grossberg 1988), the new contribution in the present paper is the FLETE module which produces invariant trajectories under force rescaling. The FLETE module's basic strategy to manipulate the force of a movement is a non-specific co-contractive signal sent to antagonist muscles at a joint. Since such co-contraction may inadvertently produce limb rotations by changing the lengths of opponent muscles, it can disturb the position code invariance of the VITE module if other processes are not prepared to enforce it. Bullock and Grossberg propose that the processes to compensate for the

unequal amplifications of the co-contractive signals are the opponent population of Renshaw cells which essentially balance the signals to the opponent muscle groups to prevent limb rotation without negating the force scaling of the co-contraction.

Bullock and Grossberg's scheme addresses a core concern of Round One theorizing, that of how to minimize executive responsibility. It does so by extending a common strategic feature of Round One, namely, appealing to artifactual mechanisms; specifically, incorporating mechanisms whose origins lie in human efforts to implement systems with biological qualities such as self-regulation. Thus, there are only two degrees of freedom for an executive subsystems to manipulate – the non-specific GO and co-contractive signals associated with the intended speed and force of the environment. Responsibility for transferring these two intentional signals into controlled movement trajectories is assigned to subsystems (VITE and FLETE) embodying multiplicative gating, reference signals, feedback loops, comparators, and error-correcting devices (for example, the processes used to create the DVs and to balance the co-contractive signals). A cornerstone of the general program of Grossberg and his colleagues is the assumption that intricate, invariance-preserving components of the kind found in VITE and FLETE have evolved for use in many different evolutionary specializations. Assuming that evolution has created such components may be valid and Bullock and Grossberg present supporting evidence. Nonetheless, a different tack can be pursued in which proposed autonomous subsystems achieve adaptive sensory-motor control without explicit computation and representation *and* without undue emphasis on reference signals, feedback loops, comparators, error-correcting devices, and so on.

Feldman's λ model (Abdusamatov et al. 1987; 1988; Feldman 1986) addresses explicitly the control of limb movement without the assumption of such constraints. In this model the responsibility for the control of a movement is not completely neural in nature as in the Bullock and Grossberg scheme but is shared between the nervous system and the inherent dynamics (Bingham 1988) of the effector system used to produce the movement. That is, there is a neurally specified central parameterization of the dynamical properties (for example, the stiffness, damping and equilibrium-point) of the muscle synergy of the effector; and the control of limb movements is determined by setting these dynamical parameters. Feldman's λ model proposes that the

primary parameter that needs to be set is the λ value, the equilibrium position of the point attractor dynamics underlying the stretch reflex.

Feldman's model and Bullock and Grossberg's models do share features. Both have intentional specification of the speed of the movement and the amount of force. In the λ model the force of a movement is controlled, as in the Bullock and Grossberg model, through the central specification of a co-contraction of antagonistics c (Abdusamatov et al. 1987) while the speed of a movement is controlled through the central specification of the synergy's damping parameter μ . In addition, the λ model posits the central control of the position of the arm at a given point in time. This property of the limb is the result of setting the stretch reflex resting lengths r of the antagonists muscles involved.

The λ model is a refined version of the Spring-To-Endpoint (STE) model of limb movements. Bullock and Grossberg (1988) have criticized earlier versions of this model primarily for not countenancing a gradual shift in the equilibrium position during the evolution of a movement that seemed to be underlying some empirical findings (Bizzi et al. 1984). The λ model addresses these data by embracing a continual shift in r . 'The command r develops at a constant rate μ to a final value which determines the final equilibrium position of the joint' (Abdusamatov et al. 1988: 184). Using constant velocity shifts in the equilibrium point to model single joint movements against zero load and with load increasing as an exponential function of the joint angle, simulations of the model yielded properly formed movement kinematics. Using the assumption that the torque produced is a function the magnitude of the EMG signal and the shape of the invariant characteristic curves, simulations yielded the three-burst EMG pattern typical of fast one-joint movements.

