Chapter 12

Information in Movement Variability About the Qualitative Dynamics of Posture and Orientation

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Movement variability is examined within the context of perception and adaptive control of posture and orientation. Variability is viewed as movement that does not serve immediate control objectives. However, it constitutes a pattern of stimulation that provides task-relevant information about the dynamical interaction between an animal and its environment. In principle, information about the animal-environment system facilitates adaptation of control strategies to task-relevant variations in the system. Thus, the movement variability that provides this information may be an essential feature of an adaptive control system rather than irrelevant activity or noise. There are four aspects to a program of research that would demonstrate a functional role for movement variability: (a) The properties of the animal-environment system that are relevant to the task should be identified theoretically and empirically. (b) Perception of task-relevant properties should be demonstrated phenomenologically or behaviorally. (c) Relations should be identified between task-relevant properties and patterns defined by the movement variability. (d) Adaptation of control strategies to variations in the animal-environment system should be related to systematic variations in patterns of movement variability. Examples are presented for each of these research issues.

PERCEPTION AND ACTION

The fundamental premise of this chapter is that the study of perception is necessary in movement science. Perception is important because it is the basis for the essential properties of animate movement. In the present work, adaptability and goal-directedness are considered to be the essence of animate movement (as opposed to inanimate motion). Perception allows for adaptation of movement patterns to variations in the animal, the environment, and the task so that the goals of the animal are accomplished. The study of perception is the study of how an animal comes to know itself and its environment; more broadly, it is the study of knowledge or epistemology. An ecological epistemology provides the foundation, and the broader context, for this work (E.J. Gibson, 1991; J.J. Gibson, 1979; Lombardo, 1987;
Multiple Methodologies

A variety of scientific methodologies are presented in this chapter. This reflects the fact that there are many methods that can be exploited in the study of perception. One way in which these methods differ is in the process of scientific observation (or data collection). One could introspect or reflect on one's own knowledge, and experience, in a particular situation. Such phenomenological methods have not been fashionable, or at least central, in the scientific study of perception for some time (see Boring, 1929/1957; Evans, 1973; Heidbreder, 1919). However, reflection can be of some value in pedagogical contexts, and ultimately it can have an influence on scientific investigations (e.g., Bailey, 1991). Other, more common, methods require that one investigate another person's perception. For example, the investigator may simply watch a person perform an activity with interacting with that person. However, there is generally an interaction between investigator and the person who is the subject of the investigation, and there be extended verbal or nonverbal communication between the investigator and subject (cf. Locke, 1988; Sanderson, James, & Seidler, 1989). In this approach, the subject is a participant in the investigation, in that both the subject and the investigator have some control over the evolving content of, and the process of observation; however, in other words they form each other (cf. Bain, 1991). Because the investigator necessarily has less control of the activities of the participants, methodology is usually considered to be unacceptable in experimental investigations. However, such loosely constrained interactions provide a way to improve the external validity of experimental manipulations, observations, and analyses. For example, interaction with pilots outside of an experimental context is useful if an investigator is interested in the perception and control of aircraft motion (e.g., Brown, Cardo, McMillan, Riccio, & Simcari, 1991); interaction with athletes outside of an experimental context is useful if an investigator is interested in the perception and control of balance in sport (e.g., Bailey, 1991). Such interactions are especially enlightening when the participants include instructors who are skilled in reflecting on, communicating, and their own knowledge of a situation.

Experiments in perception require that the investigator have some control over the situation in which perception is studied. Although there is debate over the extent of control that is adequate or appropriate (see, e.g., J.J. Gibson, 1979; Riccio, Martin, & Stoffregen, 1992), it is usually considered desirable to maximize control that the experimenter has over the process of observation and the content of what is observed. For example, the experimenter may probe the subject about the phenomenology (conscious experiences) or elicit behavioral responses (or actions) in a specific set of conditions (e.g., Flach, Riccio, McMillan, & R. Warn...
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1986; Riccio & Cress, 1986; Riccio et al., 1992; R. Warren & Riccio, 1985). Verbal or nonverbal responses of subjects are generally described in written or spoken instructions and, thus, are constrained by the accuracy and precision of communication between the experimenter and the subject. Experimenters may attempt to minimize the ambiguity of responses by reducing the task to a binary decision. The decision can be indicated by a verbal response such as yes or no, same or different, or a nonverbal response such as a key press. Thus, the subject indicates whether objects or events are perceivable or not (i.e., above or below threshold) or whether they are differentiable or not (i.e., greater than or less than a just-noticeable difference). However, such decisions can be ambiguous if the instructions are not specific about the aspects of the situation to which the subject should attend and upon which the subject’s response should be based. Achieving specificity of instructions is not a straightforward matter in complex (natural) situations. This problem applies equally to verbal and nonverbal responses. The reductionistic solution to this dilemma is to simplify the situation to the point where a passive subject has little, if any, choice about what to attend to and how to respond. This maximizes the experimenter’s control over the process of observation and the content of what is observed, but it eliminates a fundamental property of perception: the obtaining of stimulation and the search for information by an active perceiver (see E.J. Gibson, 1981; J.J. Gibson, 1979; Reed & Jones, 1982). In the present work, the activity of perceivers is not sacrificed for experimental control. Management of this trade-off is considered to be an important component of good experimental design (e.g., Riccio et al., 1992).

Multiple Mappings

Verbal descriptions and overt actions provide intrinsic measurement systems for that which is perceived. Because they are dependent on the perceiver, such measurement systems have great potential for meaningfulness and representativeness (see Coombs, Dawes, & Tversky, 1970, for a discussion of these properties of measurement systems). In other words, there is potentially a close correspondence between the descriptions or actions in a particular situation and perceivable properties of the situation. However, the entities and operations (e.g., numerical, algebraic, geometric, or set-theoretic properties) in such loosely constrained measurement systems are generally not well understood. Mathematical properties are more developed in highly constrained extrinsic measurement systems such as those provided by standardized laboratory devices and instruments. However, there is little or no reason to believe that such measurement systems are meaningful or representative with respect to that which is perceivable, because they are independent of the perceiver or their relation to the perceiver is not obvious (J.J. Gibson, 1979; Kugler & Turvey, 1987). Because of these complementary properties, the correspondence between intrinsic and extrinsic measurement systems is an important area of investigation. More generally, the correspondence between different measurement systems (intrinsic or extrinsic) is enlightening, because the various methods of scientific observation differ with respect to precision, accuracy, and generality.
The study of perception is replete with investigations of the mappings between measurement systems (Figure 12.1). Scientists are generally committed to particular methodologies and particular measurement systems. Consequently, methodologies, measurement systems, and mappings delineate areas of study and relatively autonomous subsets of the scientific community. The measurement systems and mappings that are relevant to the present work are those that represent purposeful interactions of an animal with its animate and inanimate environment. All other mappings are considered to be nested within this ecological “outer loop.” An appreciation of the nested systems of measurement is ultimately required for a comprehensive understanding of perception. However, in the present work, it is assumed that a unified view of the physical, biophysical, neurophysiological, and psychophysiological aspects of perception should be pursued after, and be guided by, ecological

![Diagram](image-url)

**Figure 12.1** Multiple mappings in the study of perception and action. The boxes represent measurable aspects of the animal or the environment. Next to the arrows connecting the boxes are typical names for the corresponding areas of study. The shaded boxes represent observables in the present work.
analyses and investigations. For example, it is assumed that ecological principles will have much greater explanatory value and generative power for neurophysiology than neurophysiological principles will have for the study of purposeful interactions of an animal with its environment (cf. Kugler & Turvey, 1987).

An Ecological Approach

In ecological approaches to perception and action, interactions between an animal and the environment are considered to be fundamental (J.J. Gibson, 1979; see also Beek & Bingham, 1991; Dainoff & Mark, 1987; Flach, 1990; E.J. Gibson & Schmuckler, 1989; Kondo, 1985; Kugler & Turvey, 1987; Loveland, 1991; Morbeck, Preschoft, & Gomberg, 1979; Newell, 1986; Owings & Coss, 1991; Riccio, in press; Riccio & Stoffregen, 1988; Robinson, 1972; Shaw & Kinsella-Shaw, 1988; Shaw, Kugler, & Kinsella-Shaw, 1990; Tobias, 1982; Valenti & Good, 1991; Vicente & Rasmussen, 1990; W.H. Warren, 1984). This is not to say that an ecological approach focuses on a subset of an animal's overt behavior. The medium, substrates, and surfaces that make up the terrestrial environment always have consequences for movement (J.J. Gibson, 1979; see also Stoffregen & Riccio, 1988). Thus, to study movement independently of the environment is to ignore general constraints on movement. An ecological approach assumes that movement science should develop from the most general principles (e.g., Kugler & Turvey, 1987). One way to discover general principles in movement science is to study the most pervasive characteristics of the interaction of an animal with its environment. Postural behavior is arguably the most pervasive aspect of this interaction, and, consequently, it is the starting point of the present work (E.J. Gibson et al., 1987; Riccio & Stoffregen, 1988) and of work in related fields (Kondo, 1985; Morbeck et al., 1979).

