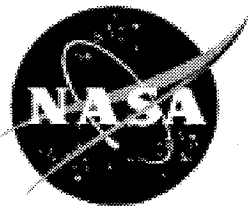


NASA/TP 3703



Multimodal Perception and Multicriterion Control of Nested Systems:

I. Coordination of Postural Control and Vehicular Control

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January 1998

Acknowledgments

The ideas presented in this report grew out of several projects in which Dr. Riccio was involved while at the Wright-Patterson AFB (1984-1988, 1991-1993). One project, conducted with Grant McMillan, involved the analysis of drive algorithms for a dynamic seat that would allow the associated pattern of somatosensory stimulation to substitute for the vestibular stimulation that is present during whole-body movement. Another project, conducted with Gregg Zacharias and Rik Warren, involved the development of Optimal Control Models for learning in flight simulators. A key project, conducted with Frank Cardullo and John Sinacori, involved the analysis of new approaches to motion cuing in flight simulators. The conclusions of these and other Air Force projects were integrated in a series of AFOSR-sponsored projects conducted with Grant McMillan, Rik Warren, and Robert Eggleston while Dr. Riccio was on the faculty at the University of Illinois (see e.g., Riccio, 1995). The ideas in this report are being applied, with Jacob Bloomberg at NASA JSC, to several problems involving human perception and performance in orbital or trans-orbital conditions. We are indebted to these colleagues for their insights and creativity regarding multimodal perception and human performance in aerospace environments. We would also like to thank John Flach, Peter Beek, Robert Shaw, William Mace, Tom Stoffregen, Bill Paloski, and Victoria Tepe for comments on this report and on various preliminary versions of the report. While preparing this report, Dr. Vernon McDonald was supported in part via a contract with the National Space Biomedical Research Institute.

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Preface

This series of three reports will describe the challenges to human perception and motor control that result from whole-body perturbations during locomotion. Our approach to this set of problems is based on the assumption that individuals, in the context of their surroundings, are adaptive nonlinear control systems with multiple levels of nesting, multiple inputs and multiple outputs. We consider interactions between individuals and their surroundings to be the fundamental unit of analysis for research in human perception and movement. Our approach to the analysis of nested biological control systems was developed over more than a decade of research on human-machine interactions in aerospace operations. The early research was conducted in collaboration with the Air Force Armstrong Laboratory at Wright-Patterson AFB, OH (see e.g., Brown, Cardullo, McMillan, Riccio & Sinacori, 1991; Riccio, 1995; Zacharias, Warren & Riccio, 1986). Recent research also includes collaboration with the Neuroscience Laboratory at the NASA Johnson Space Center in Houston, TX (see e.g., McDonald, Riccio, Irvin & Bloomberg, 1998).

The first report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: I. Coordination of Postural Control and Vehicular Control," describes the theoretical and operational foundations for our analysis of human-environment interactions. This report focuses on the coupled biological control systems involved in piloting an air vehicle and in stabilizing perception and movement in the cockpit. It is emphasized that the analysis is not limited to vehicular control. The analysis is presented in a way generalizes to all forms of locomotion and to other activities that involve whole-body perturbations. In addition, the report motivates and facilitates comparisons between conditions of real and simulated vehicular motion. This provides a framework for assessing human perception and performance in real-world conditions, in controlled conditions that allow for more refined measurement and evaluation, and in simulations that are intended to foster the development of skill.

The second report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: II. Constraints on Crew Members During Space Vehicle Abort, Entry, and Landing," applies our theoretical framework for nested human-environment interactions to the problems of flight crew perception and performance during planned and potential aerodynamic maneuvers of space vehicles. This report presents an approach to identification of task demands on perceptual and motor systems on the Flight Deck, to the measurement of perturbations to and interactions among the various subsystems of the human body, to the assessment of the skills involved in coordinating the nested subsystems in the presence of such disturbances, and to the development of Flight Deck displays and controls that promote such skill and that increase robustness of the human-machine system.

The third report in the series, "Multimodal Perception and Multicriterion Control of Nested Systems: III. Assessment of Visual Stability During Treadmill Locomotion," applies our theoretical framework to the problem of eye-head-trunk coordination during walking or running. This report presents a method for evaluating visual resolution and gaze stability during common activities involving whole-body motion. The functional visual assessment test (FVAT) that is described provides a measure of visual acuity that is sensitive to coordination between the oculomotor subsystems and other biomechanical subsystems of the body. This approach enhances diagnostic sensitivity to a variety of physiological impairments, and it enhances diagnostic relevance with respect to operational or everyday activities.

Abstract

The purpose of this report is to identify the essential characteristics of goal-directed whole-body motion. The report is organized into three major sections (Sections 2, 3, and 4). Section 2 reviews general themes from ecological psychology and control-systems engineering that are relevant to the perception and control of whole-body motion. These themes provide an organizational framework for analyzing the complex and interrelated phenomena that are the defining characteristics of whole-body motion. Section 3 of this report applies the organization framework from the first section to the problem of perception and control of aircraft motion. This is a familiar problem in control-systems engineering and ecological psychology. Section 4 examines an essential but generally neglected aspect of vehicular control: coordination of postural control and vehicular control. To facilitate presentation of this new idea, postural control and its coordination with vehicular control are analyzed in terms of conceptual categories that are familiar in the analysis of vehicular control.

1. Series Introduction: Coordination of Posture and Locomotion

1.1 Purpose

The purpose of this report is to identify the essential characteristics of goal-directed *whole-body motion* or *locomotion*. The potential manifestations of locomotion—such as walking, running, swimming, driving a car, sailing a ship, or flying an aircraft—are sufficiently diverse that general discussions are difficult. Consequently, this report focuses on the perception and control of aircraft motion. Aircraft motion provides a rich and coherent context for more general theoretical arguments concerning whole-body motion. While the discussion is couched in the particulars of vehicular control, it is emphasized that this report is not a review of research on vehicular control, aircraft control, or manual control; and the conclusions of this report are not limited to these domains of inquiry. To promote further generality, whole-body motion is discussed from the perspectives of Gibsonian *ecological psychology* (J. Gibson, 1979) and *control-systems engineering* (see e.g., Levine, 1996). The centrality of these complementary perspectives is due to the fact that they have generated a significant body of theoretical and empirical research in which the interaction between a human being and an environment, and the linkage between perception and action, are fundamental. The structure of the report is designed to provide one method for organizing the vast scientific literature that is relevant to the perception and control of whole-body motion.

1.2 Structure of the Report and Its Relations With Other Work

The report is organized into three major sections (Sections 2, 3, and 4). Section 2 reviews general themes from ecological psychology and control-systems engineering that are relevant to the perception and control of whole-body motion. These themes provide an organizational framework for analyzing the complex and interrelated phenomena that are the defining characteristics of whole-body motion. The intent of this section is not to persuade the reader that this is the only way to conceptualize whole-body motion or its investigation. It is simply intended to make explicit the lens through which we view the phenomenon of whole-body motion in this and related reports (e.g., Brown, Cardullo, Riccio, McMillan, & Sinacori, 1991; Flach, Riccio, McMillan, & R. Warren, 1986; E. A. Martin, McMillan, R. Warren, & Riccio, 1986; Riccio, 1993, 1995; Riccio & Stoffregen, 1988, 1991). An advantage of the organizational framework presented in the first section is that it reveals, and facilitates connections with, the diverse body of research that is relevant to whole-body motion.

Section 3 of this report applies the organization framework from Section 2 to the problem of perception and control of aircraft motion. This is a familiar problem in control-systems engineering and ecological psychology. Section 4 examines an essential but generally neglected aspect of vehicular control: coordination of postural control and vehicular control. To facilitate presentation of this new idea, postural control and its coordination with vehicular control are analyzed in terms of conceptual categories that are familiar in the analysis of vehicular control. Thus, Section 4 is an elaboration of Section 3. This section is important insofar as it reveals the inseparability of postural control and locomotion in general.

A companion report (Riccio, 1995; see Appendix B) examines the perception and control of whole-body motion (or "self motion") in flight simulation and virtual environments. It addresses research in which the information in stimulation is experimentally manipulated. This is important because the emerging technology of virtual environments provides the means by which the essential characteristics of whole-body motion can be studied experimentally. In contrast, the present report concentrates more on what should be studied, that is, "the meaningful environment" for whole-body motion (cf., J. Gibson, 1979). Both reports consider the consequences of information pickup insofar as they address research in which whole-body motion is controlled by an active observer.

1.3 Style and Scope

Extensive conceptual analyses, such as presented in this report, are unusual in investigations of human-environment interactions (although see J. Gibson, 1979). Control-theoretic analyses, in particular, usually proceed expeditiously from block-diagram representations of a system to formal mathematical models of the system and its behavior; that is, the epistemological implications of these models are rarely examined extensively. Such implications generally follow from mathematical assumptions (e.g., initial values, boundary values, parameterization, equation structure) that are heavily influenced by criteria such as solvability and computability. Different mathematical techniques have different assumptions and implications, and these differences can proliferate as models develop. If modeling techniques are driven primarily by domain-specific mathematical expedients, they are likely to diverge with respect to the phenomenon that they can explain. It is in this sense that particular programs of research in control-systems engineering and ecological psychology may appear to be incompatible. Mathematical models must converge, however, if they are motivated by similar conceptual analyses of the systems and behavior they are intended to explain. Thus, the conceptual treatment of whole-body motion in this report should not be interpreted as an argument against mathematical modeling. It is a precursor to mathematical models of the perception and control of whole-body motion.

We reassess assumptions that are pervasive in the study of self motion. This results in a broader domain of inquiry and an emphasis of issues that have been relatively neglected in research on self motion. The intent in this report is to acquaint the reader with the diversity of research that is relevant to the perception and control of self motion (hereafter referred to as whole-body motion). A detailed discussion of such a diverse body of research is beyond the scope of this report. For these reasons, the reader should expect to be left with many more questions than answers. With this in mind, references and terminology from other disciplines have been carefully selected to expedite searches through the broader scientific literature that is relevant to whole-body motion (see Appendix A).

2. Human-Environment Interaction

2.1 Ecological Psychology and Systems Engineering

The human-environment interaction is fundamental in an ecological approach to perception and action. Perception and action are inseparable aspects of this interaction, and they should not be studied independently. Ecological investigations that focus on perception must view action in an environment as an important context for perceiving. Research on perception includes the identification of what is perceivable (i.e., information in stimulation). In the context of action, essential information is often an emergent property of an interaction with the environment and, thus, may be available only in the interaction. The pickup of this information allows for the adaptive modification of action and the achievement of particular performance objectives. Ecological investigations that focus on action must view perception in an environment as a context for action. Research on action includes the identification of what is achievable (i.e., mechanics of movement). In the context of perception, essential movements are often exploratory and these movements make information available about general characteristics of the human-environment interaction. These general characteristics can be exploited in the modification of action or behavioral objectives. In human-environment interactions, perception supports action and action supports perception.

Perception and action are so fundamentally intertwined that differentiation between these concepts is potentially misleading. It is important to emphasize at the outset that the juxtaposition of these concepts should not imply that they have independent status epistemologically. At the same time, a considerable amount of research in phenomenology, psychophysics, biomechanics, and neurophysiology treats perception and action as if they were separable. Such research constitutes a broader scientific context within which ecological research is conducted, and it would be unwise to wholly neglect this context. The use of separate terms, perception and action, reflects this context but the juxtaposition of these terms herein connotes their inseparability.

The fact that action has perceivable consequences and that perception allows for the guidance or modification of action means that a human-environment interaction can be conceived as a *closed-loop system* (cf., J. Gibson, 1979, p. 225). The behavior of such systems is modeled mathematically in control-systems engineering (D'Azzo & Houpis, 1981; Kuo, 1982). The mathematical techniques used in control-systems engineering are sufficiently diverse (e.g., spanning, in principle, the entire science or sciences of dynamics) that it is difficult to identify the defining characteristics of "control theory." The only common assumptions in control-systems engineering are the coupling between perception and action and the complementarity between a controller and a controlled process. Beyond this, there is a style of analysis and synthesis that is uncompromisingly functionalistic. This functionalism is characterized by careful consideration of the breadth and depth with which any system is described. Descriptions of system components are commensurate with the task or function of the system which is considered at the outset. And there is as much consideration of what a system cannot do as what it can do. That is, a system is described with respect to what it can achieve and with respect to the domain of events with which the achievement is possible.

The development of mathematical models in control-systems engineering is aided by *block diagrams* that represent both the separable components of a system and the functional relations among these components. The components are persistent characteristics of systems that can be identified over changes in systems. Thus, consideration of *invariance* and *transformation* underlies the development and use of block diagrams for the analysis of a system's behavior (cf., J. Gibson, 1979, pp. 13-14). The components and relations in a block diagram depict the measurement system (i.e., the set of primitive entities and operations) that is specific to a particular domain of inquiry. Thus, while block diagrams used by various investigators (e.g., Pew & Baron, 1978; Flach, 1990) may be pictorially

similar, they may have fundamentally different meaning. The diagrams in this article are based on an ecological approach to perception and action. The focus is on information that is relevant to the control of orientation and self motion by multisegment organisms with multiple sensors (Riccio, 1993; Riccio, E. J. Martin & Stoffregen, 1992; Riccio & Stoffregen, 1988, 1990, 1991; Stoffregen & Riccio, 1988).

The pictorial similarity of block diagrams is due to the fact that they are generally constructed from arrows, branching points, circles, and rectangles. Arrows represent the “flow of control energy or information” from one component of the system to another (DiStefano, Stubberud, & Williams, 1967, p. 13; cf., Kugler & Turvey, 1987, pp. 7-9). Branching points indicate that energy or information flows from one component of the system to several other components. Circles (summation points) generally represent simple concatenation operations such as addition or subtraction. The outputs of these operations are dimensionally similar to the inputs. Rectangles (blocks) represent cause-effect relations such as the *transfer function* for some subset of the system or the perception-action relations for some human activity. These dynamical relations generally depend on the spatiotemporal characteristics of change in the system. They describe dissipation, storage, transformation, or transfer of energy within or between subsystems. The outputs of these dynamical subsystems are often dimensionally different than the inputs. The amount of detail in a block diagram is determined by the invariants and transformations that are considered in the analysis of a system’s behavior (see e.g., Flach, 1990; Stark, 1968).

Figure 1 represents a basic level of detail in control-systems engineering. The components at this basic level are described below. Common mathematical descriptions of these components and the relations between them are extensively available elsewhere. Flach (1990), in particular, has presented an ecological perspective on this basic level of analysis in control-systems engineering and on some of the associated mathematical formulations. Control-theoretic terminology used by Flach and others is retained where possible, and it is blended with ecological terminology to highlight similarities and differences between various programs of research in control-systems engineering and ecological psychology.¹

¹ One problem created by this blending of terminology is the term *differentiation*. It is never used in this report to refer to a particular mathematical operation. In other work, the mathematical usage is explicit when equations are included. In ecological psychology, differentiation is associated with discrimination and elaboration of detail through the process of perceptual learning and, more than any other concept, it emphasizes that perception unfolds over time and that living systems are in a continual process of development (see e.g., E. Gibson, 1969, 1991). To avoid confusion in this chapter, the term is always used in phrases such as “differentiation between” observable states, “differentiation among” states, or “differentiation” of one state “from” another.

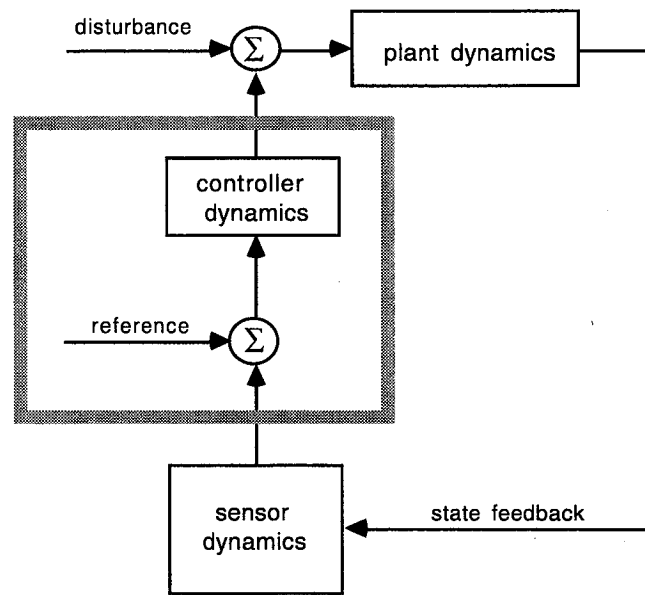


Figure 1. Basic level of detail in control systems engineering. See text for explanation of terms and components. The box around the controller and the reference input indicates the details that are not represented in subsequent diagrams. In the other figures, this box is associated with relations and operations (adaptive control) that are different than those represented in this figure.

