TASK-SPECIFIC DEVICES
AND THE PERCEPTUAL BOTTLENECK *

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An approach to the problem of organization in human action is presented. The approach describes the observable forms of behavior in terms of the dynamics of *task-specific devices (TSD)*. The properties of a TSD delineate problems for research. The properties are task specificity, smartness, determinism, soft assembly and reduction, controllability, scale specificity, assembly over properties of organism and environment, and modifiability to new purpose. Nonlinear properties of four subsystems of the human action system are described. The subsystems are the link-segment system, the musculotendon system, the circulatory system, and the nervous system. A methodological dilemma is created by the need to do justice in description to all four subsystems while at the same time not being completely overwhelmed by the extreme complexity. A strategic resolution is to describe the simpler dynamics of TSD's. This strategy holds the promise of working backwards to the complex dynamics of the subsystems from which a TSD is assembled. Finally, TSD's require perceptual access to the dynamics. The characteristics of the human perceptual system lead to the perceptual bottleneck. Information about the dynamics of actions and events must be preserved over two mappings. One mapping is from the dynamics to the kinematics of an event. This introduces the identification problem in perception. How do the qualitative properties of an event allow an observer to recognize it? The second mapping is from the ratio-scaled kinematics of an event to the nonratio-scaled structure of the optic, acoustic, and haptic arrays. This introduces the scaling problem in perception. How do the qualitative properties of an event allow an observer to judge the scale values in an event?

Introduction

In studying human action, we aspire to understand how an extremely complex *physical* system can become organized to produce

coherent and functionally effective behavior. This problem has been characterized, in part, as 'the degrees of freedom problem' (Turvey et al. 1978; Whiting/Bernstein 1984/1967). How do the very large number of degrees of freedom in the human body become constrained in the performance of behaviors that may be described in terms of relatively few degrees of freedom? Although the reduction in degrees of freedom is an important aspect of the problem of organization in human action, this formulation of the problem is ill posed. The reason is that we are unable to specify the initial degrees of freedom whose number is to be reduced. Describing the degrees of freedom of the *human action system (HAS)* constitutes as much of a problem for research as does describing the means by which the degrees of freedom are constrained. (See Kay (1986) and in this volume for further discussion of this point.)

The degrees of freedom of the HAS are associated with the dynamic properties of its various components which include bones, tendons, ligaments, nerves, blood and blood vessels, and muscles. In the HAS, there is an enormous profusion of dynamic properties, each distinct in character. For example, muscles vary considerably in their fiber layout from pennate to parallel. Their dynamic properties vary accordingly. Fiber arrangement determines the force levels available from a muscle as well as the form of its nonlinear stiffness curve. Each muscle exhibits a stiffness that is distinct in form as well as in the scale of force values. Similar variations occur in other types of dynamic properties (e.g., damping).

Analysis of the HAS, including an enumeration of its degrees of freedom, requires the description of an extremely large number of distinct dynamic properties varying in both form and scale, as well as type. However, a particular action performed by the HAS only involves a limited selection of the large variety of dynamic properties available. The wrist joint is kept fairly rigid in a lob style of overhand throwing which, therefore, does not involve the considerable compliance of the long tendons spanning the wrist. Analysis requires discovery of the particular dynamic properties that are employed in performing a specific action. However, such analysis is extremely difficult by virtue of the fact that HAS dynamics are nonlinear. The nonlinearity of the component dynamics in human action means that superposition does not apply. The behavior of the HAS cannot be anticipated by adding or superimposing the behavior of the components measured in isolation.

Conversely, the components cannot be derived from the measured behavior of the whole by some subtractive procedure. Discovering the component dynamics that have been organized to produce the dynamics of specific human activities is a supremely difficult inverse problem.

The notion of *task-specific devices (TSD)* provides a framework organizing the problems raised in studies of human action. In this framework, the collection of dynamic properties associated with the anatomy of the HAS are resources from which the HAS selects and assembles a TSD. The degrees of freedom associated with the dynamics of a TSD are reduced from those associated with the dynamic properties of the components used to assemble a TSD. The research strategy advocated in this paper is to describe TSD's in specific instances and to work inversely from the dynamics of a TSD to the resource dynamics of the HAS. This formulation offers several advantages. The reduced degrees of freedom associated with a TSD are those which can be observed and measured directly. Further, the description of a TSD is in dynamic terms. Because the means of reduction are themselves dynamical (Kay 1986; Marmo et al. 1985), the job of working backwards from the reduced degrees of freedom to those originally selected and assembled by the HAS is facilitated by adopting dynamical system theory as a framework for research.

Difficulties of the inverse problem related to the nonlinear and dissipative character of the resource dynamics require that every means at our disposal be used in a coordinated effort to reveal the dynamic resources of the HAS. Investigations running the gamut from cadaver to behavioral studies contribute useful results. An effective understanding of human behavior requires a simultaneous focus on the unique and particular properties of the diverse biological materials as well as on the physical laws that constitute scaling relations between properties. Exclusive focus on the anatomical components hinders an understanding of how relations are established both among the components themselves as well as between the components and the properties of terrestrial events. Alternatively, exclusive focus on general scaling relations impedes an understanding of how the great variety of particular types and scales of actions and events arise. The problems associated with type and scale in human behavior call for an approach that is at the same time uniform and pluralistic, relational and hypostatic. Fortunately, the field of nonlinear dynamics provides an approach that conforms to this requirement (Szücs 1980).

A second inverse problem, the *perceptual bottleneck*, arises in the study of human action because TSD's are assembled and maintained actively to achieve specific task goals. To select and assemble dynamic properties to be used in the performance of a task, the HAS must have perceptual access to the available dynamics. Information about dynamics is mapped through kinematics into the transforming distributed structure of the optic, acoustic, and haptic arrays. The inverse problem is to understand how array structure maps back through kinematics to the dynamics in a manner that is specific to both the type and scale of the dynamics. The bottleneck is created by the scaling limitations of perceptual information. Although the dynamics of actions and events are ratio scale specific, the patterns to which the perceptual systems have access are not ratio scaled. Thus, information about the ratio scaled nature of dynamic properties must be conveyed in nonratio-scaled forms.

An approach to the study of human behavior in terms of TSD's and the perceptual bottleneck is elaborated below. A discussion of difficulties introduced by the diverse nonlinear properties of the HAS provides motivation for the TSD approach. This is followed by a description of the properties of a TSD which direct attention to specific questions for research and thus, organize the study of human action. Finally, the challenge of the perceptual bottleneck is described in terms of the identification and scaling problems.

The human action system

When the human action system is mobilized to perform a task, the dynamics of (at least) four subsystems must couple in such a way as to produce coherent and functionally effective behavior. These four subsystems comprise the *inherent dynamics* of the HAS. They are the link-segment system, the musculotendon system, the circulatory system, and the nervous system. [1] These inherent dynamics are coupled, in addition, to the *incidental dynamics* introduced by circumstances associated with a task. Each of these dynamic subsystems is characterized by its own set of idiosyncratic properties. Studied in isolation, many of these properties have been characterized as placing severe limits on

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[1] Less tightly coupled subsystems include the respiratory and nutritional systems.

achievement in human action (Amis et al. 1979; An et al. 1981; Hill 1985; Inman and Ralston 1968; McMahon 1984; Wilkie 1950). For instance, the force–velocity relation for the contractile elements of skeletal muscle would seem to place strict limitations on the power that can be developed and transmitted to the articulators via the passive elastic tendons (Inman and Ralston 1968; McMahon 1984; Hill 1985; Wilkie 1950). However, the power generated by muscles when used in the performance of common tasks far exceeds the amounts originally predicted by these results. Studies of running, jumping, kicking, and throwing have revealed that the properties of muscle are organized to overcome merely apparent limitations (Alexander 1977, 1984; Bobbert et al. 1987a; Bober et al. 1987; Jöris et al. 1985). The passive elastic components of the actuators are used very effectively as power amplifiers yielding a substantial increase in power over that available directly from the contractile machinery (Bobbert et al. 1986a,b; Cavagna 1977; Cavagna et al. 1977; Cavanagh and Kram 1985). This is accomplished by allowing elastic components to absorb energy produced at slower rates by the contractile elements, and subsequently, to return that energy at faster rates. If a task requires high power output, using this trick to good effect can make the difference between success and failure. However, taking advantage of this property of skeletal muscle requires that movements be organized in specific ways. The successful performance of any task requires that particular properties available to the HAS be used to meet task demands. How does the HAS orchestrate the complex and peculiar, inherent and incidental dynamics involved in a task to achieve an organization that successfully accomplishes the task goals? This is the fundamental problem confronting the science of human action.