In distributing the responsibility of the movement across both neural and effector dynamics, the λ model produces a self-organized, emergent limb trajectory without the assumption of neural mechanisms that simulate cybernetical devices. It has further parsimony because the positional (r) and co-contractive (c) neural signals that set the equilibrium point and stiffness of the effector, respectively, do not comprise different neural modules as in the Bullock and Grossberg scheme. As a matter of fact, in the λ model they are written in the same language. For both commands particular relations of the resting lengths (λ_i) of the antagonist muscles make up these signals ($r = (\lambda_1 + \lambda_2)/2$ and

$c = (\lambda_1 - \lambda_2)/2$). In the λ model only one kind of unit is manipulated by the nervous system to produce changes in both position and stiffness. Hence, although Bullock and Grossberg warn against using lumped parameters such as λ , in this case the use of one such parameter has the significant effect of reducing the number of degrees of freedom that the nervous system must control.

(b) Elaborating neural-like accounts with an emphasis upon global, not local processes

The complexity of biological movement systems, with functional richness exhibited at both micro and macro scales, allows many different approaches to the causal basis of acts. Neural and non-neural interpretations can be pursued. In pursuing a neural-like explanation, Bullock and Grossberg formulate their account in terms of one of several possible perspectives on nervous system function. Their approach exemplifies applied connectionist simulations. The goal is to reproduce specific behavioral data; this is achieved by discrete activation-passing mechanisms emphasizing stable, stationary final states of network activity (Cohen and Grossberg 1983; Hirsch 1989). One alternative neural-like explanation emphasizes continuous, non-stationary and structurally stable dynamics of highly non-linear interactions. Theoretical accounts with such an emphasis do exist and are being applied to neurophysiological data. These accounts draw their analogies from the oscillatory and field-like qualities of neural, chemical, and thermodynamic activity (Basar 1983; Adey 1988; Freeman and Skarda 1985; Frohlich 1988) and suggest novel ways of conceptualizing the collecting of neural components into functional units. Although no models of this genre have been advanced to address the coordination issues of concern to Bullock and Grossberg, there are implications that their basic precepts may bear importantly on such issues.

(c) Getting beyond simulations and moving toward 'true' models

Success at simulating the characteristic qualities of a biological movement system with discrete activation-passing neural networks rests on two closely related features. First, the underlying properties are mathematical rather than physical and are, therefore, open to relatively unconstrained manipulations. Second, the parameters of the proposed

dynamical systems can be initialized in ways suited to the behavioral phenomenon in question. Success at simulating kinematical data can be achieved, therefore, without necessarily involving the actual factors playing constraining roles in the full phenomenon. As observed by Rosen (1988), a software simulation, as a formal system, has within it no counterpart or decoding of the extraneous hardware necessary to implement the simulation. The consequence of this formalization is that a necessary component of the causal structure of the system being simulated is not preserved in the simulation. Such omissions can lead to the adoption of arbitrary mechanisms required to establish agreement between simulation and data. In contrast to a simulation, a model maintains the full set of relationships between those grains of analysis relevant to the required behavior (for example, the dimensionless invariants preserved in engineering modeling such as Reynolds, Froude, and Prandtl numbers). Designing a model faithful to the phenomenon of interest involves one of two possible strategies. In order to submit to the same pattern of forces as the target phenomena, an analogue material scale-model could be built. This would eliminate software simulation (e.g. McGeer 1990). Alternatively, a software-hardware model may be possible provided that the constraints and forces present in the real phenomena are faithfully encoded in order to reproduce not only the behavioral data, but also to minimize the number of unqualified mechanisms and parameters of the model itself. Determining what these factors might be necessitates a thorough examination of the sources of constraint, and thus sources of a given dynamic's selection rather than cause. A case in point is the phenomenon of synchronization or resonance. This phenomenon, central to the control of individual muscle lengths in the VITE module and ubiquitous throughout the organic and inorganic world, has been simulated by Grossberg for many years (Grossberg 1982). However, Bullock and Grossberg's VITE module achieves synchronization through refference principles and reliance on a signal representing the required future muscle lengths (the Target Position Command). In providing evidence of this crucial component of their theory, they only state, 'The TPC is likely to be computed in the posterior parietal cortex' (target article, p. 18). The idea, supposedly, is a neural medium within which tokens are assumed to be processed as discrete, quasi-symbolic entities. An alternative direction would be expressed by the question, Can the resonance requirement of a biological movement system be explained by general