A central assumption in the present work is that the most important and pervasive aspects of the animal-environment interaction are the affordances of postural behavior for perception and action, that is, the functional consequences that body configuration and stability have for the pickup of information or the achievement of overt goals. It follows that an essential characteristic of postural behavior is the effective maintenance of the orientation and stability of the sensory and motor platforms (e.g., head or shoulders) over variations in the animal, the environment, and the task. Furthermore, it has been argued that this requires perceptual sensitivity to the functional consequences of body configuration and stability; animals should perceive the relation between configuration, stability, and perception or action performance (Riccio & Stoffregen, 1988). It has also been argued that the topological, rather than the metric, properties of these relations are important (Riccio & Stoffregen, 1988; cf. Kugler, Kelso, & Turvey, 1980; McGinnis & Newell, 1982). Body configuration or movement must change adaptively when variations in the animal, environment, or task change this functional topology. However, topological properties may persist over variations in the animal, environment, or task. Body configuration or movement need not change adaptively when there is persistence of the functional topology; that is, body configuration and movement need not change, or be robust, or insensitive to functionally inessential variations in the animal, the environment, and the task (see Riccio & Stoffregen, 1988, 1991).
The animal-environment interaction is a dynamical system, and the functional and topological characteristics of this interaction are the dynamics of the system (see, e.g., Riccio & Stoffregen, 1988; Riccio, in press). It is important to distinguish the dynamics of a system from the movements of a system. Movements are observables of system components and movement variability is generally defined in terms of particular parameters in these observable outputs. Dynamics are the cause-effect relations within the system (e.g., the relation between the "inputs" and "outputs" from the components). Inputs to system components can be either information or energy from other system components. If change in one component of a system causes change in another component of the system, there is a dynamical relation between the observable outputs of these components; the outputs of one component are inputs to the other component. Dynamical relations between two components of a system can be complex in that they can be influenced or mediated by other components of the system and by other systems. This is essentially the case when the inputs to one component are based on an "evaluation" of the outputs of another component with respect to particular functional criteria or objectives (see Riccio, in press). The complexity and variability of these multiple and partial relations can frustrate the analysis of adaptive systems. In the present work, phenomenological methods improve the external validity of the experimental investigations, and it helps isolate essential characteristics of complex systems. It should be noted that there is considerable disagreement about the role of phenomenological methods in ecological psychology and movement science. However, it is an important part of the ecological approach described in this chapter (cf. Gumucio, 1977; Ryan, 1983; Théoret, Coello, & Butterworth, 1991).

**Exploration and Adaptation**

Robustness of postural behavior gives animals the freedom to adopt orientation configurations, and movements that are not optimal with respect to particular task-relevant criteria (e.g., stability) and, thus, allows them to generate exploratory variation in postural behavior (Riccio & Stoffregen, 1988; cf. McCollum & Lee, 1989; Thelen, 1985). Exploratory behavior generates stimulations, and the obtained stimulation is "textured" by the dynamics of the animal-environment interaction (Riccio, in press). The pickup of information in exploratory behavior (e.g., movement variability) by active perceivers has been demonstrated in a variety of paradigms (Barnes-Cikota & Turvey, 1991; Beck, 1989; Beck, Turvey, & Schmidt, 1999; Bingham, Schmidt, & Rosenblum, 1989; Chen & Turvey, 1991; E.J. Gibson, 1977; E.J. Gibson et al., 1987; Mark, Balfour, Craver, Douglas, & Fox, 1990; Newell & McDonald, 1992; Solomon, 1988; Solomon & Turvey, 1988). In control-systems terminology, exploratory behavior provides for persistent excitation of the perception-action systems, which is an important characteristic of adaptive control (cf. Camurca & Wij, 1988; Chalmers, 1987; Narendra, 1986; Riccio & Stoffregen, 1988). Excitation (or stimulation) is persistent (and thus affords adaptation) to the extent that it spans the range of the animal-environment state space in which there is functionally relevant variability (dynamical variability). If stimulation spans the entire range of states over which...
dynamical variability occurs, then it is sufficiently rich to specify these functionally relevant variations and, consequently, to allow for adaptive control (Canudas de Wit, 1988; Chaffin, 1987; Narendra, 1986).

The characteristics of the animal-environment state space that are functionally relevant must be identified before hypotheses about informative exploration can be formulated and tested. The present work focuses on (a) the orientations and configurations for which perception and action are optimal (attractors), and (b) the limiting orientations and configurations (separatrices) within which perception and action can be maintained without a qualitative change in postural behavior (Bailey, 1991; E.J. Martin, 1990; Riccio et al., 1992; Riccio & Stoffregen, 1988, 1991). These directional (i.e., orientation-dependent) constraints on posture and orientation describe what is explored. Functionally relevant variation in these aspects of the animal-environment system should also be identified before exploratory behavior is investigated. The present work is based on a broader program of research on variations in attractors and separatrices that are due to (a) locomotion, (b) objects that are carried by an animal, (c) mechanics of the support surface, and (d) looking at or manipulating objects (Riccio, in press; Riccio & Stoffregen, 1988, 1990, 1991; Stoffregen & Riccio, 1988, 1991; see also Kondo, 1985; Morbeck et al., 1979; Robinson, 1972; Tobias, 1982). This dynamical variability is the reason for exploratory movement variability.

**DIRECTIONAL CONSTRAINTS ON BEHAVIOR**

The remainder of this chapter presents, and describes the motivation for, four experimental paradigms that have been developed for the ecological study of directional constraints on posture and orientation. Although the research focuses on perception of these constraints, it is also relevant to research on movement variability. The hypotheses in these experiments assume that movement variability provides information about the dynamics of posture and orientation; that is, the characteristics of movement variability are assumed to be lawfully related to the underlying dynamics. This assumption is implicit in research on movement variability conducted within the biomechanics and motor control communities. In these communities, characteristics of movement variability, and factors affecting these characteristics, are generally used to develop models about persistent properties of movement systems: Movement variability informs the scientist about the dynamics of the movement system. In the work presented in the following sections, it is further assumed that movement variability can inform individuals about the dynamics of their own movement systems and, thus, that movement variability can have a functional role in adaptive systems.

**Dynamics of Balance**

Pendulum dynamics in general, and balance in particular, are pervasive dynamical properties of the interaction between an animal and the terrestrial environment (Kugler & Turvey, 1987; Stoffregen & Riccio, 1988). The direction of balance is
generally determined by the vector sum of gravitational force and inertial forces due to acceleration, and it is contraparallel to the direction of this "gravitoinertial force" vector. When the orientation of the body deviates from the direction of balance, torque is produced by the nonalignment of gravitoinertial and support-surface (resistive) forces. Thus, alignment with the direction of balance minimizes the torque or effort required to maintain a particular orientation. However, this does not mean that animals necessarily align with the direction of balance. The goals of perception and action often require that animals achieve other orientations or configurations (Riccio & Stoffregen, 1988). Nevertheless, orientation with respect to the direction of balance always has consequences for control. The magnitude and variations of the torque acting on the body are specific (lawfully related) to the orientation of the body with respect to the direction of balance (Figure 12.2, a-d; cf. Stoffregen & Riccio, 1988). The orientation of the body relative to the direction of balance is specified by patterns of body movement together with the actions required to resist such movements. Thus, the perception of orientation could be based on the dynamics of balance, which are always relevant to interactions with the environment.

Classical theories of orientation assume the comparison of body axes to some (usually static) external reference frame such as gravity or anisotropic patterns in optical stimulation (Howard, 1982; Schöne, 1984). This is problematic, because such reference frames are not necessarily relevant to the animal-environment interaction. For example, the direction of gravity is irrelevant to orientation underwater when the body's center of mass is at or near its center of buoyancy. This severely attenuates the effects of gravity on body dynamics; that is, orientation-dependent constraints on control of the body are minimal. In fact, the perception of orientation is notoriously poor underwater, where errors in pointing "up" can be as large as 180°. Perception of orientation by unrestrained animals is much better on land (see Riccio & Stoffregen, 1990). The critical difference on land is that it matters whether or not segments of the body (e.g., head, torso) are balanced with respect to the coupled gravitoinertial and support-surface forces (Riccio & Stoffregen, 1988; Stoffregen & Riccio, 1988). In an ecological approach, the direction of balance is the fundamental referent for the perception and control of orientation (cf. the discussion of the "behavioral vertical" in Roberts, 1978). This does not require the perception of gravity or gravitoinertial force (Riccio & Stoffregen, 1990; Stoffregen & Riccio, 1988).