The complexity of inherent dynamics

In tackling this problem, the most immediate challenge is presented by the overwhelming complexity of the HAS. Each of the four subsystems of the HAS includes a confusing diversity of nonlinear properties. The magnitude of the complexity derives not only from the number of dynamic properties but also from the nonlinear character of the properties. Nonlinearities pervade the subsystems.

The link-segment system

The articulators are jointed link-segments. The inertial properties of

this system vary nonlinearly with its configuration. The inertial resistance of a link to rotational motion is a function of the mass distribution of a link relative to the momentary axis of rotation. The mass distribution for each link depends not only on its unique shape and on the particular distribution of soft and bony tissues, but also on its orientation with respect to the axis of rotation (Hogan 1985; Saltzman 1979). The inertial resistance of the hand to rotation at the elbow depends nonlinearly on the angular position at the wrist. If the wrist is rotating as well as the elbow, then (nonlinear) interactions result.

Multisegmental limb motions are characterized by considerable interactive dynamic effects (Phillips et al. 1983). Hollerbach and Flash (1982) have shown that even for a two-segment/two-joint system, significant interaction effects occur. They distinguish between inertial torques, which are proportional to joint acceleration, and velocity torques which are proportional to products of joint velocities. Inertial torques are produced by the segments pushing off from one another resulting in action and reaction according to Newton's third law. Centripetal torque is proportional to the square of the velocity at a joint. Centripetal torque produced by rotation at the elbow, for instance, would cause the hand to move towards a line extended from and parallel to the forearm. Coriolis torque is proportional to the product of velocities at two different joints. With simultaneous flexion at the shoulder and extension at the elbow, coriolis torque will tend to extend the shoulder during portions of a reach.

Inertial torques go through zero with switching from acceleration to deceleration near the midpoint of a typical reaching movement. Velocity, on the other hand, reaches its peak at the midpoint. Thus, velocity torques have their strongest effect when inertial torques are weakest. Hollerbach and Flash point out that the scaling of such movements in time has no effect on the relative contributions of these torques. On the other hand, the variations in the different types of torque over a movement depend in very complex ways on the joints and segments involved in a movement and on the particular ways that they move. The form of movement is determined, in part, by the energy derived from the actuators.

The musculotendon system

The actuators consist of active contractile elements as well as passive elastic tendonous elements. Active and passive elements both exhibit distinctive nonlinear force transduction characteristics.

When stretched, tendon exhibits a stiffness characterized by two discontinuously connected regions (Proske and Morgan 1987). The transition between the regions is sudden and corresponds to a discontinuous increase in the slope of the length-tension relation. Further, the stiffness within each region is nonlinear. However, the nonlinear stiffness in both regions can be represented approximately as linear with a discontinuous, and thus, nonlinear transition between the regions. Alternatively, the whole curve can be approximated as exponential, preserving the nonlinear aspect of the stiffness throughout, but ignoring the marked discontinuity.

The contractile component of muscle exhibits a complex array of interacting nonlinear properties. The isometric contractile force–length curve is highly nonlinear. The specific form of the curve varies with the fiber-layout structure of the muscle from pennate to parallel (McMahon 1984). Parallel fibered muscles are likely to exhibit a local maximum in the curve. The curve is the sum of a curve for passive elements internal to a muscle and a curve which reflects the actively developed tension. Developed tension reaches a maximum at an optimal muscle length. This corresponds to a local maximum in the summed curve depending on the shape of the passive curve. Skeletal muscles can be categorized roughly according to whether their architecture is more or less multipennate, bipennate, unipennate, or parallel. However, each of the myraid skeletal muscles exhibits a fairly distinctive fiber-layout structure. Accordingly, the force-length curve for each muscle is distinctive including the location of the optimum length.

Muscles that are actively shortening produce less force than in isometric contraction. They shorten more rapidly against light than heavy loads. This is attributed to the contractile elements being damped by a viscous mechanism (Hill 1985; McMahon 1984). The result is the nonlinear force–velocity relation for striated muscle (Inman and Ralston 1968; Wilkie 1950). Since power equals the product of force and velocity, this relation also determines the nonlinear power characteristics of the contractile machinery. The speed of shortening determines the rate at which energy leaves a muscle. Maximum power output occurs when the force and the contraction velocity are between a third and a quarter of their maximum values.

The form of the force–velocity curve is different entirely for lengthening muscle (McMahon 1984). Force levels are much higher than for shortening velocities up to a lengthening velocity at which the

tension drops dramatically and discontinuously. If a smooth rise in tension is required, the timing of lengthening contractions is constrained by the discontinuity in the length–tension curve for tendon (Proske and Morgan 1987). If the tension of the contractile component is rising during a lengthening contraction, then a smooth tension rise is facilitated and a sudden drop in tension is avoided.

A complex coupling exists between activation and stretch (Heglund and Cavagna 1985; McMahon 1984). Potentiation occurs when contracting muscle has been pre-stretched while active. The result is an elevated force–length curve for the muscle. Potentiation increases in magnitude with the speed of stretching and decreases with the time elapsed after pre-stretch (Bobbert et al. 1987a).

Each of these properties constrains the amount of power that can be developed by the actuators. The particular type of muscle, its length, its direction of length change, the rate of length change as well as the specific nature of the muscles' antecedent activity and the length of the tendonous elements all determine the momentary output of a muscle. The way each of these properties varies in relation to the others over a movement determines the amount of energy available to be invested in a particular action.

The circulatory system

Ultimately, the mechanical energy produced by the actuators is derived from metabolic energy supplied through the circulatory system. The reaction time between the onset of muscular contraction and acceleration in heart rate is 0.5 seconds (Hollander and Bouman 1975). The degree of acceleration in the heart rate tends to follow the strength of contraction. However, this initial acceleration typically overshoots the rate appropriate for the metabolic demands of contraction. Cardiac response to the initiation of a bout of exercise is a transient overshoot with a duration of less than a minute followed by settling to a sustained state that is proportional to the intensity of exercise (Laughlin and Armstrong 1985). Thus, blood flow is adjusted to the metabolic requirements of active muscle as exercise continues (Wigertz 1970).

The control of blood flow is a subtle affair. Blood flow to the muscles depends not only on the level of activity in particular muscles, but also on the fiber types within a muscle. Blood flow within a muscle is heterogeneous according to the distributions of different fiber types (Laughlin and Armstrong 1985). The mechanisms responsible for this

are unknown. Task specific alterations occur in blood flow depending on the muscle groups and different fiber types used in different tasks.

Dynamically, blood flow is a function both of global perfusion pressure and local resistance to flow (Åstrand and Rodahl 1977; Bloch and Iberall 1982; Laughlin and Armstrong 1985; Morton 1987). Changes in local resistance require changes in the radius of circulatory vessels while the global pressure is due to the action of the heart together with the sum of the local resistances. Given this interaction, in particular, hemodynamics is highly nonlinear.

The nervous system

Nerve cells exhibit a variety of properties, most of which are nonlinear (Rasch and Burke 1978). The foremost characteristic of the nerves is their ability to transmit impulses. Some of the nonlinear attributes of this behavior are the all-or-none response to stimulation and the implied threshold, the absolute and relative refractory periods following a response, and subliminal states of depolarization or hyperpolarization. These properties can be captured in a network representation whose behaviors are typically nonlinear (Arbib 1964, 1972; Lee 1984; McCulloch 1965; Skarda and Freeman 1987). Corresponding network node properties would be level of activity, threshold, ceiling and floor values, resting levels, relaxation times and hysteresis effects (Lee 1984). Connections between nodes may have direction, strength, and sign. The effect of internode behavior would be a function of activation level with respect to thresholds and the strength and sign of interconnections. Further, nodes can be subject to tuning. In general, any behavior of dynamic systems can be captured in network dynamics.

Interactions among the four subsystems

Predicting the behavior of a system comprised of nonlinear properties is difficult because many different qualitatively distinct types of behavior can result depending on the range of values assumed by parameters corresponding to each property (Thompson and Stewart 1986). Further, the functions describing how values of each parameter vary over time and the particular manner in which those functions relate play determinate roles. Discovering the functions and the relations only from a knowledge of isolated property characteristics is not possible. More information is required.