physical principles? We answer in the affirmative in that other constraints, for example, those of a physical, thermodynamic and perceptual nature, exist in order to allow the selection of the requisite synchronization dynamic. To capture such constraints, alternative styles of biological modeling may be required – models where the languages of constraints at different levels are compatible and mutually constraining. Such a model would be distinct from a simulation since the former would also incorporate the physical properties of the substrate and, importantly, the environmental context. The power and hidden cost of formulation within Newtonian mechanics leads to models, or rather, simulations, based upon the dualism of system and environment – upon an encoding of the *effects* of the environmental forces on the system rather than on the environmental forces per se (Rosen 1988). Importantly, the realm of causality is limited to the rules governing the state transitions internal to the system alone. Such a formulation cannot provide a complete explanation of the causal basis. This is similar to Bernstein's (1967) argument against an actor's internalization of impinging environmental forces and the impossibility of an internal representation of the future trajectory of a given arm movement.

A sketch of Round Two

Biological movement systems are complex physical systems whose structures and functions are ultimately the product of physical laws at many scales of space-time. Accordingly, one can expect that the general principles behind the self-organizing and self-complexing of matter will play a selective and formative role in the patterning of movements (e.g., Beek 1989; Haken and Wunderlin 1990; Kelso 1989; Kugler and Turvey 1987). This expectation undercuts the thesis that an explanation in neural-like terms is proprietary for a theory of animal action and promotes a search for the particular forms taken by general principles in the biological realm. At the core of this latter enterprise – revealing the general in the particular – is the challenge of developing novel methods of physical observation and measurement (e.g., Schöner 1989) together with creative applications of traditional 'well-tried and true' strategies in the natural sciences (e.g., Beek and Beek 1988).

It is also the case that biological movement systems are complex physical systems that operate continuously in structurally and function-

ally rich environments. Accordingly, one can expect that the general principles governing biological system–environment linkages at a scale commensurate with the relevant descriptions of each will play a selective and formative role in the patterning of movements. This expectation underscores the thesis that an explanation must be sought in terms of observables at nature's ecological scale, the scale at which the concepts of animal and environment, and the values of acts, are defined (e.g., Turvey et al. 1989). At the core of this latter enterprise is an understanding of information as macroscopic patternings of ambient energy distributions that are unique and specific to properties of the animal–environment system (Gibson 1979).

To illustrate the style of the second round, we sketch an interpretation of how an animal 'participates' in the lawful regularities at the ecological scale. Roughly speaking, an animal participates by harnessing dynamical regimes supportable by its effector systems – regimes that become accessible once certain neural constraints have been implemented as boundary conditions. That is to say, neuromuscular synergies possessing a self-organizing character are formed from a particular neural constraining of degrees of freedom. Although the animal does not know in any explicit manner the lawful regularities at the ecological scale (Bullock and Grossberg 1988), the animal can participate in these regularities by accessing certain properties of its effector systems, and hence, knows them implicitly. In brief, the properties that an animal accesses are the dynamical topologies of qualitative dynamics. Attractor layouts containing point attractors, limit cycle attractors or attractors of higher dimension are accessed in isolation or in combination, in parallel or in series, to create the macroscopic dynamical landscape needed to produce the trajectory of the desired action.

It is the assumption of the second round that evolution has made it possible for an animal to use the macroscopic, dynamical design characteristics of its action system to coordinate its movements. There is evidence that organisms use such design characteristics in both the timing (Turvey et al. 1988) and phasing (Haken et al. 1985) of locomotory movements. The evidence for the use of a task-specific dynamical regime in the timing of locomotory movements is reviewed briefly.

There exists a number of different time allometries that relate the mass and length of locomotory effectors to the length of the cycle period. For quadrupeds, period scales as length to the 0.5 power and

mass to the 0.3 power. For insects, period scales as length to the 1.0 power and mass to the 0.2 power. For large birds, like quadrupeds, the periodic timing scales as length to the 0.5; but for small birds, like the insects, time scales to length to the 1.0 power (Calder 1984; Peters 1983). The traditional explanation of the variance of these scaling relations emphasizes differences in biological design. However, if it is true that animals harness macroscopic dynamical regimes in order to coordinate locomotory movements, and that evolution is parsimonious with the number of strategies used to solve biological design problems, we may expect there to be a single dynamical regime underlying these various scaling relations (Turvey et al. 1988). The differences would then arise from operating this regime at different values of mass and length (e.g., the large values characteristic of the largest terrestrial mammals vs. the small values characteristic of the smallest insects). This appears to be the case.