The Active Perception of Orientation

In general, the direction of balance is primarily determined by the gravitoinertial-force vector. However, with sufficiently powerful laboratory devices, the two directions can be decoupled. Such a device, a roll-axis tracking simulator (RATS), was used to determine whether perceived orientation is influenced by balance dynamics (Riccio et al., 1992). Perception of orientation was evaluated in the context of a task that required subjects to control the roll orientation of a device in which they were seated. They were told to maintain the RATS in an upright orientation while the device was exposed to a continuous disturbance. This is important given the premise that the perceived upright should be intimately related to the act of orienting
Figure 12.2 The dynamics of falling are depicted in (a) and (b). $F_g$ is the force due to gravity, $C_m$ is the center of mass, $I$ is the moment of inertia of the body, $T$ is the torque on the body, $B$ is the direction of balance, $G$ is the direction of the gravity vector, $\phi$ is the orientation of the body with respect to $B$. The kinematics of falling are depicted in (c) and (d), where $t$ is time and $d^2\phi/dt^2$ is the second derivative of $\phi$ with respect to time. The constant of 4 in the lower left panel is reasonable given the dimensions of the human body and assuming a moderate amount of passive viscous damping in the musculoskeletal system.

(Riccio & Stoffregen, 1990; Stoffregen & Riccio, 1988). The RATS had a balance point and inherently unstable dynamics; this meant that there were orientation-dependent constraints on control. The direction of balance was experimentally manipulated across trials, so that it was independent of the direction of gravity (Figure 12.3, a and b). This experimental manipulation produced dynamical variability across trials that was functionally relevant for the control of balance. After each trial, subjects verbally estimated their mean tilt with respect to “upright.” Partial correlations between perceived tilt and measured tilt permitted the independence of balance and gravity to be assessed. The findings indicate that balance can have the predominant influence on the perception of upright. Information about balance is available only in the movements used to balance the RATS. The informativeness of these movements is inconsistent with classical theories of orientation, which movement relative to an external reference frame (e.g., gravity) would have to be viewed as “noise” that would interfere with the perception of orientation. The findings are more consistent with the assumption that perception is linked to the dynamical interaction of an animal with its environment.

The arguments presented above emphasize that perception of orientation (a direction) is meaningful only when there are orientation-dependent (directional) constraints on control. The experiments of Riccio et al. (1992) suggest that perception of orientation with respect to balance is important because it supports the maintenance of balance. If control of orientation were precluded, as in most studies of perceived orientation, the perception of orientation would have been irrelevant and unnecessary.

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**Figure 12.3** (a) The direction of balance was the primary manipulation in this study. $\varphi$ is the angle between the directions of balance and gravity. $\frac{d^2 \varphi}{dt^2}$ is the angular acceleration of the RATS. The expanding arrows indicate that the dynamics of the RATS were influenced primarily by the balance point. (b) Gravity may have had an effect on any restrained parts of the body. This effect is represented by an inflection point in the relation between torque and tilt.

(Riccio & Stoffregen, 1990). However, there is another reason why it is important to allow subjects (i.e., perception) to be active in ecological investigations. Activity provides persistent excitation of the perception-action systems that may be necessary to pick up information about the dynamics of the animal-environment interaction. Movement variability produces stimulation that is textured by the dynamics of this interaction. For example, the movement or movability of the animal may become increasingly asymmetrical with increasing tilt from the direction of balance. Such asymmetries could provide information about orientation. This hypothesis has been initially tested by injecting asymmetrical disturbances into the RATS using the paradigm described above (Riccio et al., 1992). Preliminary results indicate that the perception of orientation is systematically related to manipulations of asymmetry (Riccio & E.J. Martin, 1990). In addition, a yoked-control experiment indicated that passive observers had difficulty picking up information about orientation with respect to the direction of balance. Balance dynamics had less influence on perception when passive observers were subjected to the motions that active subjects produced to control the orientation of the RATS (Riccio & E.J. Martin, 1990). This suggests that information in movement variability (i.e., in movement of the RATS) is more accessible if the movement is produced by an active perceiver. In this paradigm, it seems that perception supports action and action supports perception.

Implications for Movement Science

The results just summarized indicate that movement variability can inform individuals about the dynamics of their own movement systems. This suggests caution in the use of models that assume that movement variability is noise in the system. Noise, by definition, is neither informative nor controllable. However, if movement variability is informative, it would be adaptive for animals to modify the characteristics of variability in order to facilitate information pickup. Modification or control of movement variability may be as simple as increasing (or not minimizing) the magnitude of movement so that patterns of movement are more salient. In addition, if patterns of movement (e.g., asymmetry) are more salient in particular regions of the state space (e.g., for particular orientations), it may be adaptive to occupy or move toward these regions even if they are not the most energy-efficient states. Evidence for systematic bias away from energy minima was obtained in the experiment described in the previous section (Riccio et al., 1992) and has been obtained in experiments by other investigators (Beek et al., 1992). In these experiments, systematic bias apparently improved the observability of the system dynamics. In any case, the informativeness and controllability of movement variability should be included in models of the movement systems. Moreover, controllability implies that the characteristics of movement variability may be different for two tasks if different information about system dynamics is required (perhaps implicitly) by these tasks. This suggests caution in generalizing from particular experiments on, and models of, movement variability, unless the task-specific constraints on movement variability are understood.
Maintenance of Orientation

The instructions in the experiments of Riccio et al. (1992) emphasized the perception of upright. The perception of upright was strongly influenced by the direction of balance, which would be an attractor with respect to the minimization of compensatory torque or effort required to maintain control (see Figures 12.2 and 12.3). However, informal observations in the RATS suggested that the threat to balance was more salient than the direction of upright. The threat to balance presumably reflected one's proximity to the limits for which orientation could be maintained (for which perturbations could be reversed). Furthermore, a model for the data on the control of orientation also suggested that the orientation limits had an effect on these experiments (Riccio et al., 1992). More generally, it has been suggested that sensitivity to control limits is important for the robust and adaptive control of posture and orientation (Riccio & Stoffregen, 1988, 1991; E.J. Martin, 1990). Sensitivity to such limits insures that perforatory and exploratory behavior remains bounded or stable. Such limits specify the domain of variations in the dynamics of the animal's environment over which exploratory behavior is sufficiently rich to promote adaptive control. Sensitivity to these limits allows exploratory behavior to be robust and goal directed.

The dynamics of the RATS were qualitatively, or topologically, similar to the dynamics of balance in more common situations such as stance (they were also similar in some subtle quantitative details; see Riccio et al., 1992). The most important similarities are considered to be the global extrema, which include the minimum for compensatory torque and the limits for maintaining orientation (see Figures 12.2 and 12.3). For these reasons, it was not surprising that control of the second-order unstable device was learned very quickly; there was apparently transfer of skill from balancing in general to balancing the RATS. However, other investigators might consider this control task to be importantly different, because of the lack of "involuntary" postural "reflexes" that are assumed to play a critical role in the maintenance of balance. In the present work, the action systems that are used to control posture and orientation, and whether or not they are consciously controlled, are not central issues. The central issue is whether or not the effectiveness of these action systems is perceivable. If the effects of a particular action system (e.g., postural reflex) are not sufficient to achieve a desired goal, and this is perceivable, then a different strategy or action system can be selected. Action systems can be selected (or avoided) whether or not they can be consciously controlled once selected. For example, if a particular postural reflex cannot keep one from falling in a particular situation, one can change the dynamics of the response by changing body configuration (e.g., changing muscular preload by leaning, or reducing the moment of inertia by crouching), bracing oneself with the arms, or even lying down. These are basic facts about the adaptive control of posture that should be considered in the outset of any theorizing about postural control.

Stability Limits for Stance

The existing research on postural control has been heavily influenced by neurophysiology (see, e.g., Nashner & McCollum, 1985; Roberts, 1978). Neurophysiological
models are ultimately important because they describe the mechanistic instantiation of postural control. However, the appeal to neurophysiology would be considered premature from a control-theoretic perspective. In control theory, the functions of a control system (e.g., as represented in a cost functional) should be specified before the components of the control system are selected, designed, or analyzed (see, e.g., Riccio, in press). Functionality either has not been addressed or has not been adequately represented in most research on postural control. An ecological approach starts with a consideration of the functions of postural control (Riccio & Stoffregen, 1988). The simplest and most basic function of postural control is to prevent an animal from falling over. Although this fact is obvious, it is noteworthy because it motivates the novel research on postural control that is described below (E.J. Martin, 1990).