2.2 Differentiation Among System Components

2.2.1 Persistence and Change

A principled basis for differentiation among the system components (cf., E. Gibson, 1969, 1991) is provided by consideration of *persistence* and *change* of functionally relevant characteristics of a system (cf., J. Gibson, 1979; Reed, 1982; Reed & Jones, 1982). One important characteristic is the domain of external influences on a system for which its behavior is bounded (a measure of stability). There can be a persistent relation between the stability of a system and certain aspects of the system dynamics. An example is the phase margin of a continuous linear control system (see e.g., Flach, 1990). The phase margin refers to the time lag in a system's outputs relative to its inputs at a particular frequency (by convention, the frequency at which the amplitude of the inputs and outputs are equal). The relation between system stability and phase margin persists or generalizes over changes in the phase margin; systems become less stable as the phase margin decreases. The appropriate diagram differentiates external influences from the system and its behavior (Flach, 1990, p. 88); however, the diagram does not differentiate the controlled aspects of the system (i.e., the *plant*) from the controller.

Other persistent characteristics may be nested within the general relation between system stability and dynamics. For example, in the *crossover model* for continuous linear control of a human-environment system, certain gain and phase characteristics persist over variations in the dynamics of the plant (McRuer & Jex, 1967). There are invariants in the frequency dependence of the amplitude and timing of system outputs relative to system inputs. These gain and phase relations are preserved because the controller compensates for changes in the plant dynamics. In this case, it is useful to differentiate the plant from the controller in order to reveal the covariation between the respective dynamics. More generally, *plants* and *controllers* are differentiated from each other because similar

controllers (e.g., human operators) can be a component of systems with different plants (e.g., vehicles or objects) and similar plants (e.g., vehicles) can be a component of systems with different controllers (e.g., human operators or computers).

Closed-loop control systems, by definition, also require information about the effect of the controller on the plant. Information is provided by components (*sensors*) that detect states of the plant. It is generally useful to differentiate the sensor from the controller and the plant because similar sensors can be used in different systems and because different sensors can be used in otherwise similar systems. Differentiation among controller, plant, and sensor is exemplified in the *optimal control model* of the human operator (see e.g., Kleinman, Baron, & Levison, 1970). This model describes the achievement of minimum error with minimum effort in a continuous linear control system over variations in the dynamics of the sensor and the plant (see also, Flach, 1990, p. 91). The controller dynamics depend on both the plant dynamics and the sensor dynamics. Optimization of performance through adaptive modification of controller dynamics is constrained by sensory and motor limitations that are explicitly considered in the model. The invariant characteristic of control behavior that is preserved by variation in the controller dynamics is optimal performance given the limitations of the human operator.

2.2.2 Plant Dynamics

This block represents the changeability of task-relevant states of the system (the plant is sometimes referred to as the *load*, the *controlled system*, or the *controlled process*). In the context of movement, the task-relevant states are the positions and motions of physical components of the system with respect to some explicit frame of reference (i.e., aspect of the environment). The changeability of these states (i.e., moveability of the physical components) is the relation between patterns of force on the components and the resulting patterns of change in the states of the components. Dynamical equations that describe this relation can be quite complex and variable; however, changeability is generally influenced by the spatio-temporal scale over which change occurs in dynamical systems. For example, viscous damping in a fluid medium provides more resistance to fast movements through the medium than to slow movements (note that the medium is the frame of reference in this example). Multiple parameters are usually used to describe the spatio-temporal constraints on moveability.²

The multiplicity of parameters for moveability in a given axis and the multiplicity of axes for movement can potentially lead to inclusion of a large number of states in the dynamical equations. The task (i.e., function) of the control system determines which states and associated frames of reference should be considered in the plant dynamics. Only the functionally relevant states should be included in descriptions of the plant dynamics. A state is functionally relevant if it changes and if change in that state has consequences for performance on the task (cf., Owen, 1990b; Flach, Lintern, & Larrish, 1990). Thus, mathematical models must be preceded by a careful analysis of the explicit and implicit tasks that a system is designed or assembled to achieve³

² Spatiotemporal constraints are generally parameterized with integer derivatives such as position, velocity, and acceleration. The use of integer derivatives maximizes computability and solvability of the equations because of the extensive mathematical foundation for classical dynamics. While other measurement systems are possible (Scott Blair, 1956) their unfamiliarity or lack of mathematical development may frustrate quantitative analyses.

³ Functionality and meaning are used in this article to emphasize the task-specificity of system descriptions and, relatedly, the fundamental relation between a system and its surroundings. There is not a sharp boundary between descriptions that are functional and meaningful and those that are not. Nevertheless, an emphasis on these concepts has been useful in the Jamesian, Gestalt, and Ecological counterpoints to elementaristic science. It is in this historical context that such terms are used in this article.

The plant dynamics generally include the functionally relevant states of the environment for a particular human-environment interaction. This can be the dynamics of surfaces, media, and objects in the *natural environment* or the dynamics of human artifacts in the *modified environment* (cf., Flach, 1990; J. Gibson, 1979, pp. 129-134). In addition, it is often appropriate to include the functionally relevant dynamics of the human effectors that are used to interact with the environment (in other situations, it is more appropriate to consider effectors as part of the controller). This can be the dynamics of arms, legs, or "neuromotor systems." It may be difficult or inappropriate to differentiate the dynamics of the environment from those of the human body. Is a vehicle or a prosthetic arm, for example, part of the human body or the environment? The answer to this question is not important for modeling and analysis of the system's behavior. It is more important to determine whether these components should be differentiated from each other than it is to label the resulting categories.

The basis for differentiating among components of the plant should be the same as the basis for differentiating the plant from other components of the system. If a model focuses on the relation between controller and plant, as in the crossover model, there is no need to differentiate among components of the plant. Components of the plant should be differentiated from each other, however, if there is functionally relevant variation in the components. It may be important, for example, to differentiate the dynamics of the arm from the dynamics of the aircraft when evaluating the controllability of an aircraft in high-G environments. Variation in the moveability of the arm due to variation in G magnitude may necessitate the design of a variable gain (or "smart") control stick in order for controllability to persist over such variations (see e.g., Repperger, Frazier, & Van Patten, 1983). Similarly, characteristics of manipulanda should influence the design of a teleoperator so that different systems (i.e., operator-manipulandum combinations) have similar characteristics, such as the ability to manipulate objects (cf., Repperger, 1991).

2.2.3 Sensor Dynamics

This block represents the *observability* of task-relevant states of the system. A state of a system component is observable if (a) there is a lawful relation between the state and the structure of ambient energy (i.e., outputs of the component) and (b) the outputs affect other components in the system (i.e., they can result in the stimulation of sensors). The relation between states and outputs is informative, and for human observers, this *information* is generally picked up by actively obtaining stimulation. An active observer can generate changes in state that result not only in disturbances in the structure of stimulation but also reveal invariants in this structure (cf., J. Gibson, 1979, pp. 243-250; Weiner, 1948/1961, pp. 113-115). This activity may not involve change in states of the plant, per se; information about persistence and change in the plant may be available in the change of other dynamical components (cf., Riccio, 1993). The obtaining of stimulation also involves orienting, exploring, and adjusting movements of the observer that optimize the pickup of information. Such activities involve change at all levels of biomechanical analysis including, for example, adjustments in the lens and movements of the eye, head, and body (J. Gibson, 1979, pp. 209-219; cf., Stark, 1968; Riccio & Stoffregen, 1988). Thus, the activity of information pickup can involve control of dynamical components that are different from the dynamical components to which the information is specific (cf., Flach, 1990, pp. 100-104; J. Gibson, 1963).

An implication of active observation is that models of human-environment systems may have to consider dynamical components that provide information for control of the plant. The *informative dynamical components* could be considered as part of the sensor. This is consistent with the ecological view of the senses as *perceptual systems* (J. Gibson, 1966, 1979), and it should be contrasted with other modeling approaches in which the senses are viewed as passive input-output

devices (e.g., Kleinman et al., 1970). If there is functionally relevant variation in the informative dynamical components, they should be differentiated from other components of the sensor and the plant. Constraints on mobility of the head and body, for example, provide information about orientation (Ricchio et al., 1992). The movements of various vehicles (e.g., cars and aircraft) and vehicle simulators impose different constraints on mobility of the head and body. Thus, the informative and context-specific dynamics of the head and body can be relevant to models for vehicular control and for the assessment of simulator fidelity. Considering the body of the human operator as an informative dynamical component is one of the revealing consequences of relaxing the pervasive and tacit assumption that the human operator is rigidly attached to the vehicle. The nonrigidity of the human operator and its role in information pickup are discussed extensively in this report.

2.2.4 Controller Dynamics

This block represents the *controllability* of task-relevant states of the system. A state of a system component is controllable if (a) there is a lawful relation between the state and inputs to the components (i.e., states of the plant are changeable), and (b) the inputs to the plant and states of the plant can be modified by another component of the system (e.g., a human operator) in order to satisfy particular *performance objectives*. In a closed-loop control system, control actions are influenced by the observed behavior of the system with respect to the performance objectives. The relations between observation and control are instantiated in a controller. The inputs to the plant are the outputs from the controller. The inputs to the controller include the outputs from the sensors which provide information about system performance relative to particular objectives. Performance objectives include general criteria such as the maintenance of system stability and more specific criteria such as the achievement of a particular orientation or trajectory of whole-body motion.

The relations between the inputs to and the outputs from the controller are perception-action relations that must be described in task relevant or functional terms (e.g., in *evaluation functions*; see Ricchio, 1993; see also Reed, 1982). The dynamics of the controller describe how actions, such as forces on the controlled subsystem, are functionally linked to perception of the controlled process (cf. Beek, Turvey, & Schmidt, 1992). Given a particular controller (perception-action linkage), a perceived state can be defined in terms of its consequences for action, and an action can be defined in terms of its perceivable effects (cf., J. Gibson, 1979, pp. 127-128).

The notion of performance objectives must be considered broadly in order to fully understand controller dynamics in human-environment systems. In general, objectives must relate to perception as well as action (Ricchio, 1993; Ricchio et al., 1992; Ricchio & Stoffregen, 1988). States of a system may be changed to make information available about the system, as in active observation. Thus, both performatory and exploratory behavior can be generated by a controller, and the activities of a controller influence both controllability and observability (cf., Flach, 1990, pp. 100-104; Weiner, 1948/1961, pp. 113-115). Moreover, the activities required for controllability and observability can be conflicting in some situations (Feldbaum, 1965). One situation that leads to conflict between control and observation arises when the observability of deviations from a desired state increases with the magnitude of the deviation from that state. This *dual control* problem requires context-specific tradeoffs or strategies by the controller (Ricchio & Stoffregen, 1988; 1991).

Dual-control strategies have been demonstrated in a variety of experiments on the dynamics of human-environment systems (e.g., Beek et al., 1992; Ricchio et al., 1992; Ricchio, 1993). In these experiments, human participants apparently controlled their interaction with the environment in a way that facilitated perception of the dynamics of the interaction. The participants adopted this strategy

even though it involved the maintenance of states that were more effortful (or less stable in the absence of variations in the system dynamics). The results suggest that the informativeness of such states promotes adaptability to variations in the system and that adaptability increases the domain of variations over which the system is stable (Beek et al., 1992; Riccio et al., 1992; Riccio, 1993).

Actuators in the nonhuman components of the system can be viewed as components of the controller. Examples include aerodynamic control surfaces such as ailerons and elevators or human control interfaces such as stick, throttle, and rudder pedals. The controller can also include human effectors such as arms and legs. However, actuators and effectors can also be considered as part of the plant. The preceding discussion indicates that adaptability is an important characteristic of a controller. Actuators and effectors should be considered part of the controller when they are selected, or their dynamics are modified, in order to satisfy a particular performance objective. That is, actuators and effectors should be considered part of the controller when they relate to *how* another component is controlled, and they should be considered part of plant when they relate to *what* is controlled. A more important issue is whether actuators and effectors should be differentiated from other components of the controller and the plant. They are not differentiated below because this report does not address the functionally relevant variation in these components.

2.3 Systems and Their Surroundings

2.3.1 Intentions and Disturbances

A system can be defined as "a combination of components that act together to perform a function not possible with any of the individual parts" (D'Azzo & Houpis, 1981, p. 7). A system and its components are defined with respect to particular functions (cf., J. Gibson, 1979, p. 245). Functions correspond to the characteristics of systems that are invariant over change in the components of systems. Systems are autonomous with respect to their stable characteristics and, thus, display steady-state behavior that can be described with fully *autonomous* (i.e., *homogeneous* or *characteristic*) equations (cf., Beek, et al, 1992; Kuo, 1982). The systems discussed in this report have explicit perception-actions relations. Plants, sensors, and controllers are fundamental components of these closed-loop control systems, and their dynamics are part and parcel of a system's autonomous dynamics. The autonomy is local in that the behavior of systems generally can be influenced by factors outside the system (cf., Kugler & Turvey, 1987, pp. 7-9). Factors in the *surroundings* of a system can either change the function of a system or disturb the behavior of the system with respect to its function⁴

Factors outside the system can affect the inputs to a system component, the states of a system component, or the outputs from a system component; and they can be represented as *disturbance* inputs at any of these points in a block diagram (Figure 1). For example, a disturbance could be an accidental movement of a control stick in an aircraft (change in controller output), a wind gust that moves an aircraft (change in states of the plant), or movement of an object that provides a frame of reference for an aircraft state (change in inputs to sensors). It is important to differentiate among these disturbances because they have different consequences for control of the systems. Differentiation among disturbances and their consequences for the control of aircraft are discussed in each of the

⁴ Functionally relevant factors outside the system are sometimes referred to as the "environment" of the system (Kugler & Turvey, 1987; Rosen, 1988), however, this usage can lead to confusion given that, in ecology, environment refers to the surroundings of an organism (e.g., J. Gibson, 1979, pp. 7-8). In a control-systems approach that is consistent with ecological psychology, aspects of the environment can be part of an autonomous system (e.g., a human-environment interaction) and should not be confused with aspects of the environment that are outside the system. It may be less confusing to refer to outside influences as the surroundings of a system.

following sections. It is argued that the information that differentiates among disturbances is generally *multimodal*. Multimodal perception is thus linked to perceptual differentiation (observability of whole-body motion) and its consequences for action (controllability of whole-body motion). The perceivable consequences of whole-body motion for the control of whole-body motion (e.g., changes in trajectory that are possible from a particular trajectory) are examples of *affordances*. Affordances are central in ecological psychology because they are the *raison d'être* for perception in adaptive organisms (see e.g., E. Gibson, 1988, 1991; J. Gibson, 1966; 1979). A major theme in this report is the necessity of multiple perceptual systems for perceiving the affordances of whole-body motion.

Factors that change the function of a control system also change the relations between perception and action. A simple change in perception-action relations is represented by the reference input (i.e. evaluation function or *objective function*) in conventional block diagrams (e.g., Figure 1). Flach (1990, p. 105) has appropriately identified such inputs to a human-environment system with the changing (or changeable) intentions of an individual (i.e., functions of the system). The diagrammatic and mathematical representation of a change in function is indistinguishable from a disturbance on the observable output. In general, disturbances and changes in function can affect systems in the same ways, and differentiation between these external effects may be unnecessary in the analysis of isolated control systems. However, all systems exist in some meaningful context (J. Gibson, 1979, pp. 33-43); and in context, changes in function can meaningfully be differentiated from disturbances. The meaningful context for control systems is discussed below largely in terms of the interaction and coordination between postural control and vehicular control. The treatment is relevant to the nesting of human-environment interactions, in general, and it reveals a special category of affordances. The affordances in nested human-environment interactions are special because the events that have affordances for the control of action include other controllable actions; some aspects of behavior have affordances for other aspects of behavior (cf., Reed, 1982; Riccio, 1993; Riccio & Stoffregen, 1988, 1991). The pervasiveness of nested systems and perception of their mutual affordances is another major theme in this report.

2.3.2 Coupled Control Systems

Given that changes in function and disturbances arise from outside the system, they are generally defined in terms of states that are not homogeneous with the system states. Equations that describe the behavior of such "externally forced" systems are referred to as nonautonomous or nonhomogeneous (cf., Beek, et al., 1992; Beek & Bingham, 1991; Kuo, 1982). If the dynamics of the external forcing are not defined, the nonhomogeneous terms in the equations are represented as explicit functions of expedient noncausal variables such as time, and it is more appropriate to consider the forcing as a disturbance than a changing function. If, however, the external forcing is subjected to an analysis that is commensurate with the analysis of internal system dynamics, the resulting nonhomogeneous equations can provide some insight into a system in its meaningful context. A system and its context (i.e., external forcing) would be viewed as interacting dynamical systems where the behavior of one system would have consequences for the behavior of the other system (cf., Riccio & Stoffregen, 1988).