This problem occurs as well when the collected activity of the HAS system is considered. The subsystems have been distinguished as separate systems for purposes of description and analysis. However, none of these subsystems is viable independent of the others. There are strong interdependencies among the subsystems meaning that they combine in a highly nonlinear fashion. *The behavior of the whole system cannot be derived by adding together or superimposing the behavior of the components.* Most investigations of the HAS attempt to circumvent some of the complexity by taking into account only a subset of the four subsystems (e.g., Hasan et al. 1985; Hogan 1985; Hollerbach 1982; Lee 1984; Partridge 1979). However, the extent of the interactions among all four of the subsystems indicates that an account which leaves out any of the subsystems is likely to be incorrect as well as incomplete.

There are strong interactions between the link-segment system dynamics and the musculotendon system dynamics due at least to the following factors: First, mechanical energy can be returned to, as well as derived from the muscles (Alexander 1984; Bobbert et al. 1986a,b; Cavagna 1977; McMahon 1984); second, the power that can be generated by the muscles depends on their length which corresponds non-uniquely to the configuration of the articulators (Hill 1970; Hogan 1985; Inman and Ralston 1968; McMahon 1984; Partridge 1979); [2] third, the power that can be generated by the muscles depends on their velocity of shortening which corresponds non-uniquely to the velocities of the articulators (Hogan 1985; McMahon 1984; Partridge 1979; Wilkie 1950); forth, the power from the muscles depends on whether they are shortening or lengthening which depends non-uniquely on the direction of motion of the articulators (McMahon 1984; Partridge 1979); and fifth, the transfer of energy among the link-segments depends on the use of multi-joint muscles (Aleshinsky 1986; Bobbert et al. 1986a,b; Hogan 1985). In addition, the mechanical energy of the articulators can be transformed from one form to another allowing the energy to be conserved (Alexander 1977; Aleshinsky 1986; Cavagna et al. 1977; McMahon 1984). Mechanical energy can be exchanged between translatory and rotational forms as well as between kinetic and potential forms. The organization required for such transformations to take place depends on the behavior of the actuators (Aleshinsky 1986).

[2] The correspondence is non-unique due to the interaction between the passive elastic components and the variable inertial properties of the system (McMahon 1984; Partridge 1979; Stern 1974).

Actuator dynamics also interact with the dynamics of blood flow. The actuators require a blood supply to function and the blood flow in the muscles is controlled in part by muscular contraction as well as by the heart pressure (Asmussen 1981; Åstrand and Rodahl 1977; Laughlin and Armstrong 1985; Morton 1987). (See McMahon (1984) and Åstrand and Rodahl (1977) for what follows.) If no oxygen from the blood is available, then muscle metabolism is anaerobic. The total amount of energy that can be derived from sources in a muscle through anaerobic metabolism is sufficient only for a few minutes of work. Energy metabolism produces waste materials that must be removed from a muscle. In anaerobic metabolism, not only does the blood not bring in oxygen and metabolites, but it also does not remove catabolites, in particular, lactate. McMahon (1984) notes that the incursion of a large lactic oxygen debt is to be avoided. Physical discomfort is caused. The debt may take an hour of rest to repay and subsequent performance is decreased due to a continuing state of acidosis. Such a debt can be avoided by generating energy through aerobic metabolism.

Aerobic metabolism uses oxygen and metabolites carried in the blood to synthesize the ATP that fuels contraction. Energy available through aerobic processes are essential for the continued performance of work over a period longer than a few minutes. This requirement places constraints on the form and nature of muscular activity and the work performed. There exists a critical intensity of work beyond which the oxygen transporting system cannot supply enough oxygen to keep up with energy demands (Asmussen 1981; Laughlin and Armstrong 1985; Morton 1987). The force levels in concentric contractions of the muscles cannot exceed 10 to 20 percent of maximal isometric strength (Åstrand and Rodahl 1977). It is not only the energy demand that is at issue. Because contractions act to squeeze blood out of a muscle, the ability of the blood to enter and perfuse the muscle must be considered (Asmussen 1981; Laughlin and Armstrong 1985; Morton 1987). Contractions also contribute to blood transport in a positive way. Muscles in rhythmic contraction pump venous blood and thus, aid cardiac output. Åstrand and Rodahl (1977) report that fainting can occur in some conditions without this effect. Because of the interaction between muscular action and blood flow, the strength of contractions in relation to the duration of the contraction periods and the intervals between periods of contraction determine the length of time the work can be endured. In studying the patterns of behavior of the actuators in the

performance of a task, the power generating capabilities of muscles cannot be separated and understood independent from the patterns and processes of their metabolism.

Interactions causing occlusion of blood flow occur not only as a function of actuator behavior, but also as a function of the behavior of the articulators. Anyone who has ever painted a ceiling or had to change the lightbulb in an overhead fixture has experienced the effect of poor blood flow due to the orientation of the articulators in the gravitational field. Note that these effects are felt quickly after the limbs are placed in an upright position. Motions of the limbs producing centrifugal effects can prevent blood from flowing proximally back up the limb. Also, particular positions of the joints in the context of muscular contractions cause blood to cease flowing in major blood vessels (Rohter and Hyman 1962). This means that interaction occurs not only between hemodynamics and articulator dynamics or between hemodynamics and actuator dynamics independently, but also among all three taken together in a three-way interaction. Finally, all three of the systems described so far interact with the nervous system.

Due to interactions among the various nonlinear properties of muscles and between the musculotendon and link-segment systems, the response of muscle to neural impulses varies widely (Hasan et al. 1985; Partridge 1979). This response is also a function of interactions between the muscular and circulatory system. However, the nervous system connects via both afferent and efferent endings to the blood vessels (Bloch and Iberall 1982). These connections are not well understood. Arteries to the muscle terminate at an arteriole just before the blood enters the muscle bundle. Internal to the bundle is a capillary network which collects to a venule and back out into the veins. The afferent and efferent innervation of the arteriole is well understood, however, both afferent and efferent innervation to the capillaries is unknown. So, questions as to the locus and nature of vaso-control cannot be considered yet. Nevertheless, given the nature and extent of the interactions between the circulatory and musculotendon systems, the neural interactions with one cannot be independent of the neural interactions with the other.

Methodological dilemma and strategy

We confront a methodological dilemma. The complexity that results when all four subsystems of the HAS are considered simultaneously is

forbidding. The situation becomes even worse when the incidental dynamics associated with tasks is included as well. Furthermore, the HAS is highly nonlinear. The system cannot be understood by adding the behavior of its components studied in isolation. How might we simplify the dynamic properties of the HAS so that we can begin to describe its behavior without misrepresenting or distorting characteristics essential to its organizational and functional integrity?

A methodological strategy that may resolve the dilemma can be formulated by combining recent methodological developments in research on muscular behavior and biomechanics with those in research on motor control. The strategy is to describe, within specific functional contexts, the reduced dynamics of the HAS assembled from its diverse dynamic resources for the performance of a task. The challenge is to work backwards from a description of the reduced dynamics to an understanding of the manner in which subsystem dynamics couple and co-constrain one another to produce the observed dynamical system. Because information about both task specific dynamics and the individuated resource dynamics is required, the strategy unites the efforts of behavioral scientists and physiologists in an integrated and coherent effort using the common descriptive apparatus of dynamics.

