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Clues from the Organization of Motor Systems

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Abstract. Understanding the organizational style of motor systems is largely a matter of understanding the means by which very many degrees of freedom are systematically regulated to yield behaviors, appropriate to the circumstances, of very few degrees of freedom. The tendency for movements to be fashioned in a way in which most variables are held constant provides a motoric restriction on the formation aspects of spoken and signed language. There are reasons for supposing that a formal theory of language and a formal theory of the coordination and control of movement would be qualitatively indistinguishable. The form of both movement and language may rest with common physical principles. The machine conception and dynamics are contrasted as perspectives on the form manifested by biological systems and expression is given to the need for examining contemporary physical theory as a source for understanding the formation aspects of movement and language.

INTRODUCTION

Whether spoken or signed, language is activity and might, therefore, reflect the organizational style that characterizes the control and coordination of acts. The question to be pursued here is the degree to which the form of language is constrained by the form of movement. I begin with two prominent conceptions that oppose relating linguistic and motoric form - the cognate conceptions of language as autonomous and unique.

THE ASSUMED AUTONOMY AND UNIQUENESS OF LANGUAGE

M.T. Turvey

Beyond the methodology of linguistics, the autonomy of language is expressed in another way with potentially larger implications. The symbol/matter or linguistic/dynamic dichotomy in physical theory expresses the contrast between rate-independent rules and rate-dependent laws. Arguably, complex biological systems execute in two modes, the linguistic (informational) and the dynamic, that are complementary and irreducible, one to the other (20,32).

Related to the conception of language as autonomous is a strong historical tendency to regard language as a unique and greater achievement than movement. Movement is probably encompassed by physical and biological law, but language is a different kind of entity, a special cognitive process involving special principles. Language is peculiar to humans (although some other species may have a capability that is crudely analogous) whereas movement, as a systematic adjustment to significant particulars of an environment, is general to animals. The features of language that collectively define its unique status were delimited in the Port-Royal theory and related by Chomsky (7): In normal use language is innovative, potentially infinite in scope, free from stimulus control, coherent, and appropriate to the situation. I doubt, however, that these features are sufficient to distinguish formally language as a goal-directed activity from goal-directed activity in general (25). A more reasonable claim might be that language is a unique facility for communicating new information; a less reasonable claim, however, is that language is unique in terms of the principles by which it does so.

Language as a process is often defined as a mapping between meanings and sounds. A belief that to greater or lesser degree has guided thinking about linguistic performance for more than two decades is that the processes by which meanings become sounds and vice versa are captured in grammatical description. A strong equivalence is sometimes assumed between the processes of producing and comprehending utterances and the structural descriptions that a grammar (adequate to the demands of linguistic

PALINDROMES OF MULTIVARIABLE COORDINATION AND CONTROL

As a process, movement is similarly interpretable as a mapping between intentions and biokinematic configurations. A mapping perspective is implied in almost all discussions of movement have a biasing effect on movement towards the pre-dictates of neuropsychiatry and mathematical control theory. Commonly, discussion of movement production (see (26)) has been restricted to a single "central" representation identified as either (a) a motor program conceived as containing all the spatial and temporal details of the movement or (b) a reference system simpler than its counterpart in language. This impression is probably false. The formal structural problems of commensurate and logical depth. The better fitting together form concepts largely units and not because they are, in principle, qualitatively different gether only because the former have been studied more seriously and not because they are, in principle, qualitatively different or any less tractable.

Competence) would assign to those utterances (18). The mapping rules that linguists have identified vary in type and logical depth (number of formal steps) and are concentrated in process terms, as a succession of computations over representations of progressively greater or lesser abstraction.

unite bones, cartilages, or bones and cartilages. Joints distinguish in their design and in the number of axes on which they can change. For example, hinge joints vary on one axis (e.g., the elbow), ovoid joints vary on two axes (e.g., the wrist), and ball-and-socket joints vary on three axes (e.g., the shoulder). The division of muscles acting at a joint into agonist and antagonist groups is generally functional and temporary rather than anatomical and fixed. The division depends on the kind of joint trajectory required.