In special cases the interaction could be reciprocal, and the dynamical systems could be viewed as subsystems or components of a superordinate system (Riccio, 1993; Shaw, Kugler, & Kinsella-Shaw, 1990; Vicente & Rasmussen, 1990). That is, subsystems could act together to perform a superordinate function not possible with any of the individual parts. This could be the case if states of one system are affected by the same "external system" states on which they also have an effect (cf., Beek et al., 1992; Kugler & Turvey, 1987). The coupling among states of different subsystems could allow the nonhomogeneous forcing from an "external" system to be re-expressed in terms of states

of the system receiving the forcing. This re-expression could lead to an homogeneous description of the interacting subsystems (the superordinate system) with respect to the states of one of the subsystems (cf., Beek et al., 1992) or it could lead to a relational description for the superordinate system that would not retain information about states of the component subsystems (Kugler & Turvey, 1987).

A special characteristic of reciprocal interaction between closed-loop control systems is that the consequences of one system's behavior for the other system are observable and controllable (cf., J. Gibson, 1979, pp. 135-137; Reed & Jones, 1982). One subsystem could be considered as a controller and the other could be considered as a plant in the coupled system, or one subsystem could be considered as a sensor and the other as a plant. In this view, each subsystem contains an "outer loop" that is closed through the other subsystem. The coupling would result in nested control systems if the inner and outer perception-action loops were modified in order to satisfy different, but related, performance objectives (cf., J. Gibson, 1979, pp. 211-219).

With respect to the functional context that coupled systems provide for each other, the effects of one system on another are more appropriately identified with changes in function than with disturbances (cf., Kugler & Turvey, 1987, pp. 407-422). The forced deviations from the free (steady state) response of each subsystem can be both meaningful and intended if they achieve some function not possible with the isolated subsystems. It follows that control of nested systems requires perception of system behavior with respect to multiple performance criteria. A major theme in this report is that nested systems must be considered as multicriterion control systems. Particular examples of nested performance criteria and interactions among the associated control systems are presented.

2.4 Intention and Adaptive Control

Intentions, as objective functions of a system, determine the relations between perception and action. The role of objective functions in closed-loop control systems is commonly conceptualized in terms of relatively simple relations among objectives, perception, and action. The most common relations explicitly assume commensurability among intended states, perceived states, and controlled states (Figure 1). More specifically, it is often assumed that the comparison of perceived and intended states generates an "error signal" that is linked to control actions through a controller or "control logic" (cf., Flach, 1990; Powers, 1973). In this view, intended states are simply a description of the goal, but they do not specify how the goal is achieved. This is an adequate characterization if all design decisions have been made and a control system has been optimized for specific performance criteria and specific surroundings. However, intelligent systems make decisions, change goals, learn about their action capabilities, learn about their surroundings, and modify their dynamics based on these changes. The role of intention in such systems includes specification of how a goal is achieved as well as what the goal is. In the associated control system diagrams, intention is appropriately identified with all adaptive elements in the system as well as any reference signals derived from the surroundings of the system.

Adaptability pervades the closed-loop systems that are exploited in human-environment interactions (cf., Flach, 1990, pp. 105; J. Gibson, 1979, pp. 245-246). Human controllers can intentionally modify action, perception, and the relation between them (cf., Canudas de Wit, 1988; Chalam, 1987; Narendra, 1986). If the dynamics of the plant are changed, human controllers can modify the inputs to the plant (i.e., their actions) and maintain certain characteristics in the output of the plant (i.e., preserve invariants in their interaction with the environment). Thus, the behavior of adaptive systems is robust to variations in the plant dynamics.

The robustness of a system is partially determined by limits on controllability. Limits on controllability include uncontrolled parameter variation (noise) in the controller and boundary conditions on variation in controller parameters (e.g., range of motion or limits on energy production). "Motor noise" is included in the optimal control model of the human operator (Kleinman, 1969; Kleinman et al., 1970; Levison, Baron, & Kleinman, 1969). The effect of motor noise is apparent only when the task requires controlled variations on spatiotemporal scales that are comparable to the spatiotemporal magnitudes of the noise (Levison, Baron, & Junker, 1976; Zacharias, 1979). Similarly, limits on range of motion or energy production become relevant only when the task requires behavior that approaches these limits. Within these limits, the behavior of adaptive systems is robust and variations in plant dynamics are inconsequential.

The actions of an adaptive controller are not simply hard-wired responses to sensory outputs. In order to satisfy specific performance criteria, the flexible perception-action relations instantiated in a controller are generally based on information about the human-environment interaction (e.g., states of the plant) rather than on the stimulation within which this information is available (e.g., output of sensors). The specificity of information in stimulation (i.e., the relation between states and outputs) depends on the components or subsystems through which the states of controlled components are observed. Variations in the sensory systems, such as substitution of one sensory system for another, will not affect the behavior of an adaptive system if there is information in stimulation for control of task relevant states and the information can be picked up by the controller. Variations in sensor dynamics may lead to modifications in the relation between sensory outputs and control actions in order to preserve the invariance of the relation between states of the controlled component and control actions. Thus, the behavior of adaptive systems is robust to variations in sensor dynamics.

The robustness of a system is partially determined by limits on observability. Limits on observability include many-to-one mappings from states to outputs (i.e., noise in the sensor) and boundary conditions on variation in sensor parameters (e.g., thresholds and saturation). "Observation noise" and threshold effects have been investigated in optimal control models of the human operator (e.g., Baron & Levison, 1975; 1977). The effects of observation noise tend to be greater than the effects of motor noise (Levison et al., 1976; Zacharias, 1979) but, in general, noise and output limits in sensors become relevant only when the task requires behavior that approaches these limits. Within these limits, the behavior of adaptive systems is robust and variations in sensor dynamics are inconsequential.

Presumably, intelligent systems would tend to avoid tasks or control strategies that exceed the system's operational envelope. It follows that knowledge of these limits is as important as the invariant characteristics that can be preserved within them. Exploratory behavior provides a means to discover both the invariants in the behavior of the closed-loop system and the associated limits (Riccio, 1993; Riccio & Stoffregen, 1988, 1991). As indicated above, informative dynamical components play an important role in this active exploratory observation of a controlled system, and they should be prominent in models of adaptive control systems. However, active observation is conspicuously absent in analytical models, such as the "crossover model" and the "optimal control model," that account for some of the adaptability in human controllers. A prudent alternative is to initiate the investigation of active observation and adaptive control by using qualitative methodologies (Riccio, 1993; Riccio & Stoffregen, 1988).

Qualitative methods focus on the categories of task-relevant information that are available in human-environment interactions. Important categories of information for vehicular control are discussed below. Control system diagrams are used to depict the "flow of information" through the human-vehicle system and to depict the functional relations among the major components of the system.

The subtleties and complexities of adaptive control (e.g., Canudas de Wit, 1988; Chalam, 1987; Flach, 1990) are not represented in these diagrams. In Figure 2, for example, controller dynamics are not differentiated from other transformations or relations that comprise adaptive control. Reciprocal interactions between sensory systems and the controller are represented to emphasize the intentional adjustments associated with active observation as well as the information picked up through active observation. More detailed block diagrams unfold as the essential aspects of purposeful whole-body motion are discussed in this report.

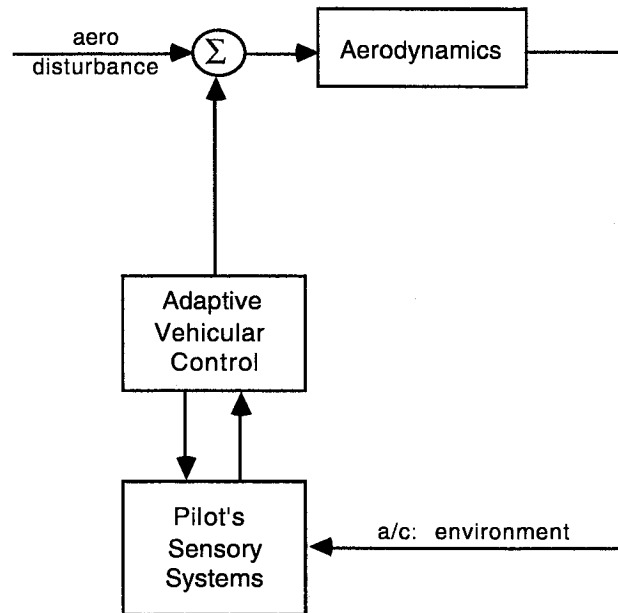


Figure 2. Core components of diagrams in this paper. See text for explanation of terms and components. Bidirectional flow of information between sensors and adaptive controller is unconventional in control systems diagrams. It is used in all subsequent diagrams in this paper as an expedient representation of a nested inner loop in which the controller adjusts the perceptual systems to optimize the pickup of information. The notation on the inputs to the sensory systems represents the fundamentally relational nature of perceivables. Events outside a system or subsystem are always perceived in relation to the system or subsystem. In this diagram, the system is the aircraft (represented by a/c), and the events are movements of the aircraft relative to some aspect of the meaningful environment.

3. Vehicular Control

3.1 Vehicular Control Relative to the Surroundings

3.1.1 Perception of Controlled and Uncontrolled Movement

Figure 2 illustrates that there can be more than one cause for the observed movement of a vehicle. The input to the sensors provides information about the change in state of the vehicle irrespective of the cause of the change. J. Gibson (1979, p. 184) referred to the pickup of this information as *kinesthesia*, and he was careful to distinguish it from feedback or reafference about controlled movement (see also, J. Gibson, 1964/1982). Control actions (i.e., outputs from the controller) are just one cause of movement. Events in the surroundings (e.g., aerodynamic disturbances) can also result in movement of a vehicle, albeit uncontrolled. Controlled and uncontrolled movement can be differentiated to the extent that they give rise to different patterns of stimulation (e.g., inputs to the sensors).

One difference between controlled and uncontrolled movement is that the former include exploratory adjustments that optimize the pickup of information; such adjustments imbue the structure in stimulation with a directedness or a progression toward equilibrium and clarity (J. Gibson, 1964/1982; 1966, 1979; Riccio, 1993; Stark, 1968). Controlled and uncontrolled movement can also differ with respect to their dynamics; and differentiating between them is possible when the observed movement is inconsistent with the dynamics of either the controlled or the uncontrolled movement. In addition, uncontrolled movement can be differentiated from controlled movement if information is available about control actions (see e.g., Herzog, 1968; von Holst, 1954; Riccio et al., 1992). Such information need not be an “efference copy” or a “template” of control actions. Any information about the timing, direction, magnitude, or higher-order patterns of control action could be sufficient to differentiate between controlled and uncontrolled movement (cf. Riccio & Stoffregen, 1991, pp. 213-219).

3.1.2 Differentiation Among Disturbances

Vehicular motion is observed with respect to particular task-relevant aspects of the surroundings. Uncontrolled motion occurs whenever there are task-relevant changes or disturbances in the surroundings, and this relative motion need not involve a transmission of force from the surroundings to the vehicle (cf., J. Gibson, 1979, pp. 93-102). Three types of disturbance are represented in Figure 3: (a) a vehicle can be displaced relative to an object, the terrain, and the inertial environment by some external force such as a wind gust; (b) a vehicle can be displaced relative to the terrain because of variation in terrain (e.g., hills and valleys); or (c) a vehicle can be displaced relative to an object because of motion of the object (e.g., movement of another vehicle). Differentiation among these events is possible if there is invariant structure in stimulation to specify persistence and change of objects and the terrain (J. Gibson, 1979, pp. 102-110). If a precipice is perceived as such, for example, the relative motion resulting from flight over the precipice is not confused with motion relative to the inertial environment (e.g., change in altitude due to wind shear).

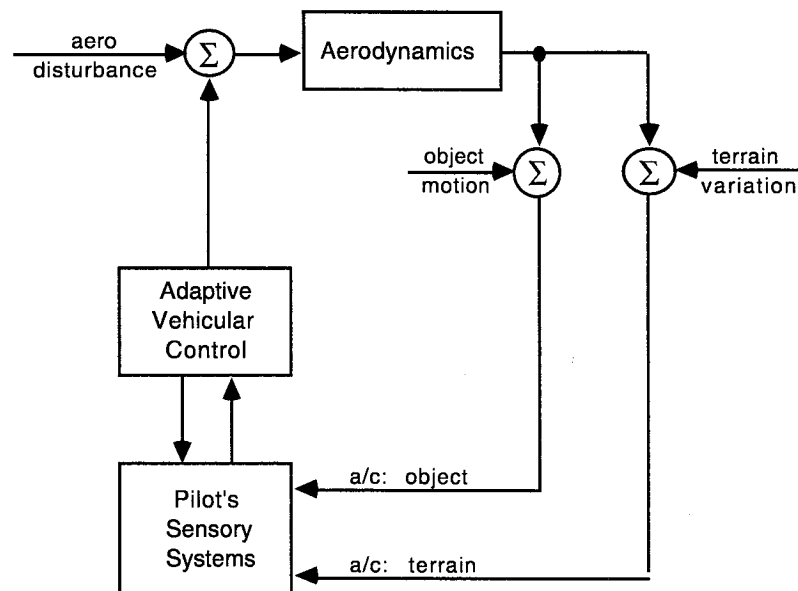


Figure 3. Differentiation among disturbances. See text for explanation of terms and components. This diagram differentiates between two aspects of the meaningful environment: the terrain and objects (e.g., other aircraft).

The availability of information in stimulation does not guarantee that the information can be picked up by an observer. Perceived variation in the level of the terrain before passage over the precipice could be different, for example, than the perceived change in above-ground-level during passage over the precipice. The difference could incorrectly be attributed to motion relative to the inertial environment and there could even be a visceral experience associated with this event. Such misperceptions are mitigated by perception of motion relative to the inertial environment. Perception of motion relative to the inertial environment is, by definition, equivalent to perception of change in the inertial environment. Perception of such motion is possible if there is invariant structure in stimulation to specify persistence and change in the inertial environment.

The inertial environment changes whenever a vehicle speeds up, slows down, or changes direction. The inertial environment is part of the *aerodynamic* environment because it influences the response of the aircraft to control inputs and external forces. Factors that effect the inertial environment are represented on the input side of the aerodynamics in Figure 3. Aerodynamics constrain the effects of forces on the aircraft while such constraints are not imposed on the effects of object motion or terrain variation. Visual perception could be sufficient to differentiate mechanical and optical disturbances if the observed motions were inconsistent with the aerodynamical constraints. That is, visually observed motion that cannot be produced by movement of the aircraft can be attributed to object motion or variation in the terrain. This would be useful if there were limitations on the visual perception of object motion or variation in the terrain.

Similar arguments have been made for differentiating object motion from postural sway when relative motion is inconsistent with postural dynamics (Stoffregen & Riccio, 1990, pp. 268-270). However, these conditions for optical differentiation are too restrictive to support controlled movement in most situations. Disturbances in relative motion due to variation in visible objects and surfaces is not necessarily inconsistent with the dynamics of the controlled system (e.g., aerodynamics), and

movement is generally controlled in the context of both mechanical and optical disturbances. Moreover, visual differentiation of such events assumes that the visual system is sensitive to variations in the inertial environment; that is, it assumes acceleration can be visually perceived. Other perceptual systems, such as the vestibular system, are stimulated whenever external forces cause variations in magnitude or direction of vehicular velocity (Stoffregen & Riccio, 1988; Young, 1984). This is obviously not the case for variations in remote objects or the terrain. Thus, multimodal differentiation among disturbances is possible; but is it necessary?

Movement is generally controlled with respect to visually observable aspects of the surroundings. We maneuver around obstacles, through apertures, and almost always with respect to the ground. It may not matter how our position and motion is disturbed in the meaningfully cluttered environment as long as we can maneuver with respect to the environment in a controlled fashion. In other words, why differentiate among the causes of uncontrolled motion when a control system acts upon only the observed effects? This could also be viewed as an argument for the sufficiency of visual perception in the control of vehicular motion: If vision is sufficient for perceiving remote objects and the terrain, then vision is sufficient for controlled movement with respect to objects and the terrain. The critical flaw in this logic is neglect of the dynamical systems by which movement is produced.