A useful paradigm in posturography is to study the effects of perturbations caused by sudden movements of the support surface (see Nashner & McCollum, 1985). Effects can be measured on body movements (kinematics), reactive forces on the support surface (kinetics), or the activity of muscle groups (electromyography). These measures are interchangeable, to some extent, if one is interested in the correspondence between parameters of the perturbation (e.g., displacement, velocity, and duration) and the strength and latency of the response. Perturbation experiments indicate, for example, that the amount of muscle activity is positively correlated with the displacement and velocity of the support surface; and such data are used to develop hypotheses about the “neural organization” of postural control (Dienes, Horak, & Nashner, 1988). However, it is noteworthy that the specification of the inputs (platform displacement and velocity) and the outputs (muscle activation) is not sufficient to provide information about the functional effectiveness of postural responses. For example, neither the inputs nor the outputs nor any combination of them indicate how close subjects come to falling over or changing strategy (e.g., stepping).

The experiment of E.J. Martin (1990) exemplifies a functional (ecological) approach to postural control. The task in this, and other, perturbation experiments is to maintain stance (e.g., not to fall over). For this reason, Martin started with the assumption that the fundamental perceivable was one’s spatiotemporal proximity to limits for maintaining orientation (i.e., stability boundaries). These limits are essentially the boundaries to the region within which postural perturbations can be reversed (cf. McCollum & Leen, 1989; Riccio & Stoffregen, 1988). The reversal of postural perturbations is dependent on the ability to generate thrust at the support surface. This requires a support surface of adequate extent and rigidity as well as the generation of muscular force (Horak & Nashner, 1985; Riccio & Stoffregen, 1988; Stoffregen & Riccio, 1988). Martin measured this functionally relevant capacity in terms of the distance of the center of pressure (i.e., thrust) from the anterior or posterior limits of the base of support (the heels or the toes, for an extensive surface) as this distance decreased during the perturbation (Figure 12.4). Building on the work of Lee (1976), Martin assumed that the most functionally relevant measure of this decreasing distance was the time to contact between the center of pressure and the stability boundaries. The meaningfulness of this perceivable would ultimately be based on its relationship to time constants for the various action systems that could be employed to reverse the perturbations (cf. Stoffregen & Riccio,
Figure 12.4 Control of orientation with respect to a postural separatrix. A typical trajectory for the center of pressure is depicted. Time is represented along the horizontal. Note that movement of the center of pressure beyond the boundary of a foot requires the use of another action system to maintain balance (e.g., support with the other foot). Derivation of functionally relevant parameters is also represented.


If the time to contact were less than the time constant of a particular action (e.g., ankle torque), then another action (e.g., stepping) would have to be used to prevent falling. Because the boundaries of the foot are relevant only to the form (on an extensive surface), they separate the domain of perturbations that can reversed by ankle torque from the larger domain within which stepping is effective. The boundaries that separate the domains of different action systems are referred to as separatrixes, and they represent qualitative transitions in the behavior of the system that can be discovered empirically (E.J. Martin, 1990; Riccio & Stoffregen, 1988).

From an ecological perspective, stability of stance is related more closely to the proximity of the center of pressure to stability limits than to the amount of movement of the center of pressure. Thus, stance could be unstable, even with very little sway if the center of pressure were close to the limits of the base of support. This can occur during stance on a narrow or short support surface or during leaning. Martin chose the latter as an ecologically valid experimental manipulation (subjects lean to varying degrees until the onset of the perturbation). This allowed Martin to test...
his a priori hypothesis that displacement and velocity of the support surface mattered only insofar as they influenced the time to contact with stability boundaries. His findings not only supported this hypothesis, but they also showed that leaning could have a larger effect on postural responses than the parameters of platform motion. For example, subjects responded sluggishly when perturbed backward after initially leaning forward, but they responded vigorously when perturbed backward after initially leaning backward. Although this effect may not be particularly surprising, it is not accounted for in other theories and experiments on postural control. Moreover, Martin found that postural responses are organized so that perturbations are reversed at a relatively constant temporal safety margin (approximately 300 ms from when the center of pressure would have contacted the stability limits without compensation). The fact that people maintain a margin of safety from a postural brink (cf. J.J. Gibson, 1979) requires significant modifications in traditional assumptions about compensatory postural responses.

Implications for Movement Science

The results summarized above emphasize that measures of movement should be functional and meaningful. The functionality and meaning of movement can only be addressed by considering the context for movement. Systems do not behave in isolation. Adaptability (and intentionality) are possible only if a system is sensitive to those aspects of its surroundings that have consequences for its behavior and if it is sensitive to those aspects of its surroundings for which its behavior has consequences (Riccio, in press). Consider the action systems used to regulate postural sway (see, e.g., Nashner & McCollum, 1985). The functionally relevant surroundings of these systems could include other parts of the body (e.g., the head), objects with which the system is physically coupled (e.g., a skateboard), or objects with which the system is informationally coupled (e.g., an object of visual regard). The characteristics of postural sway have consequences for these aspects of the surroundings or the coupling of the postural system with them (falling would have the most extreme consequences). The surroundings of a particular action system (e.g., ankle-hip synergies used for postural control) also include the complementary action systems within which it is nested (e.g., stepping to avoid falling over). The behavior of a nested action system with respect to the associated separatrix is meaningful because it provides an informational basis for the selection of a more robust action system. In the absence of this ubiquitous functional context, one is left with an isolated analysis of postural sway and, by default, an assumption that the task or function of the system is to minimize sway. Such an assumption is vacuous unless one also assumes that the function of the postural system is to minimize energy expenditure. However, these assumptions are insufficient to explain why an animal would stand instead of sit, crawl, or lie down, thus, they could never lead to an adequate theory of stance. The functional context for stance is discussed in more detail below (see also Kondo, 1985; Morbick et al., 1979; Riccio & Stoffregen, 1988; Robinson, 1972; Tobias, 1982).
Coordination of Contiguous Segments

The experiments described above suggest that attractors and separatrices play an important role as intrinsic referents for perception. That is, interactions of an animal with its environment are apparently perceived with respect to dynamical attractors and separatrices. This is believed to be a general property of the perception of movement by vestibular, somatosensory, and visual systems. Thus, these hypotheses about perception should apply when attractors, separatrices, or movement trajectories are of higher dimensionality than those in the experiments of Riccio et al. (1992) and E.J. Martin (1990). A simple extension beyond the concepts addressed in these experiments is to consider the properties of a two-segment system (Figure 12.5, a and b; cf. Nashner & McCollum, 1985; Riccio & Stoffregen, 1988).

The emergent properties of multilink systems involve the coordination of contiguous segments. Coordination is necessary because contiguous segments exert forces against one another, and these forces are influenced by the orientation and motion of the segments. That is, the orientation and motion of one segment has consequences for the control of the orientation and motion of a contiguous segment. The torque or effort required to maintain various configurations of a two-segment system is described by an (emergent) interaction between the orientations of each segment (Figure 12.5, a and b; Nashner & McCollum, 1985; cf. Kirsikii & Shik, 1964).

![Figure 12.5](image)

Figure 12.5  Two-dimensional (a) and three-dimensional (b) representations of a configuration space for postural control. The darkly shaded area represents bipedal configurations for which bipedal stance is not possible. The relation between normal configuration and a particular evaluation metric (e.g., torque) is explicitly represented in the three-dimensional space. The dotted line in the two-dimensional projection represents the shallow gradient in torque due to bending without leaning.

There is a shallow gradient along the locus of configurations over which torques on the two segments tend to counterbalance each other, whereas there is a steep gradient along an orthogonal locus over which the torques tend to add. The orientations of both segments must be specified in order to describe this functional topology. As in the single-segment system, there is a separatrix for the maintenance of balance in the two-segment system that is partially determined by "contact" between the center of pressure and the limits of the base of support (Riccio & Stoffregen, 1988). The shape of this boundary is also influenced by (emergent) interactions between segments such as the range of motion at the joints. The consequences of movements (change in orientation or configuration) are defined by the topology of the configuration space (Riccio & Stoffregen, 1988). The system is relatively free to change orientation or configuration in the vicinity of the global minimum and, to some extent, along the shallow gradient. Changes in orientation or configuration are much more limited near the separatrix if stability is to be maintained without a change in dimensionality of the system's behavior (e.g., the use of additional segments to balance). Sensitivity to the functional topology of such configuration spaces is required for the stability of performatory and exploratory behavior.