Experiments have demonstrated how coordination of two limbs found in locomotory movements can be redescribed as a single virtual oscillator that is pendular, has minimal damping, and is governed by two potentials, namely, the elasticity assembled over the body's tissues and gravity (Kugler and Turvey 1987). The numerical solution of such a regime can be computed for the biological boundary conditions: length \propto mass^{0.3} (geometric scaling) and elastic potential \propto body mass. The computation yields scaling relations in the quadruped range of time \propto mass^{0.18} and time \propto length^{0.54} and scaling relations in the insect range of time \propto mass^{0.31} and time \propto length^{0.91} (Turvey et al. 1988). The numerical solution of the above regime also reveals that in the length range spanning large and small birds the scaling dependencies change in the manner observed. In sum, the variability of observed time allometries does not point to differences in the design of species but to differences that arise from the implementation of a single dynamical topology (a limit cycle attractor) across the full range of animal size.¹

Mutual benefits of neural and ecological/dynamical accounts

We have argued that Bullock and Grossberg's analysis represents an extremely sophisticated version of Round One theorizing on Bernstein's

¹ Recent developments in robotics have suggested that hard-wired control be replaced by dynamical constraints. For the use of passive dynamics in the development of walking machines see McGeer (1990).

problem. They have provided detailed answers to the core questions of the kinds of subsystems underlying arm movements and the manner of their modulation and interaction. Their answers are neural-like; the proposed mechanisms are shaped by both known and carefully hypothesized properties extant at the level of neural-like units. In contrast, Round Two theorizing, as sketched above, focuses upon properties and relations motivated by general law-based considerations of animal-environment systems. Proponents of Round Two share in common with Bullock and Grossberg an overarching appreciation of the need to understand coordination in self-organizational terms, but they look to physical science rather than neural science, to macroscopic levels rather than microscopic levels, and to the full system comprising animal and surround, for their inspiration. Where then do the two strategies stand in relation to each other? There is most certainly a pressing need to develop insight into the neural processes underwriting movement patterns. A sensitivity to the causes and remediations of movement disorders, for example, can only benefit from refined thinking about neural mechanisms. But will appropriate refinements come from the direction of theorizing constrained only by the characteristic tendencies of neurons and the need to fit simulations to data? Our guess is that that direction can have only limited success. Larger successes will follow, we believe, from theorizing that is constrained by an understanding of the lawful regularities at the ecological scale that make perceiving and acting possible. But if Round Two discoveries can guide Round One efforts, are benefits not to be expected in the other direction? The ideas developed by Bullock and Grossberg amount to new ways of thinking about how multiple, heterogeneous components can act cooperatively to achieve functionally coherent outcomes. Given the limited range of conceptual tools currently available for understanding such matters, the rigorous pursuit of self-organizing dispositions in any domain will necessarily have significant repercussions. Those who are inclined to Round Two theorizing and experimentation will find themselves repeatedly challenged by the novelty and range of ideas growing out of the neurally inspired work of Bullock and Grossberg.

References

- Abdusamatov, R.M., S.V. Adamovich and A.G. Feldman, 1987. 'A model for one-joint motor control in man'. In: Gatev et al. (eds.), *Proceedings of the 5th International Symposium on Motor Control*, June 1985, Verne Bulgaria. New York: Plenum Press.