The capacity of common dynamical systems to produce change in position or motion is generally influenced by the initial conditions (i.e., the state from which change is produced) and the boundary conditions (i.e., the states beyond which controlled change is not possible). For example, it is generally easier to decelerate than to accelerate relative to the inertial environment even though motion relative to moving objects or surfaces can be identical in the two cases. This is especially relevant when a system is close to its limits for producing or controlling acceleration. It follows that information about persistence and change in the inertial environment is required to predict the effects of control actions. In other words, information about acceleration is required for controlled movement. Thus, it is necessary to differentiate among disturbances that affect the inertial environment from those that do not. Except in exceedingly rare cases, controlled movement requires multimodal perception.⁵ The role of multimodal perception in the control of orientation and whole-body motion is emphasized below (see also Riccio & Stoffregen, 1988, 1990, 1991; Stoffregen & Riccio, 1988, 1990, 1991).

3.2 Dynamical Variability and Vehicular Control

3.2.1 Perception of the Aerodynamic Environment

The movement and moveability of any vehicle or body depends on the mechanical environment. The mechanical environment consists of action forces that tend to produce motion and reaction forces that tend to resist motion (see e.g., Bekker, 1960; McRuer, Ashkenas, & Graham, 1973). These include: (a) forces due to biological mechanisms (e.g., muscles) or physical mechanisms (e.g., engines) that can transform internally stored energy into kinetic energy (i.e., movement), (b) forces due to biological mechanisms (e.g., skeletons) or physical mechanisms (e.g., air frames) that can transform kinetic energy into gravitational *potential* energy (e.g., rotational into translational movement, horizontal into vertical movement), (c) the accelerative force of gravity, (d) inertial forces

⁵ J. Gibson wrote that "Visual kinesthesia specifies locomotion relative to the environment, whereas the other kinds of kinesthesia may or may not do so. The control of locomotion in the environment must therefore be visual." (1979, pp. 226-227). This should be interpreted as an argument for the necessity of vision and not for the sufficiency of vision in most situations. Furthermore, visual control of locomotion is not necessary in some special situations (D. Griffin, 1958; Lee, 1990).

that tend to resist acceleration, and (e) *rheological* forces that tend to resist the flow of a medium (e.g., lift and drag)⁶ or resist the deformation of a substantial surface (e.g., viscoelasticity).

Controlled movement requires perception of the constraints imposed by these mechanical constraints (Ricchio & Stoffregen, 1988; Stoffregen & Ricchio, 1988). Adaptive control of movement requires perception of variation in such constraints (Ricchio, 1993; Ricchio & Stoffregen, 1991). Gravity is constant for the domain of aerodynamic, terredynamic, and hydrodynamic events (i.e., for human-environment interactions), but variation in all other mechanical forces is ubiquitous. For example, inertial forces vary when we start, stop, change direction, and otherwise adapt movement to changes in the layout of the environment; and as stated above, variation in the inertial environment has consequences for the control of movement.

Controlled variation in the inertial environment is an important part of energy management in high-performance aircraft. Energy can essentially be stored in the so-called "G forces" that result from large *linear* or *centripetal* accelerations, and the release of this potential energy increases maneuverability. In principle, this variation can be perceived visually when the terrain is visible because inertial forces are lawfully related to the trajectory of movement. However, it is not known to what extent we can perceive linear and centripetal acceleration in our own movement with the visual system alone. The visual perception of acceleration has been studied mainly in experiments on "object motion" (e.g., Todd, 1981), and the visual perception of "self motion" has been studied mainly in experiments where acceleration is either small, nonexistent, or irrelevant to the task (see, R. Warren & Wertheim, 1990).

Perception of accelerative self motion can be studied with displays that depict changes in direction or changes in speed. One experiment on the perception of curvilinear trajectories indicates that observers tend to underestimate the curvature of a trajectory for self motion depicted in a visual display (W. Warren, Mestre, Blackwell, & Morris, 1991). This may be due to the information about the *absence of variations* in velocity that is available to the somatosensory and vestibular systems in such experiments. The sensitivity of these systems to acceleration is well established. In this respect it is important to note that deficiencies in the visual perception of vehicular acceleration would not necessarily be due to limitations in the visual system. Such deficiencies may exist because vehicular acceleration is fundamentally a multimodal phenomenon. The visual perception of accelerative self motion may be limited to low levels of stimulation as in special cases of postural sway (Stoffregen & Ricchio, 1990, pp. 268-270) or constant acceleration in flight (Owen, 1990b). This low-level unimodal sensitivity allows for the pickup of some information about self motion, such as velocity and perhaps the magnitude of acceleration; but multimodal sensitivity may be required to pick up information about the direction of acceleration or the radius of curvature for the trajectory of self motion (cf., Stoffregen & Ricchio, 1990; Ricchio & Stoffregen, 1991).

The resistive rheological forces are as important as the resistive inertial forces for the domain of aerodynamic, terredynamic, and hydrodynamic events (see Ricchio & Stoffregen, 1988; Stoffregen & Ricchio, 1988). Aerodynamic forces vary with properties of the air mass, such as density, and they impose constraints on the moveability or maneuverability of the aircraft. Information about aircraft motion may be available in ambient energy, that is, in the outputs of the aerodynamic plant (e.g., Figure 3). Information about moveability, however, is available only in the relations between the inputs to the aerodynamic plant (i.e., control actions) and the outputs (i.e., motions of the aircraft).

⁶ This is an unconventional description of aerodynamic forces. It is consistent, however, with a general approach to environmental constraints on self motion. In such an approach, the material characteristics of the environment that are responsible for its resistance to self motion are less important than the dependence of this resistance on the spatiotemporal pattern of action used in the control of self motion (Ricchio, 1987).

That is, the relation between control actions and their effects on the aircraft provides information about aerodynamics. Perception of such dynamics is useful whenever the dynamics of a controlled systems vary.⁷ Aerodynamics change continually due to variation in “G forces,” variation in air speed, variation in weight of the aircraft (which varies with fuel consumption), and variation in the air mass (which varies over changes in altitude, for example). Perception of aerodynamical variation is incorporated into the control system diagrams (see Figure 4) where the aerodynamic environment (or *medium*) is represented as a reference frame that is analogous to those provide by remote objects and the terrain.

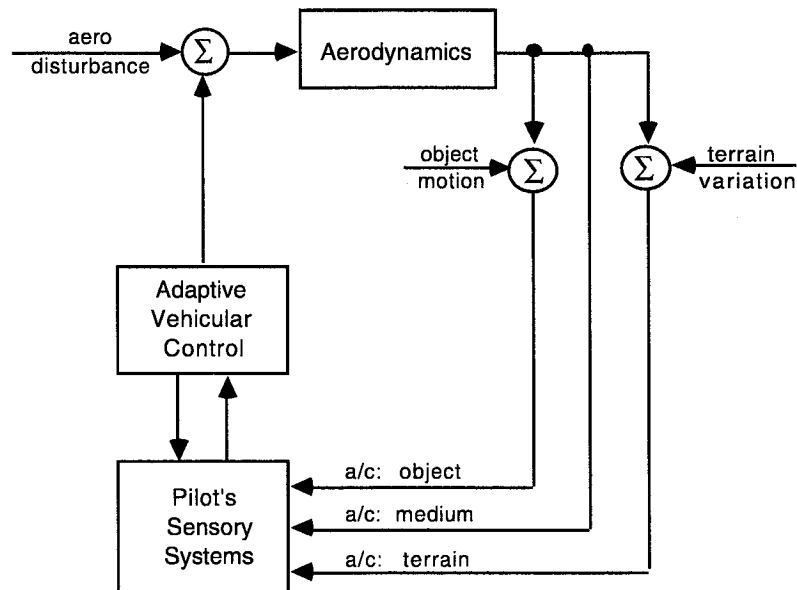


Figure 4. The aerodynamic medium. See text for explanation of terms and components. The aerodynamic medium includes the medium of support (i.e., the air mass) and the inertial “reference frame.” Movement of the aircraft relative to these aspects of the aerodynamic environment is important because of variation in the resistive rheological forces and the resistive inertial forces on the aircraft and the consequences of these forces for moveability and maneuverability of the aircraft.

3.2.2 Exploration of Aerodynamics

Perception of aerodynamics can be facilitated if the controller generates exploratory activity. It is important that such exploratory activity not interfere with the performatory activity of the controller. One solution to this dual control problem is to generate exploratory activity on spatiotemporal scales that are small relative to performatory activity (Weiner, 1948/1961; Riccio, 1993). Exploratory activity on a control stick by a human pilot, or movement of the aerodynamic control surfaces by a computer, is sometimes referred to as “dither.” The effects of dither on movement of the aircraft

⁷ Perception of lawful relations between system inputs and outputs is, by definition, dynamical. It is on this basis that one is said to perceive dynamics when one is attuned to such relations. The relations need only be lawful, and it is irrelevant whether these relations can be derived within extant measurement systems such as Lagrangian or Hamiltonian Dynamics (cf., Katz, 1925/1989; Scott Blair, 1956), unless one wants to teach these aspects of classical dynamics phenomenologically. Similarly, it is irrelevant whether the primitives or easily derivable quantities in these abstract measurement systems are perceivable as such (cf., Gilden, 1991; Gilden & Proffitt, 1989; Runeson, 1977).

are generally too small (or too fast) to be easily observable. However, variations in the aerodynamic environment may be more easily observable in the moveability of the aerodynamic control surfaces.

The control surfaces on the wings of an aircraft (e.g., the ailerons and elevators) are mechanisms for controlling the motion (e.g., changes in roll and pitch attitude) of the aircraft. These surfaces work with and against the resistive rheological forces. The ease or difficulty with which these surfaces can be moved is related to the maneuverability of the aircraft. Given this relation, the maneuverability of an aircraft is to some extent observable in the moveability of the control surfaces. In early aircraft, control surfaces were moved through systems of weights, pulleys, and cables connected to the control stick in the cockpit. Thus, the difficulty of moving the control stick was related to the moveability of the control surfaces. The pilot could, in essence, feel the resistive rheological forces on the aircraft and its control surfaces. Lack of maneuverability would be indicated by a "loose" control stick.

This information is sufficiently important to pilots that care has been taken in the evolution of aircraft design to maintain some sort of contact with the aerodynamic environment through more-or-less mechanized or computerized *force feel* systems. The key to such systems is that perception of task-relevant dynamical variation is possible when there is a lawful relation between the constraints on exploratory activity and the constraints on performatory activity. Perception of task-relevant dynamics through exploratory activity has also been observed in other activities such as the haptic exploration of surface traversability (E. Gibson, Riccio, Schmuckler, Stoffregen, Rosenberg, & Taormina, 1987), wielding tools for reaching (Solomon & Turvey, 1988), and hefting for long-distance throws (Bingham, Schmidt, & Rosenblum, 1989).

3.3 Effects of Vehicular Control on the Human Operator

3.3.1 Physiological Effects

The inertial forces on the aircraft during linear or centripetal acceleration also affect the pilot's body. In a "pull up" maneuver, for example, the trajectory of aircraft motion is an upward curve (i.e., concave up) with the pilot's head toward the center of the arc. There is *centripetal* acceleration toward the top of the aircraft that gives rise to *centrifugal* G forces toward the bottom of the aircraft. In such a maneuver, these forces make it more difficult for the cardiovascular system to transport blood toward the head (see Brown, Cardullo, McMillan, Riccio, & Sinacori, 1991; Kron, Cardullo, & Young, 1980). As the magnitude of the inertial force increases, tissues that are infused by relatively high-impedance capillaries become depleted of oxygen. The periphery of the retina has a relatively high concentration of these small blood vessels. The experiential manifestation of oxygen starvation in the peripheral retina is a progressive loss of peripheral vision ("gray out"). As inertial force increases further, there is eventually a complete loss of vision and loss of consciousness ("black out").

Such events are obviously undesirable and they impose hard constraints or limits on perception and action by the pilot. These constraints partially determine *the operational envelope* of the aircraft; that is, they set boundary conditions on controllability of the aircraft. Robust control of a system with varying dynamics is facilitated if the state of system relative to its boundary conditions is observable (cf., Riccio, 1993; Riccio & Stoffregen, 1988; 1991). Thus, the physiological effects of increasing inertial force provide information that can support robust control of an aircraft. The informational role of these physiological effects is represented in Figure 5.

The undesirable physiological effects of G forces reveal that controllability of the aircraft depends on the pilot's body as well as the aerodynamics. Thus, the orientation and trajectory of the aircraft may be controlled in such a way that both facilitates perception and action by the pilot and accomplishes

the goals of locomotion through the environment. Consider a maneuver in which the aircraft trajectory is upward and leveling off (i.e., concave down) as in flying over a hill at low altitudes. In this case, there is a centripetal acceleration toward the terrain and a concomitant centrifugal force away from the terrain. If the top of the aircraft faced away from the terrain, as in normal level flight, blood would be forced toward the pilot's head by this "negative G" force. As the inertial force increases, there is "red out" of vision and eventually danger of stroke. This situation is more uncomfortable and more dangerous than if the pilot flies the aircraft inverted and experiences "positive Gs." This example illustrates two points: (a) the most appropriate orientation of the aircraft can be determined by physiological factors, that is, by consideration of the human operator; and (b) orientation and locomotion can be interdependent activities. The generality of these points is discussed below.

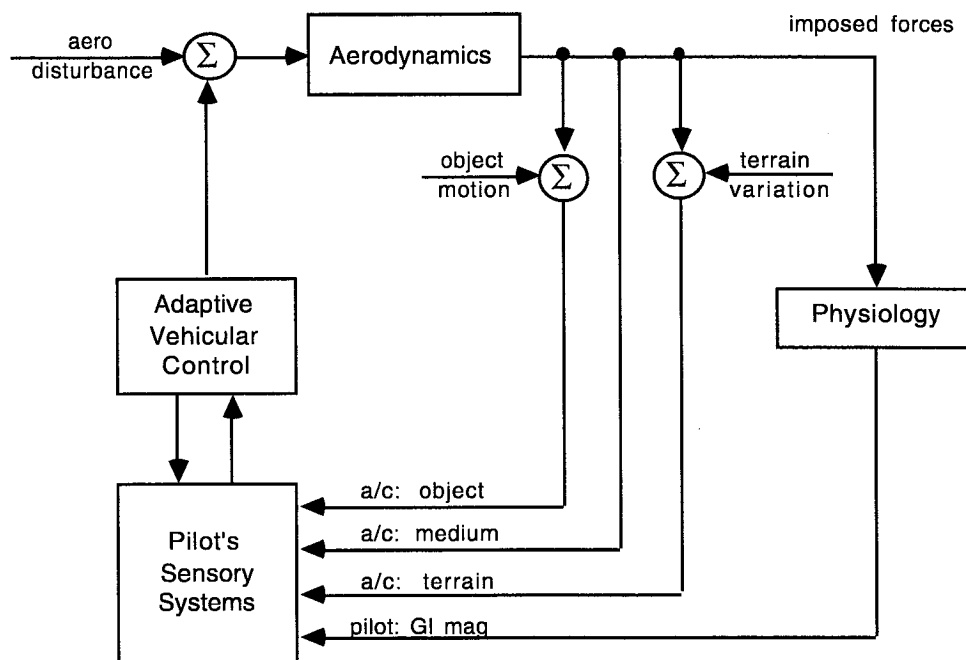


Figure 5. Physiological effects. See text for explanation of terms and components. Forces encountered during variation in the velocity vector affect the cardiovascular system of the pilot. These physiological effects are due to both micro-biomechanical effects of G-forces on tissues and fluids and neurophysiological responses to the attendant changes in blood pressure. The notation reflects that the events are perceived in relation to the pilot (e.g., the size of the pilot's field of view). The events are included in the vehicular control loop because they have affordances for vehicular control.

3.3.2 Biomechanical Effects

The constraints on vehicular control imposed by inertial forces may seem like exotic effects that are limited to high-performance special-purpose vehicles. In fact, sustained "high-G" maneuvers and the associated physiological effects are uncommon; however, variations in the inertial environment at lower magnitudes of force and acceleration are ubiquitous. Common sources of variation include *transients* due to sudden disturbances or sudden changes in direction and orientation. Examples of sudden disturbances are "bumps" and "ruts" in terrestrial locomotion and "wind shear" in flight. Examples of sudden changes in direction and orientation are "cuts" (oblique progression from a straight path) and "right-angle turns" in terrestrial locomotion and "snap rolls" (e.g., roll-axis

rotation from upright to inverted) in flight. *Vibration* is another common source of variation in the inertial environment. Vibration can be caused by nonflat terrain in terrestrial locomotion, continuously fluctuating wind gusts in flight, and the mechanism of propulsion in all kinds of locomotion (Boff & Lincoln, 1988, pp. 2070-2075). Vibration and transients have consequences for nonrigid organisms in general (Riccio & Stoffregen, 1988) and, in particular, for occupants of vehicles who are neither rigid nor rigidly attached to the vehicle (Boff & Lincoln, 1988, pp. 2076-2081; Griffin, 1975).