A recognition of the need to investigate the collective behavior of dynamic components in functional contexts has emerged in recent studies on biomechanics and muscle physiology. In the sixties and early seventies, two separate programs of research on muscle physiology and biomechanics could be distinguished. In one program, the mechanical and energy producing properties of muscles and the configuration of their attachments were studied in isolation from the ordinary tasks in which they are employed (Amis et al. 1979; An et al. 1981; Hill 1970; Inman and Ralston 1968; McMahon 1984; Proske and Morgan 1987; Stern 1974; Wilkie 1950). The second program involved the measurement of energy consumption in the performance of tasks such as walking, running, swimming, bicycling, and climbing stairs (Alexander 1977; Åstrand and Rodahl 1977; Coates and Meade 1960; McMahon 1984). A problem arose because the energy consumption measured in functional contexts did not correspond to the energy consumption predicted from isolated measurements on muscle. The problem was resolved by studying how the measured muscular properties are used in the performance of specific tasks. The result was that the properties of some of the components of muscle were re-evaluated and that unantic-

ipated ways of combining those properties were discovered (Cavagna 1977). The potentiation of pre-stretched contractile fibers was described as well as the power amplification that can occur with specific organizations of musculotendonous structures. Functionally specific organizations of actuator and articulator properties are now being revealed in a variety of tasks including walking, running, jumping, and throwing (Bobbert et al. 1986a,b; 1987a,b; Cavagna et al. 1977; Cavagna and Kram 1985; Jöris et al 1985; McMahon 1984). These results are being obtained though the co-constraining combination of 'bottom-up' investigations on isolated component properties and 'top-down' studies of functionally constrained behavior and organization. However, these studies provide little insight as to how the HAS actively achieves a task specific organization. How are the dynamics of bone and muscle integrated with the dynamics of something like a bicycle so that functionally effective organization results? A consideration of the incidental dynamics introduced by tasks well illustrates the problems associated with the ability of the HAS to organize in the face of a wide variety of dynamic properties including those of both biological and nonbiological origin.

Incidental dynamics

One of the remarkable aspects of the HAS is the ability to mesh its inherent dynamics with the incidental dynamics introduced by a task to arrive at a functionally effective dynamical organization. A small percentage of tasks minimize the effect of incidental dynamics, for instance, waving, saluting, some forms of sign language, pointing, and reaching. [3] The latter two tasks have been investigated in an inordinate number of studies, undoubtedly because incidental dynamics are less involved (e.g., Abend et al. 1982; Atkeson and Hollerbach 1984; Hollerbach and Flash 1982; Morasso 1983). However, trying to simplify the problem of the organization of action by studying inherent dynamics in isolation from incidental dynamics is futile because the characteristics and capacities required to mesh with and assemble incidental dynamics are the same as required for the assembly of inherent dynamics alone. For instance, one of the effects of incidental

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[3] One of the few pervasive human performances that usually involves little or no incidental dynamics is speaking.

dynamics can be to change the inertial properties of the articulators as, for example, when a hammer is wielded. However, articulator dynamics alone involve variations in inertia, since the inertia experienced at proximal joints varies continually with changes in configuration at more distal joints (Aleshinsky 1986; Hogan 1985; Saltzman 1979). The principles underlying stable organization must be the same in either case.

Nevertheless, incidental dynamics merit independent consideration because they contribute significantly different forms and scalings to the dynamical configuration of the HAS. The form of the stiffness and damping of a bicycle pump and the manner in which the stiffness and damping scale over progress in pumping up a tire are not intrinsic to the dynamics of the HAS. Three classes of incidental dynamics can be distinguished according to the types of dynamic properties involved in a task. First, the simplest tasks introduce inertial properties, dissipative properties, and mechanical constraints (e.g., surfaces, rods, joints, and filaments) (Drillis 1963). Examples include pumping air into a bicycle tire, drawing with a pencil on paper, swinging open a door, or carrying a bucket of paint by the handle. The next class of incidental dynamics includes potentials that are able to absorb, store, and return energy to the HAS passively. The most prominent potential is the gravitational potential which is part of the inherent dynamics as well. Other potentials reside in springs and elastics. Tasks that fall into this class include bouncing a ball, jumping on a pogo stick, shooting archery, and juggling. Finally, the most complex incidental dynamic properties involve independent sources of energy. Broad types of incidental energy sources include moving bodies of water, wind, motorized machines, and animals or people. Controlling task-specific dynamics consists essentially of controlling energy transformations. This can become much more difficult with sources of energy other than the muscles as, for example, in operating a jack hammer (Berthoz and Metral 1970; Dagalakis et al. 1987; Harrison 1963). Tasks including incidental energy sources are surfing, flying a kite, riding a horse, shaking someone's hand, running a portable power saw, starting a moped, ballroom dancing, participating in a bucket brigade, or operating a tiller.

There is not much that can be accomplished by the HAS without the facile and efficient ability to perceive, and to organize using, the dynamic properties of the surroundings as well as of the action system

itself. In all cases, the performance of a task requires that the dynamics available to the HAS be organized into a system that behaves in a functionally specific and effective manner. How is the functionally specific dynamical organization exhibited by the HAS related to the inherent and incidental dynamics from which it emerges? This is the problem of task-specific devices.

Task-specific devices

A number of investigators are approaching actions as *softly assembled, smart, task-specific devices* (Bingham et al., in review; Fowler and Turvey 1978; Kelso et al. 1980; Kugler 1983; Kugler and Turvey 1987; Runeson 1977a; Saltzman and Kelso 1987; Solomon and Turvey, in press). According to this approach, the dynamic properties available to the HAS constitute resources that are employed to advantage in the assembly of a temporary, low dimensional, deterministic machine that is used to achieve the goals specific to a task. Thus, for instance, launching a projectile is achieved via a softly assembled throwing machine (Bingham et al., in review). This approach retains the task-specific orientation found to be necessary, in biomechanical studies, for discovering functional organization among dynamical components of the HAS. In addition, the approach adopts the methods and ideas of nonlinear qualitative dynamics.

This type of model has three advantages. First, given the nonlinear nature of the component properties of the HAS, nonlinear modeling is essential. Qualitative methods in dynamics have provided an impressive understanding of nonlinear systems (Abraham and Marsden 1978; Thompson and Stewart 1986). Second, recently developed methods in qualitative dynamics may provide a means by which to tackle the complexity of the HAS in a manner that does justice to all of the subsystem dynamics. For instance, qualitative methods may allow the dimensionality of the assembled resource dynamics to be derived from the measured task-specific trajectories (Kay 1986; this issue). Third, perceptual information is characterized in qualitative terms. Qualitative dynamics provides the means for tackling the problem of perceptual access to dynamics (Bingham 1987b).

The notion of a TSD is associated with a web of properties that capture many of the problems to be investigated in the science of human action and perception.

A task-specific device is 'task specific'

A TSD may be described and analyzed as a dynamic system. However, its dynamics are not identical to either the incidental or the inherent dynamics of the HAS or to any subsystems of the inherent dynamics. The cardinal constraints on the form of the dynamics for a TSD are functional, those associated with the task goals (Reed 1982). These are its raison d'être. Task requirements operate through the control structure of a TSD to constrain functionally its dynamical structure. Controllability requires a *reduction* in the complexity of the resource dynamics. The high dimensional dynamics available to the HAS must be reduced to a low dimensional dynamical structure that can be controlled via a small number of parameters (Fowler and Turvey 1978). Logically, the dynamics of TSD's can be characterized by a simple and direct relation between control parameters and behavior, that is, by a one-to-one correspondence between particular parameters and specific types of task-related output (Kay 1986; Saltzman and Kelso 1987). To emphasize, task specificity implies reduction in the dimensionality of the dynamics. The reduction must be specific to the functional requirements of a task.

A number of problems for research arise naturally in the context of TSD's in human action. How are the complex, high dimensional, nonlinear component dynamics of the HAS coupled and reduced to produce the controllable, low dimensional dynamics of TSD's? What are the sources of constraint used to reduce the effective dimensionality of the dynamics? Most important of all, how is a dynamical structure that is appropriate for a specific task determined? How is a relatively simple and direct mapping between the control structure of a TSD and the required types of task-specific behavior established?

A task-specific device is 'smart'

The strategies used in assembling TSD's are 'smart' in taking advantage of unique properties of the resource dynamics to achieve particular task goals. Stating that TSD's in human action are smart seems somewhat redundant. After all, the only resources available to the HAS are those of its own inherent dynamics together with those dynamics incidental to the task situation. However, smartness implies

that the HAS uses these resources to advantage, meaning that the HAS achieves, at least, *locally optimal* structuring of the dynamics with respect to a task (Cavagna 1977; Cavanagh and Kram 1985; Fowler and Turvey 1978; Hatze 1983; Kugler and Turvey 1987; Nelson 1983). For this to be possible, the HAS must have information about the relative optimality of alternative ways of structuring its own dynamics (Kugler 1983; Kugler et al. 1980, 1982; Kugler and Turvey 1987).