Time Scales and Dual Control

Exploratory behavior is important because of variation in the functional topology of an animal-environment interaction. Common variations include changes in the location, size, and shape of the basin represented in Figure 12.5 caused by variations in velocity of locomotion and by fatigue, injury, or carried objects. Variations in the functional topology that are caused by variations in the characteristics of the support surface require additional dimensions in the representation; see Riccio & Stoffregen, 1988). Stability can be maintained over such dynamical variations if they are more gradual than the rate at which an animal can adapt to the variations (see Figure 12.6, a-c; see Riccio & Stoffregen, 1991). Adaptation is dependent on the pickup of information. The experiments described earlier indicate that animals can pick up information about the functional topology of the interaction with the environment (i.e., postural attractors and separatrices). This information seems to be picked up primarily through movement that stimulates the proprioceptive systems. This suggests that attractors and separatrices provide texture (or structure) to stimulation. Such structure may include parameters defined over movement variability (Riccio et al., 1992; Stoffregen & Riccio, 1988).

Both muscular action (inputs to an action system) and variations in the animal-environment system (dynamics of the system) can cause changes in orientation and configuration (outputs of the system). For example, one would tend to fall over if (a) one leaned away from the direction of balance while standing (muscular initiation of falling) or (b) one did not lean into a turn during vehicular motion (falling initiated by change in the direction of balance). Information about falling provides feedback about postural actions (e.g., leaning) or variation in the animal-environment system (e.g., the direction of balance). Thus, there is a potential ambiguity in feedback about movement, which would frustrate an attempt to identify variations in the animal-environment system through exploratory behavior (Riccio, in press).
Figure 12.6  Adaptive control of posture represented in a postural configuration space and an associated performance time-history (hypothetical). Performance might be described, for example, in terms of the magnitude of perturbations for which stability can be maintained. Performance drops after a change in the dynamics of interaction with the environment. (a) The original performance level is approached asymptotically as the animal discovers the control actions that are appropriate for the new dynamics. (b) Performance may be terminated if adaptation is not quick enough (in this case, cessation of performance results in a fall). (c) Performance may be maintained at a degraded level, that is, without adaptation. 

ambiguity can be reduced if exploratory behavior (e.g., movement variability) occurs on temporal scales that are smaller than the temporal scale for variations in the animal-environment system (dynamical variability). It is also desirable that exploratory behavior not interfere with performatory behavior; that is, it should not result in loss of control (Figure 12.6; Riccio & Stoffregen, 1991). This dual-control problem could be minimized if exploratory behavior occurs on spatial and temporal scales that are smaller (i.e., of lower amplitude and higher frequency) than those characteristic of performatory behavior (cf. Wiener, 1948).

A pervasive source of high-frequency low-amplitude movement variability is muscle tremor (Akamatsu, Hannaford, & Stark, 1986; Stein & Oguztoreli, 1976). Such tremor exists in postural movements in the range of 8 to 12 cycles per second (Lippold, 1970; Mori, 1975), which is an order of magnitude higher than the range of controllable postural frequencies (Johansson, Magnusson, & Åkesson, 1988; Maki, 1986). It is possible that low-frequency modulation (e.g., variation in amplitude, frequency, or symmetry) of the high-frequency variability provides information (i.e., feedback) about low-frequency postural dynamics. Because data on high-frequency variability is commonly filtered out in research on postural control, its functional role in such behavior is unknown. A study by Watanabe, Yokoyama, Takata, and Takeuchi (1987) is an interesting exception. The data reveal a negative correlation between the magnitudes of high-frequency and low-frequency variability in the center of pressure during bipedal stance. Because stability is primarily dependent on the relatively high-amplitude sway at low frequencies, the data suggest that tremor (high-frequency variability) promotes stability. An implication of this hypothesis is represented in Figure 12.7. Enhanced postural tremor is hypothesized for orientations or configurations that are close to the separatrix because of the effort in leaning or bending. The tremor could promote stability (reduced sway), where the consequences of high-amplitude sway would pose the greatest threat to balance, by providing informational support for controllable (low-frequency) changes in orientation and configuration. The role of postural tremor in proprioception could be analogous to the role of eye tremor in vision. These sources of movement variability seem to provide ubiquitous exploratory behavior that enhances perception without interfering with the controllable movements that are both larger and slower (cf. J.J. Gibson, 1979; Howard, 1982). Perception of the functional topology for postural control, facilitated by postural tremor, could increase coordination among the segments of the postural system (cf. Newell et al., 1989; Newell & McDonald, 1992).

Multiple Evaluation Functions

The functional topology of the interaction between an animal and the environment has been discussed primarily in terms of the mapping between orientation or configuration and torque or effort (Figures 12.2, 12.3, 12.5). However, it is implicit in the preceding discussion that orientation and configuration can be evaluated with respect to (can be mapped into) other parameters (Figures 12.6, 12.7). For example, orientations and configurations could be evaluated with respect to the likelihood of falling or stepping, the magnitude of movement, or the asymmetry of movement. The
Figure 12.7 Time scales for movement in a postural configuration space (cf. Figures 12.2, 12.3, 12.5, and 12.6). Insets represent hypothetical frequency spectra of postural sway for various orientations and configurations. Bimodal spectral distributions are typical for postural sway. One mode represents controllable low-frequency movements, and the other represents relatively high-frequency physiological tremor.

topology of these mappings (e.g., the shape and location of the basins in a configuration space) could be different for different parameters or evaluation functions (Fig. 12.8, a–d). The parameters that are relevant are determined by the tasks in which the animal is engaged (Riccio & Stoffregen, 1988). Performance on a particular task (e.g., visual tracking) will be sensitive to some postural parameters (e.g., magnitude of movement) and not others (e.g., likelihood of stepping); a different set of parameters (e.g., effort) might be relevant to a different task (e.g., prolonged standing). This is important because it means that the functional topology for postural control can vary across the plethora of tasks for which postural configuration stability have functional consequences (Riccio & Stoffregen, 1988, 1991). The variations in the animal, the environment, and the task must be considered in a comprehensive approach to postural control (Riccio & Stoffregen, 1988; cf. Beed & Bingham, 1991; Newell, 1986; Saltzman & Kelso, 1987). This dynamical variability can frustrate the analysis of information in movement variability, because it can be difficult to identify the dynamical characteristics to which patterns of movement variability are specific. Phenomenological methods can facilitate the identification
Figure 12.8 Hypothetical relations between orientation and various parameters (a-d) on which orientation could be evaluated. Note that the "shapes" of the evaluation functions can vary.

of the appropriate situation-specific evaluation function and the associated functional topology. That is, phenomenology can provide insights about the meaning of particular movement patterns.

Relations Between Configuration and Stability

An ecological approach to the perception and control of posture and orientation has been presented in the preceding sections in the context of theory and experiments. However, one experimental involved highly constrained control of orientation in a
laboratory device (the RATS), and the other involved an activity (standing) with which subjects had a lifetime of experience. Although there are strong theoretical reasons for believing that these experiments have considerable generality, it could be argued, on purely empirical grounds, that they are special cases. The power of an ecological approach should also be demonstrable in situations that involve the development of skilled behavior (cf. Newell, 1986) and are relatively unencumbered by contrived experimental methods. This has been done in an investigation of skilled and unskilled performance in a cheerleading stunt (Bailey, 1991). In the stunt (the "liberty lift"), one cheerleader stands, on one foot, on the hands of another cheerleader (the other leg is retracted by raising the thigh and flexing the knee). One cheerleader (the "base") holds the other (the "top") directly overhead by supporting the toe of the top’s shoe with one hand and the heel of the shoe with the other. One difficulty of investigating such a complex behavior is that the relevant performance measures are not transparent to the investigator. Consequently, it is important to exploit loosely constrained interactions between the investigator and a skilled participant prior to the quantitative phase of the investigation. Bailey (1991) reflected on his own knowledge of, and experiences in, the stunt. He also interviewed other cheerleaders to determine the essential aspects of skilled performance in the stunt. It was generally acknowledged by the elite cheerleaders in this study that the perception and control of the top's configuration and stability was essential for both the base and the top. In addition, the relation between configuration and stability was considered to be critical for skilled performance. Beginners who were able to perform the stunt (but not in a skilled, stable, or aesthetic manner) could not differentiate good and bad configurations, and they did not understand the relation between configuration and stability. It was generally acknowledged that these aspects of the stunt were difficult to teach and to learn. For these reasons, Bailey's investigation focused on the perception and control of configuration and stability.