Because of the nonrigidity of the body and nonuniformities in the mass and moment of inertia of various body segments, relative motion of body segments is generated by the vibration and transients encountered during locomotion. Such disturbances also give rise to relative motion between the occupant and the vehicle. The relative motion can provide informative patterns of somatosensory stimulation (see Figure 6). For example, there are biomechanical relations between movement of the aircraft and the changing patterns of contact between the pilot and the aircraft seat. Somatosensory stimulation can facilitate vehicular control when there are such lawful relations (cf. Flach, Riccio, McMillan, & R. Warren, 1986; E. A. Martin, McMillan, R. Warren, & Riccio, 1986; Strughold, 1950). Somatosensory stimulation is also produced when there is movement of the pilot relative to manual controls, and visual stimulation is produced when there is movement of the pilot relative to cockpit. This stimulation provides information about vibration and transients to the extent that it is lawfully related to vehicular motion (see Figure 6).

It is difficult to determine from performance measurements whether this information is actually used for vehicular control. Use of this information could improve vehicular control, but the relative motion that provides this information could degrade vehicular control by interfering with perception and action *in the cockpit*. The consequences of uncontrolled movements for perception and action have been studied outside the context of vehicular control, that is, outside the context in which they could be informative. For example, movements of the head relative to the cockpit can degrade the pickup of information from instruments and displays (Boff & Lincoln, 1988, pp. 2082-2101; Dennis, 1965; Griffin & Lewis, 1978; Lewis & Griffin, 1980; Moseley & Griffin, 1986; Moseley, Lewis, & Griffin, 1982). Uncontrolled body movements can also degrade manual control performance (Boff & Lincoln, 1988, pp. 2106-2117; Lewis & Griffin, 1977, 1978, 1979). This *biomechanical feedthrough* (Repperger et al., 1983) or *breakthrough* (Levison, 1978) is represented as a separate point of disturbance injection in Figure 6 because information about activity on the control stick (e.g., Herzog, 1968) allows this disturbance to be perceptually differentiated from aerodynamic disturbances.

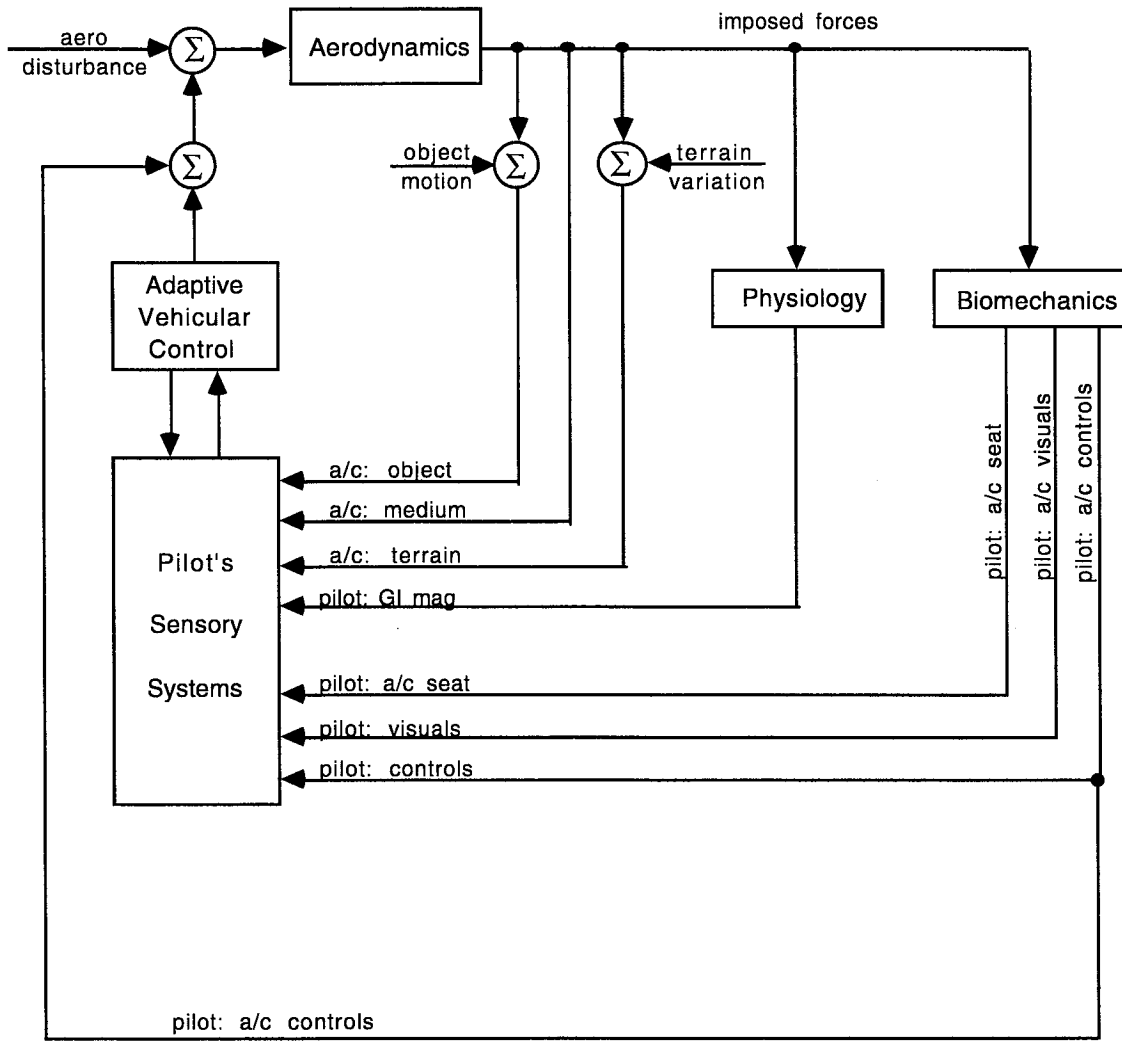


Figure 6. Biomechanical effects. See text for explanation of terms and components. Forces encountered during variation in the velocity vector can cause movement of the pilot relative to various aspects of the cockpit environment. The notation reflects that the events are perceived in relation to the pilot (e.g., looking at instruments, manipulating controls). The events are included in the vehicular control loop because they have affordances for vehicular control.

4. Coordination of Postural Control and Vehicular Control

4.1 Postural Control in Vehicles

4.1.1 Postural Restraint in the Cockpit

The preceding discussion indicates that there are important consequences of mobility and flexibility of the pilot in the aircraft. On the one hand, movements of the pilot that are due to vehicular motion can provide information for vehicular control. On the other hand, uncontrolled movements of the body can interfere with perception and action in the cockpit. If uncontrolled movements interfere with vehicular control, reduction of uncontrolled movements should improve vehicular control. One method of reducing uncontrolled movements is to reduce mobility and flexibility of the pilot by adding *passive restraints* in the cockpit. For example, adding shoulder restraint pads to the conventional lap belt and shoulder harness in the cockpit of a high-performance vehicle improves tracking performance when the pilot is subjected to sustained or fluctuating lateral forces that are due to vehicular motion (Van Patten, Repperger, Hudson, & Frazier, 1983). Reduction of uncontrolled movements through such a system of passive restraints improves both the precision and accuracy of control; fewer control errors are made and there is less cross-coupling among the various degrees of freedom in the multi-input multi-output control that is typical of flight.

The pilot, and other occupants of a vehicle, also reduce uncontrolled movements through adaptive *postural control* activity. It is important to emphasize that postural control is the most fundamental aspect of perception and action (cf., J. Gibson, 1966; 1979). The various segments of the body must be actively stabilized whenever one is not passively stabilized (Ricchio & Stoffregen, 1988, 1990). Even when it is reasonable to maximize passive restraints on the torso (e.g., in a vehicle), it is important to allow some mobility of the head and limbs to facilitate looking at, around, and through; and to facilitate reaching and manual control. Mobility can be increased through reduction of passive restraint, but this also increases the demands on active stabilization, that is, on postural control.

4.1.2 General Constraints on Postural Control

Limb- and body-pendulum dynamics in general, and balance in particular, are pervasive properties of human-environment interactions (Kugler & Turvey, 1987; Stoffregen & Ricchio, 1988). Constraints that are specific to pendulum dynamics are imposed by gravitational and resistive inertial forces. The sum of these forces is sometimes referred to as the *gravito-inertial force vector* (see e.g., Young, 1984, pp. 1046-1051). The magnitude of the gravito-inertial vector is nonzero whenever a body is in contact with a support surface, and the direction of this vector generally determines the *direction of balance* for a body in contact with a surface of support (Stoffregen & Ricchio, 1988; Ricchio & Stoffregen, 1990). When the orientation of the body deviates from the direction of balance, torque is produced by the non-alignment of gravito-inertial and support surface forces. Alignment with the direction of balance minimizes the torque or effort required to maintain a particular orientation. However, this does not mean that people necessarily align with the direction of balance.

The goals of perception and action often require other orientations or configurations (Riccio & Stoffregen, 1988). Nevertheless, orientation with respect to the direction of balance always has consequences for control. Fluctuations in orientation become more variable and asymmetric as tilt from the direction of balance increases (Riccio, 1993; Riccio et al., 1992). The controllability of orientation is also constrained by the properties of the support surface. For example, postural control with various body segments is limited by passive restraints such as seat belts and shoulder harnesses. Pushing on support surfaces with the legs and arms can be used to compensate for torques due to tilt or imbalance (cf., Riccio & Stoffregen, 1988; Zacharkow, 1988), but such postural control strategies can lead to inappropriate actions on the control stick and rudder pedals (Van Patten et al, 1983). A different, but related, strategy involves coordinated adjustment of the configuration of major body segments in order to minimize imbalance (Nashner & McCollum, 1985). In an aircraft cockpit, the major body segments that can be coordinated in this way are the head and the upper torso. The interaction between these body segments with respect to balance and imbalance is represented in Figure 7 (cf., Riccio & Stoffregen, 1988).

The dynamics of balance in the cockpit vary because of variation in the gravito-inertial vector within and across typical flight maneuvers (see e.g., Brown et al., 1991). Linear and centripetal acceleration of the aircraft change both the direction and magnitude of the gravito-inertial vector. Changes in the direction of this vector shift the location of the *potential gradient* for balance in the postural configuration space. Changes in the magnitude of this vector change the steepness of the gradient and change the size of the region within which postural perturbations can be reversed (Figure 8). Thus, postural control in vehicles must be robust, or it must adapt, to variations in both the direction of balance and the *consequences of imbalance*. Adaptability is also important because the evaluation functions, and associated potential gradients, for postural control are influenced by situation-specific factors other than torques on the body segments (Riccio, 1993; Riccio & Stoffregen, 1988; 1991).

The visual system and the manual-control system are nested within the postural control system (J. Gibson, 1966, 1979; Reed, 1982). Postural orientation and configuration may be modified to facilitate perception and action. For example, the pilot may tilt the head away from the direction of balance to scan a "tilted" horizon. In addition, the pilot may move the head or torso to minimize movement with respect to the inside of the cockpit even when this increases movement with respect to the direction of balance. Such nonmechanical influences on postural control are analogous to effects that variations in remote objects and the terrain have on vehicular control. System diagrams for postural control should represent the observability of postural orientation and configuration with respect to balance, support surfaces (e.g., an aircraft seat), manipulanda (e.g., control stick in the cockpit), and objects of visual regard (e.g., cockpit instruments). Figure 9 is a simplified diagram that represents these essential aspects of postural control.

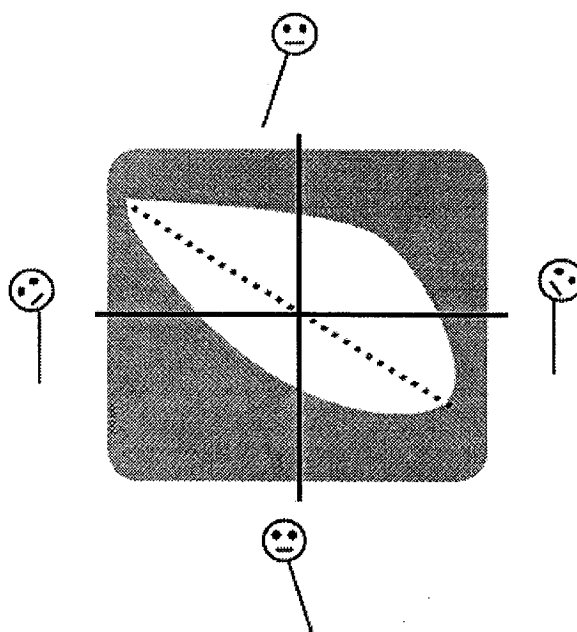
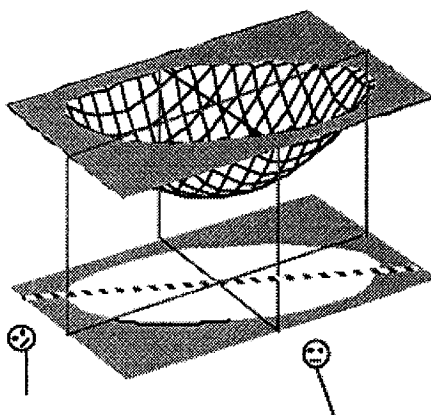


Figure 7. A configuration space for postural control. Upper panel represents relation between tilt of the head and torso with respect to the direction of balance (e.g., the gravito-inertial force vector) and the effect of the associated body configurations on an evaluation metric (e.g. torque on the body as a whole). The shaded area represents the configurations for which postural control is problematic. The dotted line represents a shallow gradient in the configuration space over which tilts of the head and the torso tend to counterbalance each other with respect to the evaluation metric. The border to the shaded region and the dotted line represent qualitative characteristics of the configuration space that are preserved over metric transformations (e.g., changes in size and location due to inertial variations; see Figure 8). The lower panel represents only the qualitative characteristics of the configuration space. Axes are included to represent the relevant continua; but they are perceptually arbitrary with respect to location, scale, and orthogonality (Ricchio & Stoffregen, 1988). The qualitative characteristics of the space are the only important perceptual landmarks. (From "Information in movement variability about the qualitative dynamics of posture and orientation" by G. E. Ricchio, in press, in: K. M. Newell & D. M. Corcos (Eds.), *Variability and Motor Control*. Copyright 1992 by Human Kinetics, Champaign, IL.)

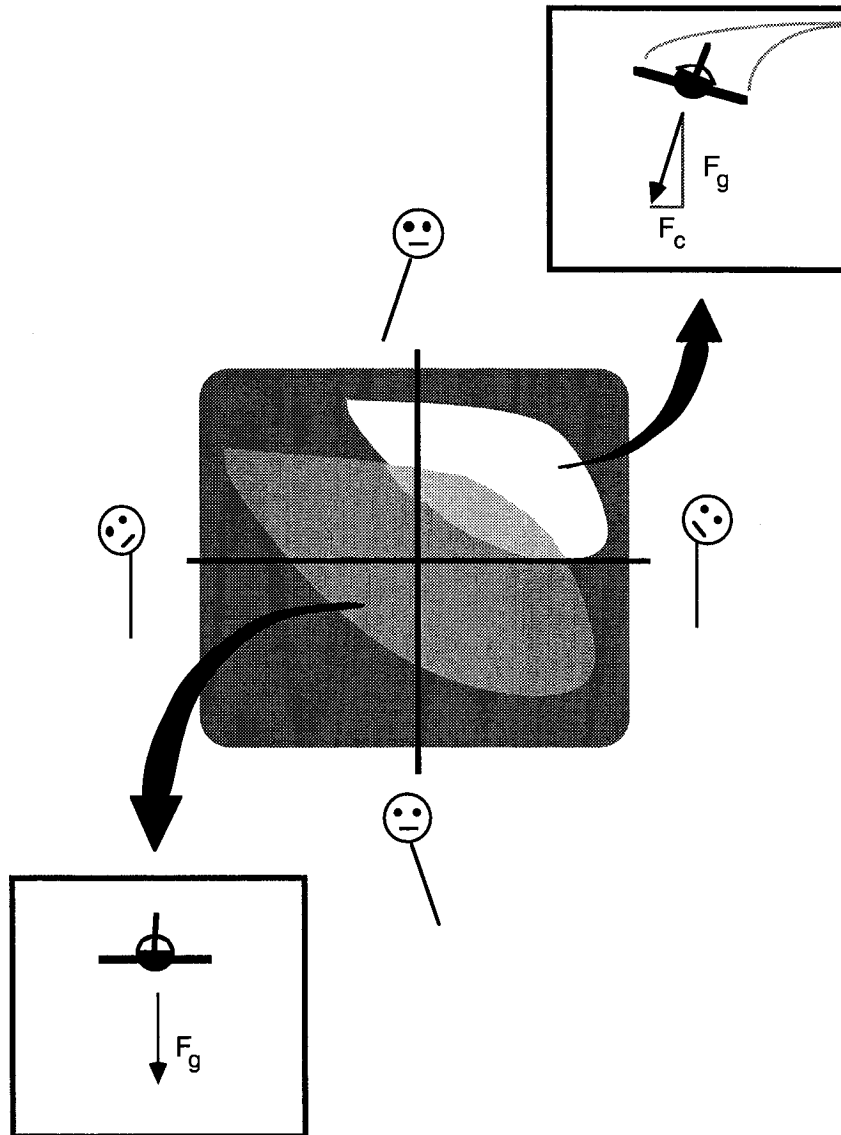


Figure 8. Vehicular constraints on postural control. Lightly shaded region represents configurations for which posture is controllable during level flight (lower inset). Unshaded region represents configurations for which posture is controllable during a change in heading (upper inset). In this diagram, the axes reflect the orientation of the head and torso with respect to an arbitrary fixed aspect of the environment (e.g., gravity).