- Abdusamatov, R.M., S.V. Adamovich, M.B. Berkinblit, A.V. Chernavsky and A.G. Feldman, 1988. 'Rapid one-joint movements: A qualitative model and its experimental verification'. In: V.S. Gurfinkle et al. (eds.), *Stance and motion: Facts and concepts*. New York: Plenum Press.
- Adey, W.R., 1988. 'Electromagnetic field interactions in the brain'. In: E. Basar (ed.), *Dynamics of sensory and cognitive processing by the brain*. Berlin: Springer-Verlag.
- Basar, E., 1983. Toward a physical approach to integrative physiology. I. Brain dynamics and physical causality. *American Journal of Physiology* 245, R510–R533.
- Beek, P.J., 1989. *Juggling dynamics*. Amsterdam: Free University Press.
- Beek, P.J. and W.J. Beek, 1988. Tools for constructing dynamical models of rhythmic movement. *Human Movement Science* 7, 301–342.
- Bernstein, N.A., 1967. *The control and regulation of movements*. London: Pergamon Press.
- Bingham, G.P., 1988. Task-specific devices and the perceptual bottleneck. *Human Movement Science* 7, 225–264.
- Bizzi, E., N. Accornero, W. Chapple and N. Hogan, 1984. Posture control and trajectory formation during arm movement. *Journal of Neuroscience* 4, 2738–2744.
- Bullock, D. and S. Grossberg, 1988. Neural dynamics of planned arm movements: Emergent invariants and speed accuracy properties during trajectory formation. *Psychological Review* 95, 45–90.
- Bullock, D. and S. Grossberg, 1991. Adaptive neural networks for control of movement trajectories invariant under speed and force rescaling (Target article). *Human Movement Science* 10, 3–53 (this issue).
- Calder, W.A. III, 1984. *Size, function and life history*. Cambridge, MA: Harvard University Press.
- Cohen, M. and S. Grossberg, 1983. Absolute stability of global pattern formation and parallel memory storage by competitive neural networks. *IEEE Transactions on Systems, Man and Cybernetics SMC-13*, 815–826.
- Feldman, A.G., 1986. Once more on the equilibrium-point hypothesis (λ model) for motor control. *Journal of Motor Behavior* 18, 17–54.
- Freeman, W.J. and C.A. Skarda, 1985. Spatial EEG patterns, non-linear dynamics and perception: The neo-Sherringtonian view. *Brain Research Reviews* 10, 147–175.
- Frohlich, H., 1988. *Biological coherence and responses to external stimuli*. Berlin: Springer-Verlag.
- Gibson, J.J., 1979. *The ecological approach to visual perception*. Boston, MA: Houghton-Mifflin.
- Grossberg, S., 1982. *Studies of mind and brain*. Boston, MA: Reidel.
- Haken, H., J.A.S. Kelso and H. Bunz, (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics* 51, 347–356.
- Haken, H. and A. Wunderlin, 1990. 'Synergetics and its paradigm of self-organization in biological systems'. In: H.T.A. Whiting, O.G. Meijer and P.C.W. van Wieringen (eds.), *The natural-physical approach to movement control*. Amsterdam: Free University Press.
- Hirsch, M.W., 1989. Convergent activation dynamics in continuous time networks. *Neural Networks* 2, 331–349.
- Keele, S.W., 1968. Movement control in skilled motor performance. *Psychological Bulletin* 70, 387–403.
- Kelso, J.A.S., 1989. 'Phase transitions: Foundations of behavior'. In: H. Haken (ed.), *Synergetics of cognition*. Berlin: Springer-Verlag. pp. 249–268.
- Kugler, P.N. and M.T. Turvey, 1987. *Information, natural law and the self-assembly of rhythmic movement*. Hillsdale, NJ: Erlbaum.
- Kugler, P.N., J.A.S. Kelso and M.T. Turvey, 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.
- McGeer, T., 1990. Passive dynamic walking. *Robotics Research* 9, 62–82.
- Peters, H.P., 1983. *The ecological implications of body size*. Cambridge, MA: Cambridge University Press.

- Rosen, R., 1988. Similarity and dissimilarity: A partial overview. *Human Movement Science* 7, 131–153.
- Schöner, G., 1989. Learning and recall in a dynamic theory of coordination patterns. *Biological Cybernetics* 62, 39–54.
- Turvey, M.T., 1990. Coordination. *American Psychologist*.
- Turvey, M.T., C. Carello and N. Kim, 1989. 'Links between active perception and the control of action'. In: H. Hatem and M. Stadler (eds.), *Synergetics of cognition*. Berlin: Springer-Verlag.
- Turvey, M.T., R.C. Schmidt, L.D. Rosenblum and P.N. Kugler, 1988. On the time allometry of coordinated rhythmic movements. *Journal of Theoretical Biology* 130, 285–325.