An ecological approach to postural control provided the theoretical foundation for Bailey's investigation (Riccio & Stoffregen, 1988). An hypothesis was that the optimal configuration of the top, referred to as "hollowing out," was one in which the constellation of forces acting on the top were at equilibrium, and that this equilibrium configuration would appear relatively stable and effortless (aesthetic). The optimal configuration is determined primarily by gravity and the forces exerted by the base to maintain balance of the top. The base is responsible for the fine control by pulling down on the heel or the toe of the top. This control is characterized by movements on small spatial and temporal scales. The role of the top is to "stay tight" (be relatively stiff), which presumably helps to suppress fine postural control movements that would interfere with the control by the base (an important but difficult aspect of the stunt for the top is allowing the base to do most of the balancing). However, the top has coarse control of the stunt, through adjustments in configuration, because some configurations are inherently more stable than others. The interviews suggested that stability is evaluated, by both the base and the top, with respect to the movement of the foot (primarily dorsiflexion and plantar flexion). Thus, movement of the foot provides the informational basis for fine control by the base, coarse control by the top, and coordination between the two (i.e., dynamical coupling between the base and the top).
The relation between configuration and stability was justified on both theoretical grounds (Riccio & Stoffregen, 1988) and empirical grounds (reflection, observation, interviews). Perception of configuration, stability, and the relation between the two is also suggested. Stronger evidence that these aspects of the stunt are perceived is provided by the adaptation in the configuration that allows the stunt to be achieved in novel conditions. Bailey found that configurations changed systematically in both the beginners and the experts when the base modified the dynamics of the stunt by pulling excessively either on the heel or the toe (dynamical variability), although the beginners were more variable in each condition (Figure 12.9, a and b). Bailey hypothesized that configurations were modified by the top so as to achieve stability and equilibrium, and that the perception of stability and equilibrium was based on parameters defined over variability of foot movement (movement variability). In other words, information in movement variability facilitated the adaptation in body configuration that was required by dynamical variability in the stunt. In order to test this hypothesis, the angles of the upper body, the lower body, and the foot with respect to a vertical reference line were measured through frame-by-frame analysis of videotapes. The angles were sampled 10 times per second. The data were then separated into two time scales: variations that were faster than once per second, and variations that were slower than once per second. The high-frequency variations in the foot angle were assumed to reflect movements that were not controllable by the top. Presumably they would arise from muscle tremor or manual control by the base. The low-frequency variations in the upper and lower body angles were assumed to reflect controlled movements by the top. The low-frequency variations in the

![Figure 12.9 Postural configurations observed when toe is pulled down (toe), when heel is pulled down (back), and under normal conditions (norm) in cheerleading stunt (based on actual data). Ellipses represent 50% bivariate confidence regions in three experimental conditions for a beginner (a) and an elite (b) cheerleader. Numbers on axes indicate mean degrees from vertical. Note that posterior tilts (negative numbers) increase to compensate for downward pull on the toe.

foot angle were assumed to reflect manual control by the base and the effects of variations in configuration (upper and lower body angles).

Stability was defined as the standard deviation of the foot angle for each second of data (i.e., for each set of 10 data points). Although stability was considered to be a characteristic of equilibrium (cf. Riccio & Stoffregen, 1988), equilibrium was also defined with respect to the skewness (asymmetry) of the foot angle for each second of data. Nonequilibrium states (falling forward or backward) would be characterized by movements that were larger or more frequent in plantarflexion dorsiflexion. The standard deviation and skewness for each second of data were compared to the mean upper body angle and the mean lower body angle for each second of data. Two sets of relations defined the topology of the configuration space. In one, the upper and lower body angles were evaluated in terms of the standard deviation of the foot angles. In the other, the body angles were evaluated in terms of skewness of the foot angles. The relations were described with quadratic response-surface regression (see Box & Draper, 1987). The results revealed significant effects of postural configuration on the standard deviation of foot angle: \( R = .766, F(5,24) = 6.80, p < .001 \); and on the skewness of foot angle: \( R = .603, F(5,24) = 2.74, p = .043 \) (quadratic relations are depicted in Figure 12, a and b).

The coordinated changes in body angles and the associated changes in parameters of foot movement, within each trial, are represented by the trajectories in Figure 12.10. These trajectories indicated that the cheerleaders symmetrized the movement of the foot; that is, the top moved to a configuration for which movements of the foot were symmetrical. The relation between configuration and the standard deviation of foot movement was generally saddle shaped, and trajectories were attracted to the seat of the saddle. This means that cheerleaders did not tend to minimize variability of foot movement. Minimal variability might occur in states, such as leaning, where the body is especially stiff. Such states may not be very robust perturbations because of the proximity to the separatrix, and it may not be possible to maintain them for very long. The cheerleaders tended to reduce variability but not below, a level that was associated with symmetrical movements. This suggests that a certain amount of variability may be necessary to notice an asymmetry in movement. Both the beginners and the elite cheerleaders symmetrized movements but apparently the beginners required more variability in order to perceive symmetry. Because symmetry is a general property of equilibrium movements (Riccio & Stoffregen, 1988; Stoffregen & Riccio, 1988), it should be a familiar criterion for novel tasks. However, the movements for which symmetry is relevant can be task-specific. Beginners may not be as perceptually sensitive as elite cheerleaders to symmetry in movements of the foot. The exploratory data from this study, together with the preliminary data on perception of orientation in the RATS (Riccio & Martin, 1990), suggest that symmetry of movement variability is an important parameter in the perception and control of orientation and configuration.

Implications for Movement Science

In the experiment of Riccio et al. (1992) the direction of balance was known a priori, to be a key topological feature (attractor) in the dynamics of the system.
Figure 12.10 Quadratic response surfaces that describe how postural configuration influences movement variability (a) and symmetry (b). Isovariability and isosymmetry contours are also presented. Trajectories for each 10-s trial are represented in the lower contour plots. The initial configuration for each trial is indicated by an open circle. Negative numbers indicate posterior tilt of body segment.

Note: From "Topological Dynamics and Performer's Conceptions of Coordination, Control, and Skill in a Cheerleading Stunt," an unpublished honor thesis by M.A. Bailey, 1994, University of Illinois at Urbana-Champaign. Adapted by permission.
the experiment of Martin (1990) the anterior and posterior boundaries of the face were known to be key topological features (separatrixes). In other situations, such as the cheerleading stunt described above, the functional topology is largely unknown. Bailey's (1991) exploratory experiment demonstrates that the functional topology of an action system can be revealed in patterns of movement variability. The relationship between these patterns and the underlying dynamics is analogous to the relationship between patterns in the optic array and the substantial environment. The environment structures the ambient light, and the environment is revealed in this structure (I.I. Gibson, 1979). Similarly, the dynamics of an action system structure the movements of the system, and the dynamics are revealed in this structure.

A variety of analytical techniques can be used to identify structure in the optic array or in movement. Examples include Fourier analysis, autocorrelation, cross-correlation, analysis of dimensionality, and Gestalt methods. Such ad hoc pattern recognition techniques provide little, if any, information about the sources of structure. A qualitatively different approach in visual science (or movement science) is to identify the source of structure in the optic array (or movement). In visual science, this informational approach is exemplified by the identification of the optical structure that reflects the layout of the environment (e.g., I.I. Gibson, 1979). Examples of informational (or system identification) approaches in movement science include identification of movement patterns of a wrist-pendulum system and the concomitant tissue strains, that relate to the inertia tensor of the pendulum (Solomon & Turvey, 1988); frequency-amplitude patterns that relate to the dynamical coupling between two wrist-pendulum systems (Kugler & Turvey, 1987); and responses of systems to punctate disturbances (Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984) or continuous disturbances (Johannsen et al., 1988).

An informational approach to the analysis of structure in movement generates hypotheses about specific patterns of movement and their relation to the underlying dynamics. For example, symmetry is an important property of systems in equilibrium (Onsager, 1931), and the magnitude of asymmetry is a plausible metric for distance from equilibrium in near-equilibrium systems (Stoffregen & Riccio, 1988). Bailey's (1991) data suggest that the effect of distance from equilibrium on asymmetry of movement is very robust, in that it can be revealed in the skewness of a relatively small amount of data. The use of skewness as a dependent measure in movement science is not unprecedented (see Newhall & Hancock, 1984), but it may be considered too unreliable for general use. Bailey's (1991) study emphasizes that such general conclusions about skewness are inappropriate. The usefulness of skewness as a dependent measure is determined by the relative sensitivity of skewness to experimental effects and extraneous influences (i.e., sources of error); and the relative sensitivity of any measure varies across experiments, because it is determined by experimental design and grounding of the experiment in theory. In Bailey's (1991) study, hypotheses about symmetry and its relation to postural control were well grounded in theory and in the context knowledge of skilled perceivers-actors. The results suggest that the concept knowledge of participants in experiments on human movement can facilitate the development of dynamical models for complex movement skills.