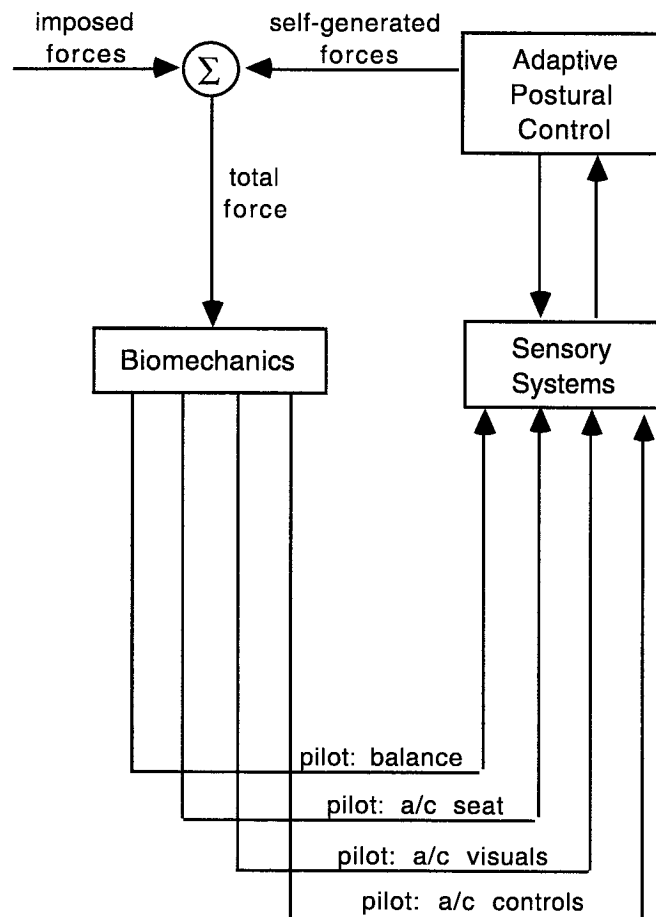


Figure 9. *Diagram for postural control. See text for explanation of terms and components. Diagram emphasizes analogies between postural control and vehicular control. Note that information about the direction of balance is available in the activity of postural control.*

4.2 Perception of Postural States

4.2.1 Exploratory Behavior

As in the diagrams for vehicular control, reciprocal interactions between sensory systems and the controller are represented in Figure 9 to emphasize the intentional adjustments associated with active observation as well as the information picked up through active observation. Active generation of change in postural states facilitates the observation of changes in constraints on postural control that are due to variation in the gravitoinertial vector and variation in the exigencies of perception and action in the cockpit. Such exploratory movements need not be fully intentional or precisely controllable. Information about the functional dynamics of posture are available in patterns of movement variability (Riccio, 1993; Riccio et al., 1992; Riccio & Stoffregen, 1988; 1991). Even uncontrolled *postural tremor* can be textured by the dynamics of the human-environment interaction. These ubiquitous movements can provide dynamical information without interfering with controlled adjustments in posture.

4.2.2 Information for Postural Control

Information about postural orientation and configuration is available in optical and mechanical stimulation, and it is available to a variety of perceptual systems. For example, information about orientation relative to balance is available to all the motion-sensitive systems. This information is available in the balancing movements of the postural control system, and the perceived "upright" is strongly influenced by the direction of balance during the act of balancing (Ricchio et al., 1992). Balance dynamics generate asymmetry in the movements or moveability of the body when the body is not upright. Presumably, perceived orientation or "tilt" is based primarily on vestibular sensitivity to such asymmetries because they are most pervasive in relatively continuous high-frequency movements (Ricchio, 1993). On the other hand, perceived orientation is highly labile and notoriously inaccurate when the dynamics of balance are either absent or attenuated, such as when a person is restrained, recumbent, or under water (Stoffregen & Ricchio, 1988; Ricchio & Stoffregen, 1990).

These facts suggest that perceived orientation is primarily determined by the active observation of balance dynamics rather than the passive observation of the gravito-inertial force vector. Perceived orientation can also be influenced by the visible surroundings. This may reflect the fact that postural control is constrained by perception of, and manual interaction with, the environment as well as by the dynamics of balance. Effects of the visible surroundings on perceived orientation may also be due to the fact they are relevant to balance whenever the surroundings are stationary and the body as a whole is neither speeding up, slowing down, nor moving along a curved trajectory.⁸ Reliance on information about orientation relative to the surroundings may be expedient when one does not perceive movement of the surroundings or variations in the velocity of self motion.

As suggested by Figures 7 and 8, information about body configuration is necessary for postural control. This information is available primarily to the somatosensory system. Moreover, the relations between orientation and configuration provide information about the tilt and slant of the support surface (e.g., the vehicle), and such information is also necessary for postural control (Ricchio & Stoffregen, 1988). For example, the tilt of the support surface determines the hip angle for which the torso is balanced. This information is available in the relation between vestibular and somatosensory stimulation, and in other patterns of multimodal stimulation. Information about movement of the support surface is also available in multimodal stimulation. One may pick up information in somatosensory stimulation about tilting (i.e., roll-axis rotation) of the support surface against the body. This could happen when the support surface changes orientation relative to the body and the direction of balance (i.e., a tilting surface), or it could happen when the body changes orientation relative to the support surface and the direction of balance (i.e., postural sway).

⁸ There is an invariant relation between one's orientation relative to the surroundings and one's orientation relative to balance within this domain of events. Direct perception requires sensitivity to invariants and to the domain with which they apply. Attunement to the structure in stimulation may occur on time scales that are short relative to the active observation of the domains within which this structure is lawfully related to aspects of the organism-environment interaction. This does not mean that sensitivity to invariants is more important than sensitivity to domains of invariance. Instead, it emphasizes that sensitivity to invariants is not sufficient for direct perception and that direct perception may unfold over time scales that are long relative to those studied in most experiments on perception (Gibson, 1979; Reed & Jones, 1982). In any case, direct perception is not viewed as an empirical question. It is an epistemological first principle that guides the search for lawful relations in ecological psychology. The emphasis on domains of invariance and the nesting of time scales for information pickup follow from this first principle.

Information about orientation of the body relative to balance is necessary to differentiate between these postural events. This is analogous to the differentiation between controlled and uncontrolled movements of a vehicle and to the differentiation among vehicular disturbances discussed above. Perceptual differentiation among the analogous postural events is necessary when the support surface can move; for example, it is necessary for postural control in vehicles. Presumably the vestibular system plays a critical role in this differentiation (Ricchio & Stoffregen, 1998; Stoffregen & Ricchio, 1988).

4.3 Vehicular Motion and Postural Perturbations

4.3.1 Differentiation Among Postural Events

Compensatory torque at various body joints would be required to reverse postural perturbations in the roll and pitch axes. It would not necessarily be appropriate to link such compensatory actions to information, in somatosensory stimulation, about movement relative to the support surface. These actions could produce instability if such somatosensory stimulation were due to rolling and pitching movements of the support surface instead of postural sway. For example, "pushing down" on the left part of a support surface in response to an upward push from this part the support surface would tend to stabilize the body if the event were due to counterclockwise postural sway. But this action would tend to destabilize the body (i.e., produce clockwise falling) if the event were due to a clockwise movement of the support surface. In the latter case, the appropriate postural action might be to relax muscles at some body joints so that movement of the support surface would not be translated to the body; in other words, one could allow inertia to stabilize the body (cf., Ricchio & Stoffregen, 1991, p. 201).

Postural control actions can become linked to inappropriate information if postural perturbations are not perceptually differentiated. Postural perturbations due to support-surface *rotations* can be differentiated from other perturbations by information about orientation relative to balance and, in some cases, by information about orientation relative to the visible surroundings. Postural perturbations due to translation of the support surface in the *horizontal* plane can be differentiated from other perturbations by information about the center of body rotation. The body will tend to rotate about a point above the support surface when the surface moves in the horizontal plane, but the body will tend to rotate about the point of contact with a stationary support surface when the body sways. This information is available to the vestibular system (i.e., in the relation between canal and otolith stimulation) and may also be available to the visual system (Ricchio & Stoffregen, 1991, p. 222; Young, 1984). *Vertical* movements of the support surface can be destabilizing whenever the major body segments are not perfectly aligned with the direction of balance; uncontrolled variations in torque on the body segments are generated in these conditions. Postural perturbations due to vertical movements of the support surface can be differentiated from other perturbations by information about vertical acceleration of the head (cf., Boff & Lincoln, 1988, pp. 2076-2081).

Differentiation of support-surface movements from other sources of postural perturbations may not seem necessary as long as orientation of the body relative to balance is perceived. From this perspective, postural actions would be appropriate if they were linked to the apparently sufficient information about changes in orientation relative to balance.⁹ However, uncontrolled postural movements generally occur together with controlled postural movements, and additional information is required to differentiate between them. It is important to differentiate between controlled and uncontrolled movements when considering the dynamics of the human-environment interaction. As indicated above, the dynamics of postural control vary within and across typical flight maneuvers. This means that there are variations in the effects of particular control actions on postural configuration and orientation. Such variations would be difficult to identify without differentiating the effects of control actions from the effects of disturbances.

It is also important to differentiate among the support-surface disturbances that are sources of uncontrolled changes in postural configuration and orientation. For example, clockwise tilt can be produced by a clockwise roll of the support surface or by a leftward translation of the support surface, but the compensatory actions are different for these two disturbances to the extent that the configuration of the body with respect to the cockpit surfaces is different. Disturbances in the vertical axis seem to be a special case. Relative to other disturbances, vertical movements have a large effect on gravito-inertial magnitude and a small effect on postural orientation. Vertical movements have their primary effect on the consequences of imbalance. Perception of these consequences probably requires a relatively time-consuming, although not exhaustive, exploration of postural configuration space (cf., Riccio, 1993; Riccio & Stoffregen, 1991). Adaptation to vertical movements of the support surface may be more difficult than adaptation to other uncontrolled movements.

4.3.2 Nausogenic Disturbances

The preceding discussion indicates that postural control actions may be linked to inappropriate information if there is a failure to differentiate among the various sources of postural movement. Linking postural control to inappropriate information would have the most serious consequences when the rates of change (or frequencies of oscillation) in postural disturbances are commensurate with the rates and frequencies of postural control. Controlled postural activity is concentrated in frequencies of oscillation below about 1 cycle per second (Dichgans & Brandt, 1978; Guitton, Kearney, Werely, & Peterson, 1986; Johansson, Magnusson, & Akesson, 1988; Maki, 1986; Viviani & Berthoz, 1975). Disturbances in this frequency range could lead to impoverished feedback about postural control or entrainment of postural control to the disturbance. Aircraft and other vehicles generate appreciable motion below 1 cps (Boff & Lincoln, 1988, pp. 2070-2081; Guignard & McCauley, 1990, p. 129). Interestingly, these are the frequencies of vehicular motion that are most highly correlated with motion sickness (Guignard & McCauley, 1982, 1990; O'Hanlon & McCauley, 1974; Lawther & Griffin, 1986). In addition, vertical movement of the support surface at these frequencies has been found to be more provocative than movement in other axes (Lawther & Griffin, 1986).

While interpretation of these data is not straightforward (Riccio & Stoffregen, 1991, p. 208), they are consistent with the notion that the postural consequences of vertical movements are qualitatively different from the postural consequences of other movements of the support surface. Vertical movements, and the concomitant variation in gravito-inertial magnitude, at rates and frequencies of postural control would be especially destabilizing because the effects of postural actions depend on

⁹ This is analogous to an argument for the sufficiency of visual kinesthesia in the control of locomotion. The argument is flawed for similar reasons.

the inertial environment. These data suggest that motion sickness is linked to postural instability (Riccio & Stoffregen, 1991; see also, Stoffregen & Riccio, 1991). If postural instability causes motion sickness, passive restraints in vehicles should significantly reduce the incidence of motion sickness. This appears to be the case (Johnson, 1953; Johnson, 1954; Johnson & Mayne, 1953; Fox, Daunton, & Coleman, 1982).

4.4 Dynamical Variability and Postural Control

4.4.1 Constraints During Curved Trajectories of Vehicular Motion

Postural control in a vehicle must be adaptive because constraints on the mobility of the head and other body segments change as a result of variations in vehicular motion. Adaptation of perception-action relations is possible if a particular change in the inertial environment is sustained for a period of time. Presumably this period of time must be long enough for the change, and its consequences for control strategies, to be perceived (Riccio, 1993; Riccio & Stoffregen, 1988, 1991). Vibration and transients due to aerodynamic disturbances and sudden maneuvers are generally too fast for adaptive change in perception-action relations. Other variations are more gradual and require modification of postural control strategies. For example, variations in the gravito-inertial vector are relatively gradual during curved trajectories of locomotion in aircraft or in terrestrial vehicles. Failures to adapt to such changes can result in postural instability, and postural instability can interfere with perception and action (Riccio & Stoffregen, 1988, 1991).

Evidence for such effects is apparent in the data of Van Patten et al. (1983). In this experiment, there were variations in the gravito-inertial vector across trials but not within the (30 second) trials in which data on vehicular control were collected. Tracking performance deteriorated and errors in vehicular control increased as a result of variations in the magnitude and direction of the gravito-inertial vector. Performance improved and errors decreased when passive torso restraints were added. Moreover, there was an interaction between variation in the gravito-inertial vector and passive restraint in that the restraints had a greater influence on performance when variations in the gravito-inertial vector were larger. Failure to adapt to changes in the inertial environment may be due to reliance on habitual postural control strategies that are more appropriate for stationary support surfaces.

4.4.2 Visual Control of Posture in Context

Postural control on moving support surfaces (e.g., vehicles) is different than postural control on stationary support surfaces (e.g., the ground). The control strategies (i.e., perception-action relations) that stabilize the body are different in these two situations. On a stationary support surface, changes in orientation relative to the direction of balance are generally accompanied by motion relative to the visible surroundings and, in this case, it is appropriate to link postural control actions to perceived motion relative to the visible surroundings. This perception-action coupling persists over variations in (i.e., motion of) the visible surroundings relative to the support surface and the direction of balance. For example, motion of the visible surroundings can have a strong influence on postural sway when such motions are small and slow (Dichgans & Brandt, 1978; Lee & Lishman, 1975; Lestienne, Soechting, & Berthoz, 1977; Lishman & Lee, 1973; see also, Stoffregen & Riccio, 1990). This postural control strategy generally is not destabilizing when the support surface is rigid, extensive, flat, and has adequate friction; that is, visually induced sway tends to be confined to the region of the postural configuration space in which one is "tolerant" to the variation in torques on the body (cf., Riccio & Stoffregen, 1988). Within the tolerance region, postural sway can be exploited to minimize variations in the distance between the eyes and objects of regard.

The visual control of posture can be problematic when the postural configuration, the support surface, or the gravito-inertial environment is unusual (e.g., Lee & Lishman, 1975). This was the case in the experiment of Van Patten et al. (1983) in which postural disturbances had consequences for vehicular control, vehicular disturbances had consequences for postural control, and in which the consequences of imbalance were enhanced by variations in the magnitude of gravito-inertial force. In this experiment, pilots had to learn a vehicle-specific postural-control strategy for which stability relative to the gravito-inertial environment, stability relative to the visible surroundings, and stability relative to the controls were all relevant to performance. While very little is known about the control of posture with respect to the combination of such evaluation functions, it is probably the rule rather than the exception (Riccio 1993; Riccio & Stoffregen, 1988, 1991).