An example illustrates the necessity. Throwing a projectile to a maximum distance requires that the kinetic energy of the projectile at the moment of release be maximized. (See Bingham et al. (in review) and Jöris et al. (1985) for what follows). However, acceleration of a projectile to a high release velocity is difficult for the HAS given the power limitations of the contractile machinery together with the limited extents of motion imposed by the architecture of the link-segments. Two strategies which take advantage of particular characteristics of thrower anatomy and physiology are employed in skilled throwing to overcome these potential limitations. The first strategy is to develop kinetic energy in the more massive trunk and proximal limb segments and to pass this energy distally along successively less massful segments, eventually to the projectile. The second strategy is to store energy in the tendons and muscles involved in wrist flexion by pre-stretching them during joint reversal and recovering that energy at higher rates just prior to release of the projectile. The organization required to realize both of these strategies simultaneously is subtle and complex. Mere knowledge of results in throwing provides insufficient information to allow either the discovery or the assembly of such organization. Both strategies involve the development, transformation, and deployment of mechanical energy. Ultimately, the HAS must have access to information about these processes in the context of alternative ways of structuring the dynamics to be able to achieve such organization. Furthermore, in different tasks, optimality is determined relative to different task specific dimensions (Hatze 1983; Nelson 1983; Stein 1982). Maximizing power output may be required in one instance while accuracy in positioning is required in another. Thus, the HAS must have information about the available dynamics from the perspective of the different properties to be optimized and it must be able to use such information to discover appropriate dynamical organization, to assemble that organization, and finally, to control and maintain that organization.

To emphasize, optimization is not of relative values of dynamic properties that have been selected and set into a relation in advance. Rather, the optimization involves the selection of alternative resources and a determination of the relation into which they are to be placed. This is illustrated by the different action modes exhibited when projectiles of different mass are thrown. Relatively light projectiles massing from zero to 500 grams are thrown usually using an overhand throw as described above. This mode of throwing uses the long extrinsic tendons that span the wrist and finger joints. When the mass of a projectile enters the neighborhood of 500 grams, a lob style of overhand throwing is used (Bingham et al., in review). The arm is kept more or less straight while being rotated about the shoulder. The wrist tendons are no longer employed, since the wrist and elbow are kept fairly rigid. For projectiles massing more than a kilogram, a shot put style of throw is employed. The organization of this mode of throwing is entirely different from the overhand mode (Dyson 1962/1970; Hay 1978). A pushing rather than a flailing arm action is exhibited. Simultaneous activation of contractile elements along the limb occurs in preference to the sequential organization of the overhand throw. Thus, the manner in which the dynamic resources are used to develop kinetic energy and transfer it to the projectile is changed. The change is instigated by changing the value of a dynamic parameter, namely, the mass of the projectile. In response, markedly different resources are used and they are placed in a considerably different dynamical organization.

The problem for research posed by the smartness of TSD's is two fold. First, an understanding of the dynamic resources available to the HAS is necessary so that a description of alternative dynamical structures and their optimality according to various criteria can be developed. Note that this description must include the incidental dynamics typically involved in tasks. The second aspect provides an even more daunting theoretical challenge. The means of characterizing the resource dynamics must adjust naturally to a variety of perspectives and to the different dynamic resources that might be employed depending on the specific nature of different tasks. The extant formal methods for optimization are not suited for this type of problem (Gelfand and Fomin 1963; Weinstock 1974). How to develop a description of dynamics which exhibits such perspectival flexibility is not obvious. Once we have a functionally coherent understanding of the dynamic re-

sources of the HAS, we must discover how the HAS is able to hone in on the large variety of different dynamic characteristics relevant to the diversity of tasks performed (Bingham, in review; Kugler and Turvey 1987; Solomon and Turvey, submitted).

A task-specific device is 'deterministic'

'Machine' is used in the usual sense. Given the state at some fixed initial time and the subsequent control and perturbing inputs to the system, the future behavior of the device is specified uniquely (Ashby 1960; Padulo and Arbib 1974). This means that behaviors conforming to task requirements may be produced via the *intermittent* manipulation of control parameters. Some tasks can be performed only by virtue of this property of TSD's. For instance, the successful operation of the two strategies used in overhand throwing does not leave much room for interference by explicit feedback control (Bingham et al., in review). The first strategy entails an extremely rapid, staggered sequence of accelerations and decelerations among successive body and limb segments effecting a flow of mechanical energy to a projectile (Jöris et al. 1985). The mechanics of prestretching used in the second strategy requires that the energy imparted to passive elastic structures in a muscle be recovered immediately (Jöris et al. 1985; Bobbert et al. 1987a,b; Proske and Morgan 1987). The majority of the power developed in throwing by these means is in the last 50 milliseconds before release (Atwater 1979; Jöris et al. 1985). The deterministic nature of these processes guarantees that they run off without explicit monitoring and control.

However, controlled actions do not always entail such rapidity. More generally, the economy of control provided by this style of organization means that the HAS can devote resources to the improvement of efficiency and precision in task performance as well as to the organization and control of concurrently performed actions or those whose performance is anticipated in the immediate future. Most importantly, the deterministic nature of TSD's means that the characteristics of the HAS can be related quite naturally to the wide world of deterministic events with which the system must couple in the performance of mundane chores. How could Tarzan succeed in swinging on vines from tree to tree unless the dynamics of his action system were naturally attuned to the dynamics of swinging?

The problems for research provoked by the deterministic nature of TSD's are as follows: What types of deterministic process is the HAS able to duplicate? What properties of the HAS limit its abilities in this respect? Is the unmodulated running of deterministic processes in human action characterized by temporal windowing? If so, what determines the size of these windows? How do they vary in size in specific instances?

A task-specific device is 'softly assembled'

The functional characteristics of a TSD are associated directly with dynamic properties. These, in turn, may be associated more or less uniquely with particular anatomical entities. Overhand throwing uses the long, and therefore compliant tendons running from the forearm muscles through the wrist to the fingers (Jöris et al. 1985). Similar structures at the ankle are used in kicking or in jumping (Bobbert et al. 1986a,b; Bober et al. 1987). Grasping, which takes advantage of skin surface properties, can often be as well executed using either the fingers or the toes (Iberall et al. 1986). An impacting blow can often be as well executed using either a fist or a foot or the head (Feld et al. 1979).

As has been noted frequently, writing may be performed successfully using either a hand, a foot, or the mouth (e.g., Greene 1972; Saltzman 1979; Saltzman and Kelso 1987). This latter example has been used to illustrate the necessarily 'abstract' nature of control structures. From this, one might retain an impression that abstractness implies strictly neural support. To the contrary, the example only indicates that the dynamic properties used in control are common to elements in the hand, foot, and mouth.

The *soft* nature of TSD's means that they are temporary, that a single device can be instantiated over different anatomical structures, or alternatively, that the same anatomical structures can be used in different devices, with the additional implication that different dynamic properties of the same anatomical structure may be relevant in different instances (Kugler 1983; Kugler et al. 1980, 1982; Kugler and Turvey 1987). Softness serves to emphasize the fact that TSD's are assembled out of the dynamic properties of anatomical structures as well as of the dynamic properties of objects associated with a task. The *assembly* of TSD's, on the other hand, requires that various and sundry dynamical properties be set into a relation. Before the high dimensional

resource dynamics can be reduced to the low dimensional dynamics of a TSD, they must be placed into a relational structure which subsequently embeds the reduced dynamics. Reduction can be only of a dynamical system, not of a mere collection of dynamic properties.

The creation of a TSD by the HAS is depicted for purposes of description and analysis as a two-part process. [4] The first process is the assembly, from a collection of dynamic resources, of a high dimensional, functionally specific dynamical system. The second process is the reduction of the high dimensional dynamical system to a low dimensional system controllable by few parameters. Reduction is represented by the projection of the dynamics onto a space of lower dimension without the loss of relevant information (Marmo et al. 1985). [5]

The relation of the reduced task-specific dynamics to the dynamical resources from which it is assembled is different from the relation of lumped parameter dynamics to unlumped dynamics. The latter is a variety of averaging requiring linearity. The former is accomplished classically via constants of motion (Marmo et al. 1985; Whittaker 1959). The effect of a constant of motion is to restrict trajectories to a region of phase space that can be projected to a space of lower dimension. For instance, for a single degree of freedom conservative system, if the sum of the squares of position and velocity is a constant, then the trajectories lie on a circle in phase space. Progress along closed orbit trajectories on a (2-D) surface can be described using two dimensions, the radius from the origin of phase space to the trajectory curve and the angle formed by the radius. However, for a circular trajectory, the radius is constant and no information is lost by using only one dimension, the angle. In this way, a reduction in the dimen-

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[4] In the acquisition of a new skill, the HAS does appear to go through stages in which a crude organization of activity subsequently is refined and tuned (Newell and Walter 1981; Newell et al. 1985; Whiting et al. 1987). Similar stages can appear as well over brief intervals in the initiation of a skilled activity (Hoy and Zernicke 1986). Although there may be some vague correspondence between these stages and the properties of assembly and reduction, I do not wish to imply that assembly and reduction are necessarily separate processes performed by the HAS. Assembly and reduction cannot be independent since the object of functionally effective assembly is the reduced system. Rather, these are means merely of describing and analyzing aspects of the problem of the organization of behavior. Reduction refers to a way of simplifying differential equations so that a solution may be found (see e.g., Marmo et al. 1985). The solving of equations has nothing to do with how the HAS organizes behavior.