Constraints Imposed by Suprapostural Tasks

In Bailey's (1991) study of cheerleading, the task was defined in terms of body configuration and movement. That is, the task of performing the liberty lift was
defined by a particular body form that was to be maintained in a relatively stable manner. Performance on many tasks is influenced by body configuration and movement, but a task is not necessarily defined in terms of body configuration and movement. For example, body configuration influences how close the eyes are to potential objects of regard and whether the objects are in the field of view. Body configuration also influences whether potential manipulanda are within the functional reach envelope. Body movement (i.e., instability) influences the precision of vision and prehension. Together, configuration and stability have consequences for the ease or difficulty of seeing or manipulating objects (Riccio & Stoffregen, 1988, 1991). Thus, visual- or manual-control performance may serve as evaluation functions for body configuration (Figure 12.11, a-d). In the present context, this means that body configuration may be perceived and controlled with respect to performance on superpostural tasks (i.e., with respect to its affordances).

Postural adjustments may be required for looking at, looking around, and looking through, or for touching, reaching around, and reaching through (cf. J.J. Gibson, 1979). In principle, these task constraints on posture can be described in ways that are commensurate with the description of high-energy constraints (Kugler & Turvey, 1987; Riccio, in press; Riccio & Stoffregen, 1988). This is important, because commensurability of “behavioral” and “physical” constraints is a necessary condition for the development of explanatory models in ecological mechanics (cf. Shaw & Kincaid-Shaw, 1988). Explanations that are explicit about the way such disparate constraints combine or interact in the perception and control of behavior should generate predictions about changes in behavior caused by changes in the task. However, the development of such models from first principles (e.g., Beek, 1989; Kugler & Turvey, 1987) is not currently possible for postural control, because very little is known about the constraints imposed by the animal, the environment, and the task in such complex activities. Empirical investigations are needed to examine the effects of these constraints on the perception and control of posture in contexts that are functionally richer than those in which posture is usually studied. For example, with empirical methods analogous to those described above (e.g., Bailey, 1991), the functional topological effects of configuration on the difficulty of manipulating an object could be compared with effects on the compensatory torque required to maintain stance (Figure 12.12, a and b; cf. Riccio & Stoffregen, 1988).

**Posture and Manual Performance**

The effects of body configuration on performance in a superpostural task have been examined with techniques similar to those used in Bailey’s study of cheerleading (Riccio & van Emmerik, 1991). The goal of this preliminary investigation was to determine whether there were functional topological relations between postural configuration during bipedal stance and performance on a manual control task. The manual control task required that a subject tap at a constant rate (approximately three times per second) and with a constant force on an electronic keyboard. This is a variant of the interval production task in which constant force is generally not a criterion (Michon, 1966). The variability of intervals in the interval production task has been shown to be influenced by work load in situations that require
simultaneous control on some other task (e.g., E.A. Martin, McMillan, R. Warren, Riccio, 1986). Thus, variability of intervals could be sensitive to the effort required to maintain various postural configurations. The constant-force criterion was added so that force variability would be a task-relevant measure in this postural control experiment. The hypothesis was that force variability would be sensitive to instability inherent in various postural configurations (cf. Bailey, 1991). Unlike in Bailey's study of cheerleading, the relations between configuration and task performance were evaluated in a situation where stance is usually very stable: The support surface was static, rigid, flat, extensive, of high friction; the room was well lit; the participant stood on two feet and was not perturbed by external forces.
Figure 12.12 (a) Hypothetical effect of a suprapostural task on a postural configuration space. The darkly shaded area represents hip-ankle configurations for which bipedal stance is not possible. The lightly shaded area represents configurations for which stance is possible but for which the task (depicted in the inset) cannot be performed. The unshaded areas represent the configurations for which the task can be performed. (b) The evaluation function for a slice through the configuration space (corresponding to the bold line in (a)).

Performing a manual task while standing was assumed to be a general skill. Consequently, it was also assumed that a person would “know” the relevant topology of postural space and, given that the environmental conditions promoted stability, would adopt a configuration that would be both stable and efficient for the task (see Riccio & Stoffregen, 1988). Under these conditions, it would be difficult to discover a relation between postural configuration and task performance, because observation of an adequate range of configurations would be unlikely. The purpose of investigating this relation was to learn what, presumably, the participant had learned prior to the experiment: that certain postures should be avoided because of their effect on task performance. Consequently, the participant was instructed to adopt a different configuration on every trial. Configuration was defined by the angle of the upper and lower body segments relative to gravity (cf. Figures 12.5, 12.6, 12.7, 12.10, and 12.12). The upper and lower body angles were displayed as orthogonal coordinates of a luminous point on an oscilloscope. The oscilloscope was placed directly in front of the participant and behind the keyboard. Thus, continuous feedback was available to the participant in terms of the current “position” in this configuration space. Auditory feedback was also provided about the force of each tap. Data were collected on the body angles and on the time history for tapping. The coefficient of variation was computed for peak tapping force and for intervals between the discrete taps. Two sets of relations defined the functional topology of the configuration space. In one, the upper and lower body angles were evaluated in terms of variability of intervals. In the other, the body angles were
evaluated in terms of variability of peak force. The relations were described
quadratic response-surface regression so as to determine the location and shape
of attractors and separatrices (cf. Bailey, 1991). In addition, distance-weighted
least squares (DWLS) regression was used to explore the relation for local vari-
ability (Figure 12.13, a and b).

The results reveal a strong quadratic relation between postural configuration
and variability of peak force; Multiple $R = .811$, $F(5,18) = 6.92$, $p = .001$. The shape
of the manifold (relation) is a saddle, with the inflection point (peak) close to the
posture. Variability of force was increased by bending and decreased by leaning.
Although any interpretation of these preliminary results is necessarily speculative,
there are some promising directions for more formal experimentation. The effect
of leaning may be due to a decrease in relatively high-amplitude low-frequency
sway near the separatrix (see Figure 12.7). Presumably, sway at frequencies near
or below three cycles per second (the tapping frequency) could modulate the ampli-
tude of tapping and, thus, be a source of variability in tapping force. The increase
in force variability with bending may reflect an instability that can be tolerated (not
necessarily consciously), because there was not an apparent threat of falling. The
correlation between variability of force and variability of intervals was essentially
zero ($r = -.007$). This suggests that force and timing are influenced by different
factors in this experiment. The results failed to reveal a significant quadratic relation
between postural configuration and variability of intervals. This may be due to the
presence of a more complex manifold for this measure of task performance. DWLS
regression indicated that there was very little change in the variability of intervals
on the shallow gradient along which torques due to upper and lower body tilt tend
to counterbalance each other (note the contour plots in Figure 12.13; cf. Figure
12.5). This is consistent with the expectation that interval variability reflects effortful-
ness (or energy expenditure). There also is a distinct asymmetry in interval variability
with respect to anterior and posterior leaning. This may be due to the fact that
posterior leaning was more effortful in this task. The effortfulness of posterior
leaning was partly due to the need to extend the arms in order to reach the keyboard.

The fact that there was not a correlation between force variability and interval
variability is consistent with the hypothesis that the former is influenced by postural
stability, that the latter is influenced by postural effort, and that stability and effort
can vary independently. If this finding holds up, then the constant-force version of
the interval production task could be a valuable tool for studying the qualitative
dynamics of postural control (see Riccio & Stoffregen, 1988). Such multivariate
tasks would be especially useful in situations where there is a competition between
information-based attractors and energy-based attractors. For example, bending over
may improve the precision with which an object can be manipulated or visually
inspected, although this may be very effortful (e.g., in the experiment described
above, if the keyboard had been lower or farther in front of the subject). Conversely,
it may be impossible to observe or reach an object if one adopts the most comfortable
or least effortful orientation or configuration (Figure 12.14, a-c). A principled basis
for modeling the interaction of information and energy is possible (e.g., Kugler &
Turvey, 1987), although it has not yet been extended to research on posture and
orientation. Nevertheless, it is clear that energy extrema alone do not predict the
behavior of adaptive systems such as animals interacting with a variable environment.
Figure 12.13  Task-relevant postural spaces for performance on the constant-force interval-production task. The vertical axis represents the coefficient of variation for peak force (a) and for intervals between taps (b). Numbers on other axes indicate degrees from vertical. Response surfaces represent the influence of orientation and configuration on performance. The surface in (a) is derived from quadratic regression. The surface in (b) is derived from DWLS regression because the quadratic fit was inadequate. Iso-performance contours are also represented. The bold arrow represents erect stance. The bold line and the dotted line in the two-dimensional projections represent the shallow gradients in torque due to bending without leaning (cf. Figure 12.5). Note that the two postural spaces are viewed from different perspectives.