Situations vary with respect to the way multiple criteria combine to constrain postural control. Experience in a particular situation should allow one to adapt to novel constraints. For example, Frigon, Delorme, and Vautrin (1991) found that the control of stance apparently adapts during prolonged exposure to moving surroundings. In their experiment, subjects adapted to the novel constraints by increasing the degrees of freedom in their control of posture. By combining flexion/extension at the hips with the action at the ankles they were able to both stabilize the center of mass and move the head with the visible surroundings.

Analogous adaptations in seated posture may be required in vehicles. For example, during a change in heading, the gravito-inertial force vector and the direction of balance change as a result of linear and centripetal acceleration. Videotapes of occupants in cars and aircraft indicate that the operators and passengers often attempt to maintain alignment of the torso with the direction of balance (Riccio, Sesek, & Powell, unpublished observations). This tends to occur for control of the head only when the eyes are closed. For turns of short duration, the roll motion of the head is reduced by allowing it to tilt relative to the torso (Figure 10). Because this tendency is observed only with the eyes open, it may facilitate looking at the surroundings outside the cockpit (e.g., scanning the horizon with eye movements). This strategy is not as prominent for turns of long duration. In addition, the partial decoupling of head and torso movements is apparently more complex in aircraft than in cars because looking at cockpit instruments plays a more important role in aircraft control. These informal observations emphasize the situation-specificity of postural control strategies and the inter-dependence of posture and locomotion.

It is important to note that the stimulation of perceptual systems is influenced by postural adjustments during a particular trajectory of locomotion. For example, the stimulation of the otolith organs and the semicircular canals depends on head movements, in the roll axis, during changes in heading. Thus, any attempt to understand the role of the vestibular system in the perception and control of whole-body motion must take into account the postural adjustments that occur during whole-body motion.

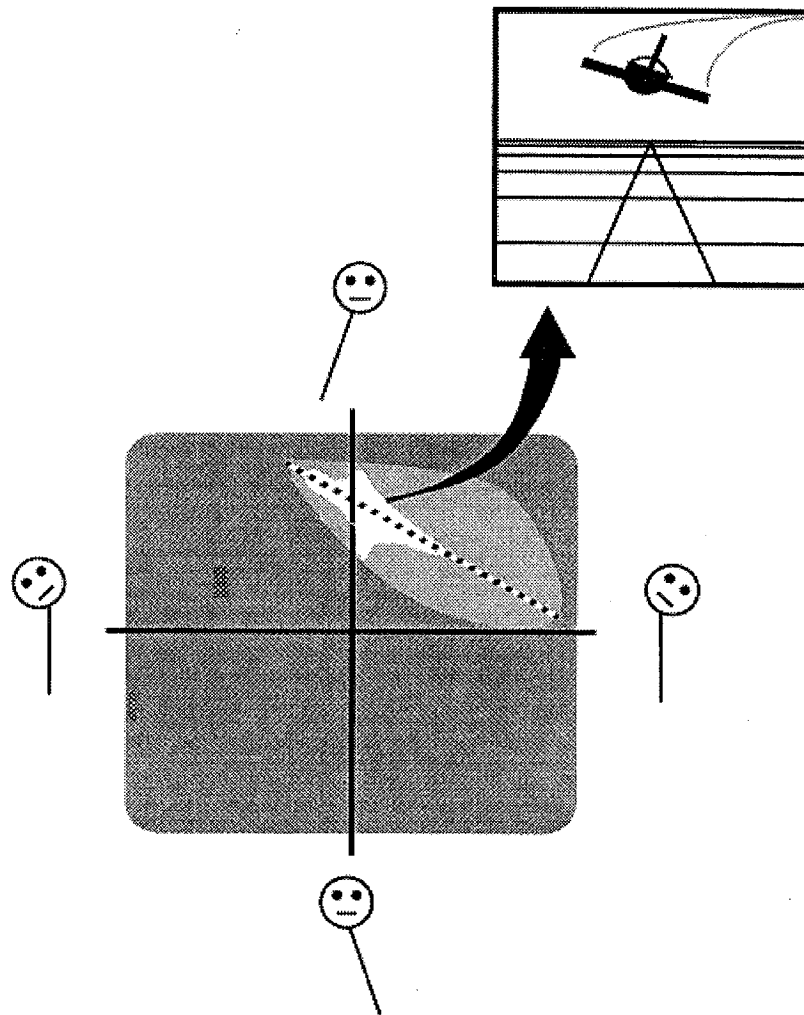


Figure 10. Multiple criteria for postural control. Lightly shaded region represents configurations for which posture is controllable during a change in heading (see inset). The unshaded region represents the configurations for which the torso is approximately aligned with the direction of balance and the inter-ocular axis is aligned with the horizon, and it reflects the concurrent influences of balance and scanning eye movements on postural control. In this diagram, the axes reflect the orientation of the head and torso with respect to an arbitrary fixed aspect of the environment (e.g., gravity).

4.4.3 Coordination of Posture and Locomotion

The meaning of the information in stimulation is influenced by the coordination of posture and locomotion. For example, perceived rotational motion or change in orientation may or may not require a compensatory postural action. Consider the control of posture in an aircraft. Disturbances on the aircraft can result in changes in orientation (e.g., pitch and roll) of the aircraft that may not be visible if outside-the-cockpit optical structure is impoverished. In addition, the visible surroundings inside the cockpits of many aircraft are often more extensive and richer in optical structure than the visible surroundings outside the cockpit, and the visible surroundings inside the cockpit are more relevant to perception and action in the cockpit (e.g., viewing instruments and handling controls). Furthermore, the support surfaces move with the visible surroundings inside the cockpit. This presents a problem

for postural control that may be difficult to overcome: posture may be controlled with respect to the support surfaces and visible surroundings inside the cockpit to facilitate interaction with the cockpit environment, but posture must also be controlled with respect to the inertial environment in order to avoid or limit imbalance (note that this is a problem even when the surroundings outside the cockpit are visible). This situation is analogous to “sway referencing” of the support surface and visible surroundings during the experimental or diagnostic evaluation of stance (see Nashner & McCollum, 1985).

It is well known that vestibular sensitivity to imbalance mitigates the destabilizing effects of these unusual environments. The situation is more precarious in vehicles because information, in vestibular stimulation, about rotation with respect to the inertial environment may or may not be relevant to postural control. During a *coordinated turn* in an aircraft, for example, the roll orientation of the aircraft changes with the direction of balance and the change in heading. The direction of balance remains roughly constant relative to the cockpit, and it is appropriate for the occupants to experience roll motion without changing orientation relative to the cockpit and the direction of balance (see e.g., Parrish, Diedonne, Bowles, & Martin, 1975). The constraints on postural control are different when driving a car along a curved path on level terrain. The roll orientation of the car does not change with the direction of balance. Occupants may produce rotational (roll) motion of their bodies relative to the visible terrain and the interior of the car in order to remain balanced or “upright.”

The use of habitual postural control strategies is problematic in vehicles because compensation for rotation can lead to instability. The relevance of perceived rotation to postural control in vehicles depends on the trajectory of locomotion (e.g., curved or straight), the type of vehicle (e.g., extent to which there is coordination between roll orientation and changes in heading), and the aspects of the environment with respect to which orientation is perceived (e.g., terrain, cockpit, or inertial environment). It is partly for this reason that postural control and locomotion are fundamentally interrelated. Locomotion is controlled in the context of postural control, and posture is controlled in the context of locomotion. This suggests that perception of locomotion (*kinesthesia*) should be considered in the context of postural control, and that perception of posture (*proprioception*) should be considered in the context of locomotion.¹⁰ The interrelations between kinesthesia and proprioception are essential in differentiating between stationary and moving support surfaces. It has been argued (Riccio, 1995) that these relations also are essential in differentiating between *observation of* an environment and *felt presence in* an environment.

4.5 Coupled Control Systems

4.5.1 Interacting Disturbances and Intentions

The importance of postural control in a vehicle indicates that the human operator is confronted with two concurrent control tasks. On the one hand, the operator needs to control the dynamical interac-

¹⁰ The use of the terms, kinesthesia and proprioception, is highly variable and somewhat confusing across the various communities in which perception is studied (see e.g., Owen, 1990a). The following definitions are used in this chapter. Kinesthesia refers to perception of change in location of the body, as a whole, relative to some aspect of the environment (i.e., self motion or “egomotion”). Visual kinesthesia, for example, refers to visual perception of self motion relative to remote objects or surfaces. Proprioception refers to perception of the position and motion of various body parts in relation to one another (i.e., postural configuration) or in relation to the environment (e.g., location of the eyes relative to an object of regard, location of the hand relative to manipulanda, or orientation relative to the direction of balance). Note that kinesthesia refers to perception of states that are relevant to locomotion, and proprioception refers to perception of states that are relevant to postural control. Kinesthesia and proprioception are related because locomotion and postural control are related, not because of redundancy or lack of specificity in the definitions for these terms.

tion between the vehicle and its medium or surface of support. On the other hand, the operator needs to control the dynamical interaction between his or her body and the interior of the vehicle. The two interactions can and should be represented as separate "plants" in the system diagrams that represent the respective control problems. Each system exists in the context of the other in that the behavior of each system influences the other. As indicated above, vehicular motion is a source of postural disturbance, and postural motion is a source of vehicular disturbances. The disturbance of each system by the other is one source of coupling between the systems. Another source of coupling derives from coordination between the controllers, that is, interdependence between the perception-action relations that are relevant to the respective control problems. The two sources of coupling are represented in Figure 11.

Coordination is possible if one has knowledge of the effect that the behavior of one system can have on the other and, thus, if one can predict the effect that a particular action in one system will have on the other system. These interactions between vehicular motion and postural motion are predictable if the respective motions are controllable. For example, the pilot can anticipate the forces experienced during controlled transients in aircraft motion. In addition, the pilot can modify postural control actions during sustained accelerations of the aircraft to accommodate the resulting change in biomechanical constraints on movement in the cockpit; that is, postural control strategies can adapt to variations in the biomechanical plant that are due to control of the aerodynamic plant. Vehicular control actions have meaningful and observable consequences for both vehicular control and postural control. Similarly, postural control actions have meaningful and observable consequences for both postural control and vehicular control. This has important epistemological implications for the perception and control of whole-body motion (or "self motion").

One implication of the coupling between postural control and vehicular control is that the intended postural configuration or the criteria for postural stability can be influenced by the intended vehicular motion. For example, during a "snap roll" or some other transient produced by the pilot, it can be advantageous for the pilot to adopt a non-upright configuration and stabilize the body against the side of the cockpit (Brown et al, 1991). In other situations, it could be advantageous to reduce postural stability to exploit "negative biomechanical feedthrough" to the aircraft control stick (cf., Repperger et al., 1983); that is, an uncontrolled body movement due to a vehicular disturbance could produce an action on the control stick that would tend to compensate for the vehicular disturbance. In any case, variation in the postural objective function (or "reference conditions") can be motivated by considering the forces encountered during the aircraft maneuver. Postural control strategies must be sensitive to the vehicular context.

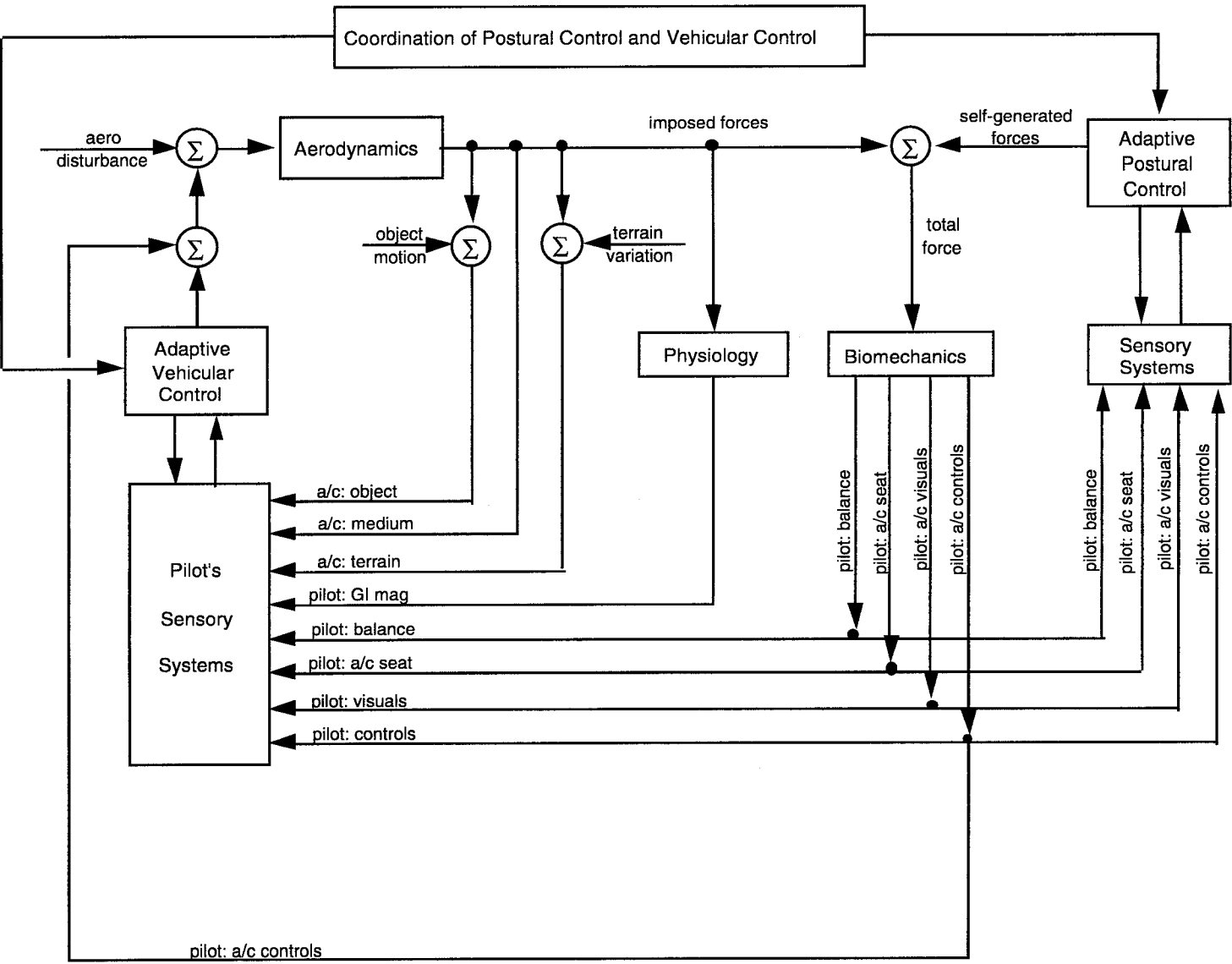


Figure 11. Coupling of postural and vehicular control systems. Control systems and the associated diagrams are linked in three ways. (a) Variation in vehicular velocity imposes forces on the postural control system. (b) Postural control and vehicular control are coordinated in that the actions of each system reflect the constraints on both systems. (c) Movement of the pilot relative to various aspects of the cockpit environment has affordances for both postural control and vehicular control. Note that the control of posture in the cockpit provides information about the direction of balance that otherwise is not available in the vehicular control system (cf. Figure 6).

Similarly, vehicular control must be sensitive to the postural context. For example, situations that demand more precise perception and action in the cockpit also require more stringent criteria for vehicular disturbance regulation. The interacting objective functions in coordinated postural and vehicular control suggest that these two control systems form "a combination of components that act together to perform a function not possible with any of the individual parts." The function that can be uniquely attributed to this superordinate system is the perception and control of whole-body motion. Whole-body motion is not adequately described by the component (or subset of components) of the system diagram that refers to vehicular control. This component does not differentiate the control of remotely piloted vehicles from the control of a vehicle in which the operator is an occupant; thus, it can only lead to models of phenomena that are common to these two types of vehicle. The experience of constant velocity motion is such a phenomenon, albeit vanishingly rare. Because the control of whole-body motion involves variations in velocity and acceleration, the postural consequences of these variations must be considered in any model of the perception and control of self motion.