[5] Ideally, no information should be lost. However, the functional context of this problem may allow this requirement to be relaxed so that only task relevant information need be preserved.

sionality of the dynamics is accomplished. Modern techniques for reduction generalize on the classical methods (Marmo et al 1985).

Dissipative dynamics are characterized often by sets of stable trajectories that attract all nearby transient trajectories (Thompson and Stewart 1986). One such attractor is a closed orbit called a limit cycle. If the transients are ignored and only the stable limit cycle orbits are described, then this dissipative system can be treated for some purposes exactly like the conservative system described above. This strategy for the analysis of TSD's as been advocated by Kay (1986, this issue) who describes the balance of energy flows within a cycle as a means by which the dimensionality of dissipative resource dynamics are reduced. A Hamiltonian (conservative) approach to the modeling of non-Hamiltonian systems also has been suggested outside the domain of human movement research (Kiehn 1987). However, a Hamiltonian approach must be restricted, perhaps to explicit control structures, because the stable behavior exhibited by the HAS in response to perturbation is a hallmark of non-Hamiltonian systems (Kay 1986). Furthermore, the stable orbits are not closed strictly. They vascillate within a narrow orbital region (Kay 1986). [6]

One of the goals of the TSD approach is to work back from the reduced task-specific dynamics to a characterization of the resource dynamics of the HAS. This inverse problem includes two basic questions. First, what were the dynamic properties selected from the entire body of resource dynamics in assembly? Second, what was the relational structure of the dynamics preceding reduction? This latter question involves the dimensionality of the pre-reduction dynamics which embed the low dimensional reduced system. Kay (1986) performed analyses to derive the dimensionality of the reduced dynamics and perhaps, also that of the embedding system. The resource dynamics are undeniably nonconservative. The quasi-periodicity of the measured trajectories are a reflection of the nonconservative nature of the underlying dynamics. The lack of strict periodicity also will allow the derivation of the embedding dimension if such a derivation is possible at all.

The problems for research implicated by soft assembly concern the nature of the assembly process. How is an initial functionally con-

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[6] To the extent that this variability in orbiting trajectories is averaged out to derive a Hamiltonian description, the averaging characteristic of lumped models is shared.

strained organization of the dynamics of the HAS established? That is, how are the dynamics of the anatomical structures, together with the incidental dynamics, identified and harnessed in the task-specific relational structure described as a dynamical system? Since, by hypothesis, the reduced task-specific dynamics can be measured and described in experiments, the inverse problem of working back to the assembled dynamics will require both an understanding of how reduction can be accomplished and techniques for measuring the properties of the embedding space.

A task-specific device is 'controlled'

In conforming to functional constraints, a TSD must be flexibly controllable. Although tasks may fall into qualitatively distinct types, they inevitably are encountered in a great variety of metric variations. For instance, consider typing on an old, cranky manual typewriter versus a new, sleek electric. Throwing to hit a target typically involves metric variations in the distance to a target. The form of the behavior and thus, the structure of the system does not change in these instances. Presumably, such variations in required output are met by variations in parameter values. In the interests of control, the response to changes in parameters in the task-specific dynamics must be predictable. Predictability means the systems must be stable (Ashby 1960; Padulo and Arbib 1974). In addition to structural stability in the face of parameter change, stability can refer also to system trajectories in state space (Poincaré stability) or in state-time space (Liapunov stability) in response to perturbations or to variations in initial conditions (Rosenberg 1977). It is very difficult to control a system in which arbitrarily large changes in response result from arbitrarily small changes in the parameters, or in the initial conditions (perhaps as a result of perturbation) (Rosenberg 1977). Furthermore, the frequency of control adjustments will be related, in part, to the relative stability of the system. For example, explicit control may be organized only to take advantage of short-term first order stability.

A potential barrier to stable organization in the performance of tasks arises from the limited capability of the inherent dynamics of the HAS to adjust to the characteristics of incidental dynamics. For instance, the HAS response to low frequency (3–5 Hz) excitation disturbance exhibits considerable instability (Dagalakis et al. 1987).

A large number of problems for research come to mind readily in the context of controllability. Which parameters are adjustable in a particular device? Which parameters are adjusted to achieve specific ends? How does the system identify which parameter to adjust? How frequently are parameters adjusted? Are adjustments discontinuous and sudden, or continuous and gradual? More generally, what is the period of adjustment? Most importantly, how is the stability of TSD's contrived and assured?

A task-specific device is 'scaled'

How does the HAS determine parameter scale values? Both the relative and the absolute parameter values must be scaled to the exigencies of a task. Accurate positioning tasks can be performed under a microscope, on a chessboard, or when placing furniture in a room. Scale requirements are met in such situations by varying the inertial scale (as well as the power output scale) of the anatomy employed in executing the task. Adjustments under a microscope are made using the fingers. Chess pieces are moved typically by using the hand and arm while the arms, legs, and the trunk of the body may be used to move furniture. The complexity of the dynamic resources used increases with the increasing inertial scale in these examples. The increase in the dimensionality of the space embedding the dynamics of the TSD in each of these examples raises the possibility that these may not be instantiations of a single TSD. For instance, reduction may not be possible to the same extent in each case. If so, then scale may be, in part, a type-specific property of TSD's with the implication that a substantial error was made by referring to these tasks in common as positioning tasks. The error is in describing task specifications in kinematic terms while ignoring dynamic characteristics essential to the nature of any task.

These problems for research are among the most intriguing. When a TSD is assembled, how does the HAS scale the relative and absolute values of the parameters to conform to the task requirements? How is the scale of task requirements recognized in the first place? If scale and type are confounded, then so are the problems of scale and assembly. The relations established among dynamic components available to the HAS would depend on the scale values associated with those components. How does the system determine when the absolute value of a

parameter needs to be adjusted? How does it discover how much to adjust a parameter? How does it recognize that the parameter has been adjusted and whether the adjustment is correct or sufficient? Qualitatively metered changes and adjustments rather than a purely quantitative metric is required given the limitations of the perceptual systems (Bingham 1987b; Kugler 1983; Kugler and Turvey 1987).

A task-specific device is 'assembled over the properties of both the organism and the environment'

The resource dynamics from which TSD's are assembled include both the inherent dynamics of the HAS as well as the incidental dynamics of a task. Aside from the gating of energy from inherent versus incidental sources, absolutely no a priori distinction can be made between the relative contributions of these dynamics to the behavior eventually exhibited by the HAS when organized as a TSD. The prerequisite for information about the available resource dynamics applies equally well to both the inherent and the incidental dynamics and the means by which the HAS becomes informed must be the same in both instances.

The perceptual bottleneck in the organization of human behavior is introduced by the nature of the *human perceptual system (HPS)* which is able to contact the dynamic properties of actions and events only through kinematics (Bingham 1985; Bingham 1987a,b; Runeson 1977b; Runeson and Frykholm 1983). The HPS is able to detect only spatial–temporal pattern. Spatial–temporal pattern constitutes information when a unique correspondence exists between a pattern and a property or circumstance. *The bottleneck is created by the necessity of there being a unique mapping between kinematic pattern and dynamics.* To the extent that the relation between kinematic pattern and dynamics is not unique, there is no information. (See Bingham (1987a,b) for additional discussion.) *The fundamental problem of human perception is to discover when and how unique mappings obtain.*

The haptic subsystem does not provide special access to the inherent dynamics. Perception via the haptic system involves the kinematic specification of dynamics no less than do the visual and auditory systems (Kugler and Turvey 1987; Solomon and Turvey, in press). The dynamic states of the muscles are monitored through the kinematic

states of so-called mechano-receptors which are stretched or compressed by the forces impinging on them. For instance, pacinian corpuscles embedded in muscle respond to a change in their diameter while Ruffini type end organs in muscle or Golgi tendon organs respond to changes in length (Bloch and Iberall 1982; Lee 1984).