On the simplifying assumption that the human body is an ensemble of hinge joints, it follows that the human body is minimally a system of 100 mechanical degrees of freedom. We know little for certain about the resolution of coordination and control in systems of such complexity. Regulating a function of, say, twenty variables is not just a matter of individually instructing twenty processes - the "curse of dimensionality" (3) or the "problem of degrees of freedom" (5) is presumably addressed in more subtle ways. Ideas are accumulating about the necessary design of a (motor) system expressing coordination and control of very many variables. The following inventory identifies some of the more significant notions; it is not exclusive.

Special Purpose Solutions Capitalizing on the Features of Real-World Complexities

For a system of very many variables, little is to be gained by being able to control individually all variables. Natural systems operate in restricted, not universal, contexts. They do not need to do everything; they are special-purpose not general-purpose in their design. What generality they do exhibit is a consequence of "smart", perhaps non-computational, solutions (23) to real-world problems gathered into a coherent style of organization (12).

Complementation of a System by Its Context of Constraint

It is meaningless to say that any complex system, by itself, has

an organization of this or that kind (22). A system's organization is as much owing to the environment to which it relates as it is to the system itself. Proprietary speakings, the organization is of the system and environment as a single unit. If the environment of a multivariable system was just another large set of variables, then the coupling of system and environment would exacerbate the "course of dimensionality". A multivariable system and its multivariable environment must complement each other to constrain mutually each other's degrees of freedom (30).

Distributed Construction of Movements

All the spatiotemporal details of a movement are not determined at the outset, in a single step by a single subsystem. The details are contracted gradually by subsystems linked by mutable dominance relations and distributed control and the abilities follows from the principle of distributed control in

(12, 27, 29).

Indefiniteness of Action Plans

This follows from the principle of distributed control and the same way to achieve the same purpose and (b) to put together the same degrees of freedom in different ways to achieve different purposes. Plans for acts are not "written" in skeletal muscles but in predictates of a more abstract kind referring to neither body parts nor to actual motions.

Local Expenditures

Subsystems are autonomous, each relating to the "external medium" of surrounding subsystems according to a locally defined rule, each doing its own thing according to local interaction. Subsystems, each doing its own thing according to local interaction, cooperate to generate "desire" states of affairs without cooperation that is independent of what has to be generated.

Cooperation may be solved once and for all in the design of the system (28).

Separation of Activation and Tuning

Subsystems have standard behaviors or generate standard functions. Activating a subsystem establishes a "ball park" of states, a family of functions. Adjustments within the ball park to fit current circumstances are achieved by a tuning operation logically separable from activation (11).

Executive Ignorance and Equivalence Classes

In a system of distributed control, any subsystem (or set of subsystems) assuming executive status will not know the actual outputs of the subordinate subsystems from which it composes an act. This follows, in part, from the ballpark/tuning distinction. The executive might activate a subsystem ignorant of its tuning; executive knowledge is approximate (of the family of functions) not precise (of the actual function). Moreover, the outputs of subsystems are coincident over various ranges of the executively specified function and can be interconverted according to a local expediency of simplicity. A number of subsystems will therefore seem equivalent to the executive. Perhaps these equivalence classes of tunings, of subsystems, of transitions (among subsystems as they are woven together), etc., identify the systematically behaving predicates over which is defined the formal structures of the "transformational" relation between intentions and skeletal motions (11).

Reducing Mechanical Degrees of Freedom Through Muscle Linkages
(or Synergies, or Coordinative Structures)

Relatively independent muscles often spanning several joints are functionally linked so as to behave as a single unit. Such linkages may comprise the most primitive independently governable actuators of movement (5). They are marked by a pronounced standardization. During a movement most of the internal degrees of freedom of a muscle linkage relate among themselves and with respect to the time frame in a fixed fashion (16,19,24).