Note: Compiled from unpublished raw data from Riccio and van Essen, 1991.
Figure 12.14 Hypothetical effects of postural instability on interactions with the environment. (a) The animal may be incapable of maintaining the configuration and stability that is necessary for the task. Attempted performance on the task may have deleterious consequences for performance on a subordinate task (e.g., maintenance of balance). (b) The animal may accept a reduced level of performance that is within its capabilities for postural control. (c) If performance on a task is impossible without the risk of additional instability, the animal may cease performance on the task but maintain performance on a subordinate task. The shaded area on the right represents cessation of the original goals.

Implications for Movement Science

The paradigm described above reflects an affordance-based view of task constraints on action systems (see Riccio & Stoffregen, 1988). Affordances are observable interactions between a system and its surroundings (cf. J.J. Gibson, 1979; Riccio, in press). The surroundings of a human action system can be the surfaces, media, and objects in the "natural" environment; human artifacts in the "modified" environment; or other systems and components of the human body. A superordinate system is formed when an action system is coupled with aspects of its surroundings, and this superordinate system may be capable of achieving goals that cannot be achieved with any of the component subsystems. These superordinate goals do not necessarily replace the goals or functions of the subsystems. Instead the goals and systems become nested: The goal-directed behavior of the system constrains the way in which the goals of a component subsystem can be achieved, and vice versa. Although the goal-directed behavior of a system imposes such task constraints on the behavior of component subsystems, the associated coupling among subsystems affords opportunities that may not be possible without the coupling. Intentional systems presumably perceive and act upon these affordances by adaptively coupling with their surroundings in ways that are consistent with the attendant constraints.

The coupling or nesting of systems to achieve nested goals is a pervasive characteristic of human behavior; however, it is generally not addressed in experiments on perception and action (although, see Stark, 1968; Vicente & Rasmussen, 1990). The exploratory investigation of Riccio and van Emmerik is an attempt to study nested action systems with methods that are familiar in movement science (e.g., Nashner & McCollum, 1985; Newell et al., 1989). The investigation is relatively simple in that only two levels of nesting are considered: posture control (coordination of the upper and lower segments of the body during bipedal stance) and manual control (tapping on a keyboard). Nevertheless, it is sufficiently complex to reveal experimental and theoretical issues that should be generally important in the study of nested action systems. An especially important issue for further investigation is the control of systems and subsystems with respect to nested evaluation functions. For example, the various segments of the body play different roles in postural control and manual control, and these roles are linked to different performance criteria. The coordinated system is heterogeneous with respect to both components and performance criteria (cf. Beck & Bingham, 1991). An intriguing question is whether such systems can be viewed as homogeneous with respect to an integrated set of performance criteria (cf. Beck et al., 1992; Riccio, in press). In the preceding section, postural control and manual control were conceptually integrated by linking manual force variability and timing variability to postural effort and stability, respectively. Further development of the paradigm is required to evaluate this hypothesis.
SUMMARY AND CONCLUSIONS

The approach to "motor behavior" in this chapter is unapologetically psychological and phenomenological. Conscious experience is not viewed as an epiphenomenon of behavior. Instead, it is believed that behavioral research should be grounded in the knowledge of interactions with the environment that can be described by investigators and by participants in the research. Although, from this perspective, behavioral research should be grounded in phenomenology, it need not be limited to phenomenology for motivation or methodology. For example, the present work focuses on aspects of behavior that are ecologically pervasive and functionally important as well as phenomenally salient. A number of fundamentally interrelated phenomena meet these criteria: self-motion (Riccio, in press; R. Warren & Riccio, 1985), object approach (Stoffregen & Riccio, 1990), orientation (Riccio et al., 1992; Riccio & Stoffregen, 1990; Stoffregen & Riccio, 1988), postural stability and equilbrium (Bailey, 1991; E.J. Martin, 1990; Riccio & Stoffregen, 1988, 1991), and motion sickness (Riccio & Stoffregen, 1991; Stoffregen & Riccio, 1991).

Investigation of this range of phenomena requires a variety of methodologies and measurement systems. In this sense, the present work is methodologically eclectic. However, it is not theoretically eclectic. All theoretical and empirical development is based on an ecological approach to behavior (E.J. Gibson, 1991; J.J. Gibson, 1979; see also Lombardo, 1987; Reed & Jones, 1982). In fact, the methodological eclecticism is made possible by, and reveals the power of, the theoretical commitment. This is in distinct contrast to more common scientific approaches for which theoretical eclecticism and a commitment to methodology are apparently acceptable.

The present work should be contrasted with different, but related, research on motor behavior that looks to physics or mathematics for much of its motivation (e.g., Kelso, 1990; Kugler & Turvey, 1987). Such research is important to the extent that it reveals principles that are general for living and nonliving systems. Attempts to identify points of convergence between such research and the present work are considered desirable (e.g., Riccio & Stoffregen, 1988, 1991). However, it should be noted that the present approach is conservative in that it does not assume consistence between research in physics and research in psychology or kinesiology. Consequently, research problems are not derived from physics or mathematics. At least initially, the research problems are unique to perception in the context of adaptable and goal-directed movement; and as stated above, phenomenology plays a central role in identifying what phenomena should be studied. Other disciplines are useful in identifying how a phenomenon can be studied. Thus, it is useful to adapt methods from psychophysics (e.g., Riccio & Cress, 1986; Riccio et al., 1992), kinesiology (e.g., Nashner & McCollum, 1985; Newhall et al., 1989; Wa spouse et al., 1987), ethology or comparative behavioral ecology (e.g., E. Gibson et al., 1987; Koné 1985; Morbeck et al., 1979), systems engineering (e.g., Flach et al., 1986; E.A. Martin et al., 1986; Stark, 1968); and ethnography (e.g., Locke, 1988); and from research on self-organizing systems (e.g., Kelso, 1990; Kugler & Turvey, 1987) and physiological control systems (e.g., Milton, Longtin, Beuter, Mackey, & Glass 1989).
The research strategy described in this chapter is reminiscent of E.G. Boring’s description of the Zeitgeist from which scientific psychology emerged: “Phenomenology comes first, even though it does not get far by itself” (Boring, 1929/1957, p. 21). The research, in general, and the view of phenomenology, in particular, are consistent with the functionalistic tradition in psychology (see, e.g., James, 1890). The essence of functionalistic phenomenology is captured in the following passage written by Edna Heidbreder: “With James, introspection was the exercise of a natural gift; it consisted in catching the very life of a moment as it passed, in fixing and reporting of the fleeting event as it occurred in its natural setting” (Heidbreder, 1933; p. 171). The present work emphasizes that the adaptive and intentional qualities of animate movement (i.e., its “very life”) can be appreciated only by studying movement in a meaningful context (i.e., an “event as it occurred in its natural setting”). This requires that the analysis of the context for a particular movement is commensurate with the analysis of the movement that occurs in that context. If the analysis of movement leads to dynamical models for particular action systems of an animal, then the analysis of context should lead to dynamical models for particular aspects of the animal’s surroundings and to models that describe the functional linkage between the animal and its surroundings. The meaningfulness of movement is revealed in this functional dynamical linkage between an animal and its surroundings.

The present work assumes that the basic “observables” in movement science are the qualitative dynamics of the interaction between an animal and its surroundings. The qualitative dynamics (e.g., attractors and separatrices) are determined by the nesting of dynamical systems and the tasks or functions of these systems. Thus, the study of nested dynamical systems should be central in movement science (Ricco, in press). The nesting of dynamical systems varies across situations, and the associated dynamical variability necessitates robust and adaptive control of such systems. Robustness and adaptation to dynamical variability require information about dynamical variability. This functionally relevant information may be available in movement variability that occurs on relatively small spatial and temporal scales. Small fast movements provide a pattern of variation (persistent excitation) that can be modulated by larger and slower variations in the underlying dynamics of the system. The pickup of information in movement variability has been demonstrated (implicitly or explicitly) in the experiments described above, and, in some cases, the information has been identified with particular patterns of movement (e.g., asymmetry). Such research on systems identification should have as important a role in movement science as it does in related research (e.g., Canudas de Wit, 1986; Chalmers, 1987; Narendra, 1986; Weiner, 1948). In summary, the nesting of dynamical systems and the informativeness of movement variability appear to be key areas for future research in movement science, and phenomenology can be an important part of the associated research methodology.

REFERENCES


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