Both the inherent and the incidental dynamics are monitored perceptually through the haptic subsystem. Individual mechano-receptors can not distinguish between stretching by muscular contraction as opposed to by the other means. Various combinations of receptor systems have been hypothesized to make such distinctions. For instance, Hasan et al. (1985) have suggested that muscle spindles together with the fusimotor system can detect departures from 'expected kinematics'. However, these proposals are controversial. How are the 'expected kinematics' to be delineated? What types of change and what degree of change is required in a specific instance before a change in trajectory qualifies as unexpected? No criteria have been offered nor has a coherent basis for discussion of the question been provided. Presumably, the HAS should be able to detect perturbations which threaten the stability of its current dynamics. Destabilizing types of perturbation will vary depending on the specific nature of the current dynamical regime.

To assemble a dynamical regime, the HAS must be able to distinguish alternative dynamic properties that might be included within the dynamical organization. If additional mass is attached to a link-segment, need that mass be distinguished from the mass of the segment when it is only the combined inertial properties that contribute to the form of the resulting activity? If the added mass has *independent* dynamical effect, then we should expect that its inertial character might be assessed independently. Otherwise, there can be no information. This is not to imply that there would be no awareness of the added mass. Obviously, energy demands would increase. Rather, organization would proceed on the basis of reconfigured inertial properties, for instance, a shift in the center of mass of the segment. This approach to the haptic system is consistent with an approach to the vestibular system and the problem of orientation presented by Stoffregen and Riccio (in press). They suggest that orientation is based on information in a person's patterns of motion. The information is about the entire force environment relevant to the maintenance of posture, including the gravitoinertial force as well as forces associated with the surfaces of support and compensatory actions.

The problems for research engendered by the need for perceptual information include the following: Which kinematic properties of actions and events does the HPS detect? In what circumstances are unique mappings between kinematics patterns and dynamic circumstances guaranteed? What are the constraints that guarantee uniqueness?

A task-specific device is 'potentially modifiable to new purpose'

If the goals of different tasks share dynamic properties, then a device organized by the HAS for the performance of one task might be modified for the performance of the other. For instance, overhand throwing shares with the imparting of a blow, as in hammering or certain karate punches, the requirement of maximizing kinetic energy and reaching peak kinetic energy at the end of a stroke (Drillis 1963; Feld et al. 1979; Jöris et al. 1985). Thus, a similar organization is exhibited in the execution of these different tasks. Furthermore, the dynamical system corresponding to a TSD may include more parameters than are actually modified in the controlled performance of a task. Controlled manipulation of these unused parameters may reveal capabilities of such a device that are relevant to new and different tasks.

A casual observation on coaching attests to relevance of TSD's to the problems of skill acquisition. I have noticed often that a coach in working to mold a sport related action will refer to some other commonly performed task. The individual who is being coached will be exhorted to perform some action, for instance an undercutting stroke with a racket or paddle, as if he or she were performing a seemingly unrelated task, e.g. stroking the hair on a baby. It is as if the coach wished to invoke a device, or at least certain properties thereof, for the skilled performance of a task.

Many of the research problems discussed within the skill acquisition domain can be formulated naturally as research problems associated with TSD's. Demonstrations are said to model a skill in a display observed by skill learners (Newell and Walter 1981; Newell et al. 1985; Whiting et al. 1987). The value of such a display would depend on the ability of the observer to recognize the dynamic structure corresponding to the skill specific device. The suggestion that tasks are fundamentally dynamic entities applies as well to skills. Although the objective in

some skilled behaviors may be described convincingly in kinematic terms, the skill corresponds nevertheless to a dynamical organization. Therefore, all skill objectives must be specified ultimately in dynamic terms. Problems for research in skill acquisition would be rephrased accordingly. What information about the dynamics of a skill can be provided via knowledge of results, via kinematic and/or kinetic feedback, or via kinematic displays? Just how much information about dynamic structure is required in particular cases? About what aspects of the dynamics does a skill learner require information?

The ubiquity of perception

Every one of these characteristic properties of a TSD involves perception. *Task specificity* requires perceptual contact with the nature of a task and task requirements. *Smartness* requires information about the relative optimality of alternative ways of structuring the available dynamics. The *deterministic* nature of TSD's makes relations to deterministic events possible. However, perceptional contact with an event is required to establish such a relation. *Soft assembly* requires information about the dynamic properties of anatomical structures and objects associated with a task. Information about the relational structures into which dynamic properties are placed is required also. Perception is relevant when we consider how the loss of functionally relevant information is prevented in *reduction. Control* requires information about stability and about conditions requiring parameter change. The *scaled* nature of TSD's means that information about the scaling of both the inherent and the incidental dynamics in a task must be available. To the extent that scale is a type-specific property of events by virtue of its being metered qualitatively, information about types of events is required. Since TSD's are *organized over properties of both the organism and the environment*, commensurable information about both sets of properties is required. Finally, information about alternative possible controls and behaviors is a prerequisite for TSD's to be *modifiable to new purpose*. Perceptual contact with dynamics is established through two mappings, a mapping between kinematics and dynamics and a mapping between the flow structure of perceptual arrays and kinematics. These mappings introduce the problem of the perceptual bottleneck.

The perceptual bottleneck

Two related characteristics of perception lead to the two problems comprising the perceptual bottleneck. The *identification problem* arises because information about dynamics must be mapped through kinematics to spatial–temporal patterns that can be detected by the HPS. The *scaling problem* arises because the ratio scaled properties of events must be mapped through nonratio-scaled informational structure.

The identification problem

Perceptual information is instantiated in spatial–temporal patterns that can be described only using the dimensions of length and time, but not mass. The patterns of flow in the optic, haptic, and auditory arrays can be described as geometric patterns that transform over time. Since dynamic descriptions include the mass dimension while kinematic descriptions only use the length and time dimensions, the informative structure of actions and events must be described kinematically. Information about dynamics must be preserved in a mapping from dynamics to kinematics (Bingham 1985, 1987a,b; Runeson 1977b; Runeson and Frykholm 1983). This circumstance leads to the identification problem in perception. How are the dynamic characteristics of events identified by virtue of kinematic information? [7]

Information in the optic, acoustic, and haptic arrays resides in structure that must be described in qualitative terms. The qualitative approach to nonlinear dynamics may provide the relevant tools for discovering where the solution to the identification problem lies. Analytically, the dynamics of a system are described by a differential equation. The kinematics correspond to a solution equation which describes a function satisfying the differential equation. Unfortunately, the analytical equations do not provide much insight to the qualitative behavior of a system or to the qualitative relation between kinematics and dynamics (Hirsch and Smale 1974). A qualitative approach, on the other hand, reveals that dynamics and kinematics locally are dual descriptions of a single qualitatively distinguished structure (Marmo et al. 1985). Geometrically, kinematics corresponds to trajectory curves in

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[7] This is a version of the problem. More generally, the identification problem is how are types of actions and events recognized by virtue of kinematic information?

phase (or state) space. Dynamics corresponds to a vector field on phase space in which each vector is tangent to a trajectory curve and of a magnitude representing the phase velocity. Qualitatively, the layout of trajectories and of the vector field is the same. The shapes in the kinematic and the dynamic portraits are identical.