4.5.2 Vehicular Information in Postural Stimulation

The preceding discussion emphasizes the coordination of postural control and vehicular control during variations in the velocity vector for whole-body motion. Controlled variations in velocity are fundamental to whole-body motion because it is hard to imagine how any goal could be achieved through whole-body motion without speeding up, slowing down, or changing direction. Another reason why variations in velocity are fundamental to the control of whole-body motion is that they involve transformations between kinetic and potential energy. Management of these energy transformations is important in all forms of movement (see e.g., Kugler & Turvey, 1987). Efficient management of the transformations between kinetic energy and gravitational potential energy, for example, minimizes the energy that must be drawn from internal energy stores to sustain or control locomotion. This is especially important in high-performance aircraft where the magnitude of gravito-inertial force can change by a factor of ten.

The magnitude of gravito-inertial force influences the maneuverability of the aircraft and it is manipulated by controlling the curvature of the aircraft's trajectory. It follows that perception of this force is useful for aircraft control. The direction of the gravito-inertial vector covaries with vector magnitude and with the orientation of the aircraft. Perception of the aircraft orientation with respect to the gravito-inertial vector is useful for controlling the coordination between changes in orientation and heading. Information about the magnitude and direction of the gravito-inertial vector is available primarily in stimulation of the vestibular system (Young, 1984). As noted above, passive observation of the gravito-inertial vector does not seem to be particularly reliable. However, information about the gravito-inertial vector is also available in the constraints it imposes on postural control, and the active observation of these constraints could support vehicular control.

Ubiquitous postural control activity provides *persistent excitation* of the human-environment system that reveals the changing dynamics of this interaction. Postural control activity is analogous to the dither of the aircraft's controls that promotes adaptive control. A possible advantage of the information in postural dither is that it does not interfere with vehicular control actions to the extent that vehicular dither can; that is, it is a potentially more efficient dual-control strategy. Another advantage is that this information is always available unless the pilot is completely restrained in the cockpit. It is not known whether this information is picked up in an aircraft and whether it supports vehicular control. Nevertheless, it is an intriguing possibility that has implications for vehicle simulations and interactions with virtual environments.

Another reason to emphasize this source of information is that it reveals another way in which control systems can be coupled. The postural control system can be considered as an *informative dynamical component* of the sensors used for vehicular control; that is, the vehicular control loop is closed through the postural control system of the human operator. The biomechanical plant can be considered an *informative dynamical component* because the associated postural control activity provides for observation of vehicle states while the aerodynamic plant provides for control of vehicle states. Active observation may be an important form of coupling in nested systems (Shaw et al., 1992). It could be generally important in the control of whole-body motion because postural control is relevant in all forms of pedal and vehicular locomotion. This is consistent with the general importance attributed to the basic orienting system in an ecological approach to perception (J. Gibson, 1966, 1979; Riccio, 1993; Riccio & Stoffregen, 1988, 1991).

5. Conclusions

5.1 Implications for Perception Science

5.1.1 Multimodal Perception

The issues raised in this report have some important implications for the study of perception. One implication is that it is dangerous to overemphasize isolated perceptual systems and sensory organs. The study of isolated perceptual systems is necessary but not sufficient to understand the perception and control of human-environment interactions. Moreover, the study of isolated perceptual systems can be misleading if the functional context for these systems is neglected. Perceptual systems must be studied in the context of the *meaningful environment* (J. Gibson, 1979). Information required for the achievement of goals must be considered at the outset, and this information may or may not be available to individual perceptual systems.

The putative dominance of visual perception does not follow from any ecological first principles such as direct perception, the perception of affordances, the temporally unbounded and developmentally nested process of perception, the obtaining of stimulation by active perceivers, attunement to invariant structure in stimulation, the nesting of perception and action systems, and the nested structure of the meaningful environment (E. Gibson, 1991; J. Gibson, 1966, 1979; Reed & Jones, 1982).¹¹ The necessity of vision for the control of locomotion in most situations does not imply that vision is sufficient for the robust and adaptive control of the nested dynamical systems involved in locomotion. The issues presented in this report emphasizes that vision is rarely sufficient for the control of locomotion. Visual perception of self motion must be considered in the context of multimodal perception because information for the affordances of whole-body motion is generally available only in multimodal stimulation. In the present terminology, kinesthesia must be considered in the context of proprioception.

5.1.2 Information in Stimulation

Another implication for perception is that the perception and control of interactions with the environment unfold over time scales that are long relative to the time scales defined by the attendant structure in stimulation. One can perceive and control variations in posture, orientation, and whole-body motion up to rates of several cycles per second, but the sensory organs associated with proprioception and kinesthesia can attune to variations as high as several hundred cycles per second (see e.g., Ormsby & Young, 1977; Young, 1984; Zacharias & Young, 1981). This bandwidth of sensitivity could be useful if the high-frequency activity is modulated or structured by controllable and task-relevant variations at lower frequencies (Riccio, 1993). There is information in low-frequency variation of high-frequency stimulation, and the phenomenology of perception presumably corresponds to the pickup of this low-frequency information. This suggests some epistemologically important analogies between nonvisual systems, such as the vestibular system, and the visual system.

High-frequency motion may be to the vestibular system what light is to the eye. They are each a medium of stimulation that is structured by the environment at the scale of human interactions with the environment. There is information in the stimulation of a variety of perceptual systems about the human-environment interaction. Such an approach to nonvisual perception, which is commensurate

¹¹ The clear presentation of these first principles, by James Gibson (1979), in the context of particular examples in visual perception is, in this sense, an unfortunate coincidence. The potential misunderstanding is avoided in his work considered as a whole (see e.g., J. Gibson, 1966; Reed & Jones, 1982) and in the work of Eleanor Gibson (e.g., E. Gibson, 1991).

with the ecological approach to visual perception, facilitates the analysis of multimodal perception. The various perceptual systems are unified by considering the information in multimodal stimulation about the meaningful environment (cf., J. Gibson, 1966; Ryan, 1938, 1940). The study of perception should begin with, and be grounded in, the *environment to be perceived*.

Perceivables for the kinesthetic and proprioceptive systems include aspects of the dynamical layout that have affordances for the nested perception and action systems. These qualitative dynamical properties of the human-environment interaction are critical regions in the relation between moveability of the body and the orientation and motion of the body (Ricchio, 1993). The direction of balance is such a perceivable (Ricchio et al., 1992). Many other potential perceivables emerge from the dynamical interaction among the nested components of the human body. This meaningful landscape is largely unexplored in perception science. Progress in understanding proprioception and kinesthesia is fundamentally dependent on the identification of these perceivables and the ability to simulate and experimentally manipulate them.

5.2 Implications for Movement Science

5.2.1 Nested Systems

The theoretical perspective presented in this report also has implications for the study of human movement. A central theme in this report is the nesting of control systems. A superordinate system is formed when an action system is coupled with 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. The goals and coupled subsystems become nested in the sense that the goal-directed behavior of the superordinate systems constrains the way the goals of component subsystem can be achieved, and vice versa. While the goal-directed behavior of a system imposes such task-specific constraints on the behavior of component subsystems, the associated coupling affords opportunities that may not be possible without the coupling.

Intelligent systems presumably perceive and act upon these affordances by adaptively coupling with their surroundings in ways that are consistent with the attendant constraints. 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. This report focuses on the coupling of the postural control system with various types of real and simulated vehicles. The coupling between the postural control system and the eye-head system is also discussed, albeit briefly. Similar functional interactions among components of the human body are discussed more extensively elsewhere (Ricchio, 1993). Such couplings reveal that the various components of the human body are generally controlled and coordinated with respect to multiple criteria.

Research on the multicriterion control of posture and whole-body motion is important because it emphasizes that different modalities or patterns of stimulation do not necessarily provide information about the same system states. They generally provide information about the multiplicity of states that are relevant to nested goals (e.g., maintenance of balance and visibility of the surroundings). Consideration of multicriterion control in human movement reduces the potential for an erroneous assumption that multiple sources of information are either redundant or conflicting (Ricchio & Stoffregen, 1988, 1991; Stoffregen & Ricchio, 1988, 1991).

5.2.2 Dual Control

Informative dynamical components are presented as a source of coupling in nested systems. Balancing the head or other body segments in the cockpit, for example, can provide information about the inertial environment that is relevant to vehicular control. Postural control in the cockpit and control of the vehicle can become coupled if the informativeness of postural control depends on the way the body segments are balanced or moved. One may tolerate the consequences of a moderate amount of imbalance in the head, for example, to enhance sensitivity to the inertial environment (cf. Riccio et al., 1992). That is, the exigencies of vehicular control could induce exploratory postural adjustments that otherwise would be avoided.

This may be a general organizing principle in human movement. A moderate amount of instability may be tolerated in component subsystems so that information in the obtained stimulation can enhance stability in the superordinate system. A moderate amount of instability in one aspect of an activity may enhance the stability of the activity as a whole (cf., Beek et al., 1992). Informative dynamical components reveal the importance of considering exploratory behavior in models of concurrent performatory behavior. This dual-control problem, and the related problem of multi-criterion control, present significant challenges to extant models of human movement. However, understanding these aspects of control in nested systems may be necessary to understand the adaptability that is an essential property of human movement (Riccio, 1993).

5.3 Implications for Modeling the Perception and Control of Self Motion

5.3.1 Rigid-Body Assumption

A great deal has been learned about the characteristics of human controllers by applying formal models from control-systems engineering to data from experiments on closed-loop manual control (see e.g., McRuer, 1980). In general, these analytical approaches focus on tasks for which the degrees of freedom in control behavior are relatively small and the performance criteria are relatively simple. The precision of the associated mathematical models is impressive as is their accuracy within this limited domain. The disadvantage of such models is that there is a tendency to lose sight of the characteristics of human controllers that are beyond the scope of the models. In the study of vehicular control, for example, the success of analytical models has fostered the assumption that the human operator is rigid and rigidly attached to the vehicle. There is nothing wrong with this assumption when it is explicitly stated. It is problematic, however, when the models that are built on such assumptions are applied to situations where the assumptions are not valid.

This report reveals that the rigid-body assumption is not valid for the control of whole-body motion, in general, and specifically for vehicular control. In some situations, analytical models based on a rigid-body assumption could accurately describe vehicular control. The rigid-body assumption would be either valid, irrelevant, or unnecessary in such situations. It is valid, for example, when variation in the velocity vector of whole-body motion is minimal; and it is irrelevant to aspects of vehicular control that are robust to disturbances of perception and action in the cockpit. The rigidity assumption is relevant to vehicular control, but unnecessary for an isolated description, if posture can be stabilized and coordinated with vehicular control. In situations where the pilot is nonrigid, for example, coordination of postural control and vehicular control could lead to vehicular control behavior comparable to that obtained when the pilot is rigid. The assumption is relevant in such situations because the way the pilot copes with nonrigidity is part of the flight control skill.

Vehicular control behavior might appear to be quantitatively similar in different situations, but the skills that underlie the vehicular control behavior could be qualitatively different. Conversely, vehicular control behavior could be quantitatively different (e.g., because of fatigue or motivation) while the skill of coordinated postural and vehicular control could be qualitatively similar. It follows that transfer of training between vehicles cannot be predicted on the basis of the quantitative similarity in vehicular control behavior (see e.g., Flach et al., 1986; E. A. Martin et al., 1986).

5.3.2 Qualitative Dynamics

Nested control systems and multi-criterion control should be central in formal models for the perception and control of whole-body motion. The mathematical basis for such models is likely to be quite different from the models that are commonly adapted from classical or modern control theory. Promising directions for modeling whole-body motion are suggested by models developed for other human-environment interactions (e.g., Beek, 1989; Beek et al, 1992; Shaw et al., 1992). Such models reflect both the exploratory and performatory aspect of human movement. They are necessarily nonlinear, and they are generally heterogeneous with respect to both components (subsystems) and performance criteria (cf. Beek & Bingham, 1991).

It is best to begin the analysis of these systems by emphasizing the critical regions in the controllability and observability of system states, that is, the qualitative characteristics of the system dynamics that emerge through the nonlinear interactions among the components. These characteristics include the classical optimal control regions for systems with invariant dynamics, but they also include regions where control breaks down as well as regions where observability of systems' dynamics is optimal (Riccio, 1993; Riccio & Stoffregen, 1988, 1991). The latter are important when the dynamics or the performance criteria of a system vary and exploratory action is necessary. Exploration of the state space or the performance envelope of a system is robust if the stability limits of the system are not exceeded.

Exploration promotes adaptation of control behavior and improvement in performance. It is virtually impossible to differentiate between exploratory behavior and adaptive modifications in performatory behavior without some understanding of the underlying dynamics. The functional dynamical layout is likely to be quite complex for the nested systems discussed in this report and, perhaps, for human-environment interactions in general. Models for whole-body (or "self motion") must shift their focus from the quantitative details of control behavior to the qualitative characteristics that bound this behavior. Accuracy and breadth of analysis must not be sacrificed for precision and depth of analysis.

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Appendix A. Topical Bibliography

2. HUMAN-ENVIRONMENT INTERACTION

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2.3.1 Intentions and Disturbances

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3. VEHICULAR CONTROL

3.1 Vehicular Control Relative to the Surroundings

3.1.1 Perception of Controlled and Uncontrolled Movement

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4.5 Coupled Control Systems

4.5.1 Interacting Disturbances and Intentions

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Appendix B. Relationship With Companion Article (Riccio, 1995)

Riccio & McDonald	Riccio
VEHICULAR CONTROL	SIMULATED VEHICULAR CONTROL
Vehicular Control Relative to the Surroundings Controlled and Uncontrolled Movement Differentiation Among Disturbances	Vehicular Control Relative to Simulated Surroundings
Dynamical Variation and Vehicular Control Perception of the Aerodynamic Environment Exploration of Aerodynamics	Dynamical Variability in Simulators and Vehicular Control Perception of the aerodynamic environment Exploration of aerodynamics
Effects of Vehicular Control on the Human Physiological Effects Biomechanical Effects	Effects of Simulated Vehicular Control on the Human Physiological effects Biomechanical effects
COORDINATION OF POSTURAL CONTROL AND VEHICULAR CONTROL	COORDINATION OF POSTURAL CONTROL AND SIMULATED VEHICULAR CONTROL
Postural Control in Vehicles Postural Restraint in the Cockpit General Constraints on Postural Control	Postural Control in Simulated Vehicles
Perception of Postural States Exploratory Behavior Information for Postural Control	Perception of Postural States in Simulated Vehicles
Vehicular Motion and Postural Perturbations Differentiation Among Postural Events Nausogenic Disturbances	Simulated Vehicular Motion and Postural Perturbations Differentiation among postural events Simulator Sickness
Dynamical Variation and Postural Control Constraints During Curved Trajectories Visual Control of Posture in Context Coordination of Posture and Locomotion	Dynamical Variability in Simulators and Postural Control Constraints during curved trajectories Visual control of posture in context Coordination in the simulator and its aftereffects
Coupled Control Systems Interacting Disturbances and Intentions Vehicular Information in Postural Stimulation	Coupling of Real and Simulated Systems Components Felt presence and virtual environments Informative interactions with virtual environments

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE January 1998	3. REPORT TYPE AND DATES COVERED NASA Technical Paper		
4. TITLE AND SUBTITLE TP 3703, Multimodal Perception and Multicriterion Control of Nested Systems: I. Coordination of Postural Control and Vehicular Control			5. FUNDING NUMBERS	
6. AUTHOR(S) Gary E. Riccio* and P. Vernon McDonald**				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lyndon B. Johnson Space Center Houston, Texas 77058			8. PERFORMING ORGANIZATION REPORT NUMBERS S-835	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER TP 3703	
11. SUPPLEMENTARY NOTES *Nascent Technologies, Ltd. **National Space Biomedical Research Institute				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified/unlimited Available from the NASA Center for Aerospace Information (CASI) 800 Elkridge Landing Rd Linthicum Heights, MD 21090-2934 (301) 621-0390 Subject Category: 54			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The purpose of this report is to identify the essential characteristics of goal-directed whole-body motion. The report is organized into three major sections (Sections 2, 3, and 4). Section 2 reviews general themes from ecological psychology and control-systems engineering that are relevant to the perception and control of whole-body motion. These themes provide an organizational framework for analyzing the complex and interrelated phenomena that are the defining characteristics of whole-body motion. Section 3 of this report applies the organization framework from the first section to the problem of perception and control of aircraft motion. This is a familiar problem in control-systems engineering and ecological psychology. Section 4 examines an essential but generally neglected aspect of vehicular control: coordination of postural control and vehicular control. To facilitate presentation of this new idea, postural control and its coordination with vehicular control are analyzed in terms of conceptual categories that are familiar in the analysis of vehicular control.				
14. SUBJECT TERMS motion, motion perception, perception, control, adaptive control			15. NUMBER OF PAGES 76	16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT None	