Strictly, the difference between kinematics and dynamics is in scope. How they are distinguished can vary. If we confine attention to a single trajectory and notice that the differential equation describes an instantaneous, 'differential' relationship while the solution equation contains a function specifying the form of the entire trajectory, then dynamics would provide a local description while the kinematics provides a more global description (Padulo and Arbib 1974). [8] However, when the entire phase space is considered, the differential equation determines all the acceptable solutions which are dense in a region of phase space while a solution equation corresponds to but a single curve in that region (Marmo et al. 1985). Viewed in this way, the dynamics would correspond to a global description while the kinematics are local. Either way, locally, the equations provide dual descriptions of the form of a trajectory. Globally, kinematic trajectories and dynamic vector fields are merely alternative representations of all the behaviors that could possibly be exhibited by a system. [9]

Dynamical systems can be used to describe actions and events which manifest in particular occurrences a finite and strongly limited number of trajectories. The trajectories exhibited by an event on a particular occasion constitute a small subset of the trajectories that can be generated by a given dynamicel system used to represent the event. The HPS detects the trajectories or worse, mere pieces of the trajectories that actually occur in an event. Thus, the information available to the HPS must be contained in the locally sampled structure of the densely filled space of trajectories. The problem is to map from the local structure of a finite and small number of trajectories to the global structure of the dynamics representing all possible trajectories that can be exhibited by a system (Marmo et al. 1985). The locally sampled structure must be unique and specific to the global structure of the

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[8] Padulo and Arbib (1974) also note that if derivatives of all orders (to infinity) are available at an instant, then for many functions the entire trajectory is determined.

[9] This is assuming, at least, a C^1 smooth system so that the vector field is defined at each point along all the trajectories. Without this condition, the relation must be revised to handle corners and other discontinuities in a piecewise manner.

system if the system is to be identified. The mapping problem corresponds to the question what structure qualitatively determines the identity of an event represented as a dynamical system? The challenge is to discover the properties that distinguish types of events and to understand how events might be taxonomized. This is essential to a solution of the problems of the perceptual bottleneck.

The perceptual bottleneck is created by the necessity that the mapping between local kinematic structure and global dynamics be unique, that is, that there be a one-to-one correspondence between that which is perceived and the informative structure that is perceptually detected. Uniqueness can always be had if the mapping is not to tokens, but to classes or kinds of system that can be systematically described. Uniqueness can be had by fiat by defining an equivalence relation among differential equations in terms of the mapping between a kinematic function and all of the differential equations which it would satisfy. Such an approach would seem to trivialize the notions of uniqueness, specificity, and information. However, if independent criteria can be established for delineating the equivalence classes, then the significance of the mapping might be retained. The need for independent criteria means that a solution to the problems of the perceptual isthmus must be sought outside the domain of dynamics. An alternative source of constraint in determining event categories is the functional context, that is, the use to which information is to be put. This observation lands us back neatly in the problem of TSD's. A logical strategy is to approach the problems of the perceptual bottleneck as constrained by the demand for information originating in the problem of TSD's.

The scaling problem

Perceptual information is not ratio scaled. The patterns in perceptual arrays have no absolute metrics associated with them. However, the dimensions associated with the dynamics and kinematics of actions and events are ratio scaled. For instance, velocity of movement in an event might be measured in meters per second. No such metric can be applied sensibly to the transformation of pattern in optic flow. For this reason, information about event dynamics must be mapped through ratio-scaled kinematic descriptions into the transforming distributed structure of the perceptual arrays. The circumstance leads to the scaling problem in perception. How is the scale associated with the dynamic

and kinematic dimensions of actions and events perceptually specified?

A solution commonly proposed for the scaling problem is to scale informational structure using anatomy. For instance, optical structure may be scaled in this approach by the magnitudes associated with the dimensions of the retina. (See Turvey (1977) for a discussion of the contrast between the anatomical and the ordinal arrays in visual perception.) However, this solution merely transforms the scaling problem for perceptual information into a problem concerning the relation between the scale values associated with the dimensions of human anatomy and the scale values associated with the dimensions of an event. How is this scaling relation to be established? A recently proposed solution to this problem uses information for eyeheight to scale environmental lengths to the lengths of the observer (Mark 1987; Warren 1983; Warren and Whang 1987). The obvious limitation of this approach is that eyeheight need not correspond uniquely to observer height. Eyeheight varies with posture, for instance, standing, sitting, slouching, lying, crouching or kneeling posture. In addition, eyeheight varies with the height of the surface of support, for instance, standing on the ground, standing on steps, standing on a hill, standing in a body of water or standing on a block (Mark 1987). This or any similar proposed solution is bound to fail since the only means by which scaling might be achieved is being ignored, that is, via the dynamics constraining actions and events. [10]

The solution to the scaling problem lies in the nature of dynamics. Dynamics is composed of two ingredients. These are uniquity conditions and scaling relations. All too often, one or the other of these two ingredients is forgotten or ignored despite the fact that a complete description of the dynamics of an event requires both (Szücs 1980). The attempt to solve the scaling problem through anatomical scaling ignores the scaling relations of dynamics in favor of a set of uniquity conditions that are inherent to the human perceptual and action systems. Whether the scaling be from perceptual information to dynamic properties or from HAS properties to event properties, the scaling problem

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[10] An alternative approach is to study how the kinematics of observer motion maps into the flow of the optic array and provides information for scale magnitudes associated with dynamic properties of the observer, for instance, height of the center of mass of the body above the ground plane. This kind of approach would be consistent with the theory of orientation presented in Stoffregen and Riccio (in press). Following on the facinating results described in Mark (1987), L.S. Mark is pursuing just such an approach to the perception of heights.

cannot be solved without the scaling relations of dynamics. The scaling relations are natural laws which describe how the properties measured in an event scale to one another. [11] The equation describing the dynamics of an event consists of a set of lawful scaling relations. The particular significance of these scaling relations for the scaling problem of human perception and action is that the lawful relations apply to the characteristics of human actions and environmental events *in common*. Relations between the observer and the environment can be established by means of these constraints. For instance, gravity acts upon the fall of a juggled ball in the same way that it acts upon the trajectory of the hand that moves to meet the ball. This constraint can be used to scale the trajectories of the ball and of the hand to one another (Beek 1988). However, this scaling also depends on the unique value associated with the gravitational acceleration.

Uniquity conditions are required to complete the dynamical description of an event (Szücs 1980). Uniquity conditions are the particular values or ranges of values that can be assumed by the parameters and variables in the differential equation describing the dynamics. These values must be specified before a relation can be established between dynamics and kinematics. Furthermore, these values are required before the equation can be used to describe a particular event. Although this requirement holds for all systems, its importance is apparent especially for nonlinear systems. This point was discussed at length in relation to the subsystems of the HAS.

Nonlinear systems exhibit radically different forms of behavior depending both on the particular scaling relations included in an equation and on the particular values simultaneously assumed by elements in the equation. To capture the particular forms of behavior exhibited by an event, both aspects of the description must be specified. Inversely, if particular forms of behavior can be associated uniquely with the scaled values in an identifiable event, then we have a potential solution to the scaling problem. If not, then I am at a total loss as to

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[11] Natural laws often contain scaling constants. This is because the units (for instance, meters, seconds, and kilograms) associated with the dimensions (respectively, length, time, and mass) of measured properties (for instance, acceleration, mass, or force) have been established in a conventional manner that is independent of and arbitrary with respect to the natural, lawful scaling relations. A scaling constant corrects the mismatch in units. Systems of units can be derived so that the lawful scaling relations between selected properties are correct without scaling constants (Baker et al. 1973).

where I might expect to find a solution. Information about scale has to be contained in qualitative characteristics of flow in the perceptual arrays.

A concluding remark: Uniquity conditions as a source of optimism

The numbers evoked in descriptions of the 'degrees of freedom problem' usually are associated with somewhat pessimistic assessments of finding a resolution to the problem. For instance, Kelso (1986) refers to there being 100 joints and 792 muscles in the human body, and over 40,000 muscles and tendons in an elephant's truck. Reference to the nerves can take us into Saganistic billions. In fact, arbitrarily large numbers can be produced by such unconstrained counting of degrees of freedom. In a sense, the problem is much worse than implied by the mere quoting of large numbers. Enumerating the degrees of freedom to be reduced is itself a problem. A deep and difficult research problem is to describe the degrees of freedom associated with the dynamical resources selected for assembly into a TSD. Nevertheless, there is reason to expect that we might be able to surmount the difficulty.

The source of optimism is the finite and particular nature of the dynamical resources of the HAS. *The possible means by which a specific task might be performed by the HAS are limited.* While recognizing the relatively abstract aspects of the problems in human action, we should not lose sight of the fact that the 'system' consists of hands and feet and head and heart. These features of the HAS consist of a wealth of unique details that serve to constrain the particular forms of activity observed. The optimism in viewing human activity as a parade of TSD's is in the tension between the softness and the smartness of a TSD.

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