Effectivities Relate Muscle Linkages

Muscle linkages comprise an equivalence class by expressing a

common effectiveness - achieving a common goal - not by sharing common degrees of freedom. These effectiveness-based equiva- lence classes comprise the "meaningful" units for syntactic- ing acts. (Their determination, by sentence, regulates characterizing the natural language production in which they work in context.)

The foregoing inventory underscores the logical dependence of a motor system and its context of constraint and, in turn, the imprecision of an autonomous perspective on motions of the body. More importantly, perhaps, the inventory suggests that it is unreasonable to assume that a formal theory of movement is less populated with predicate types, than a formal theory of language - might even be qualitatively indistinct is suggested by the common "problems" that acting and speaking/signaling must resolve. For example, how does an intent specify the constituents of its expression, be they lexical units or muscle tenses? And how are the values of these entities specified in terms of space the realization of an object from your desk top, the chain trans- versed and energy consumed. How can link displacements and their derivatives be specified in a way that is always (near) optimal for circumstances that are rarely (if ever) repeated?

Such problems, particularly where many variables are continuous, may resist algorithmic solution. Such problems, particularly where many variables are discrete, may have simple solutions on language. Perhaps this question, and formal restrictions on motor systems work imposes the task that it implies, is wrong. Communicating and acting as natural events, each defined over a large number of degrees of freedom at several scales, may have a common structure owing to their qualitative similarity "resolutions" to common physical "problems". The structures of language and action may not be different in that one is more of a window onto the world.

When the links of the arm, trunk, and hip change to effect system? And how are the values of these entities specified in terms of space the trajectory that is near optimal in terms of space traverses a trajectory that is far from your desk top, the chain trans- versed and energy consumed. How can link displacements and their derivatives be specified in a way that is always (near) optimal for circumstances that are rarely (if ever) repeated?

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mind than the other - if that statement has any meaning at all. Rather, both structures may be the same window onto physical principles that shape things biological.

CONSTRAINTS ON MOVEMENT AND NATURALNESS IN LANGUAGE

An aggregate of very many degrees of freedom is chaotic, not coordinated and controlled. Coordination and control imply constraints - a reduction in degrees of freedom. But that is not all, for constraints and degrees of freedom relate paradoxically: Constraints reduce degrees of freedom and enrich qualitative distinctions. For example, Euclidean-metric geometry is more richly endowed with concepts than topology from which it is derived through the adding of very many auxiliary conditions (constraints). Convention identifies the fixed constraint that permanently limits degrees of freedom and the time-dependent constraint that alters the trajectories (through phase space) of selected degrees of freedom in variable but regular ways. The material specifications of muscles and nerves, bones and joints - the anatomy - are fixed constraints, while many of the items of the above inventory refer to time-dependent constraints and their formal consequences. In part, understanding movement is identifying these constraint types and their interrelationship.

The fixed constraints cannot be underestimated. Vertebrates move over the ground in many ways - they walk, amble, trot, pace, canter, gallop, and hop - and they do so on two or four legs. Yet vertebrate limbs, superficially distinct, are of a common morphological design that allows for two general mechanisms - one pendulum like and one spring like - by which energy can be alternately stored and recovered within each stride. All modes of locomotion are understandable in terms of either one or both of these mechanisms (6). The fixed constraint of limb design is significant in a more general way. The possible mechanical designs permitting a given trajectory would distinguish in terms of what is required, by way of control through time-dependent constraints, to effect the trajectory. Some designs would require detailed control to

There is, however, a shallowness to this motoric constraint on linguistic form. Most noticeable, it begs the question of what principles determine the tendency toward systematic minimization of action or in the structure of language. It is the structure of action or in the structure of language. It is a question that echoes the last remarks of the preceding section

Generally, explanations of naturalness on the motor side of language reduce to "ease" or "simplicity" of production. The seven unmarked handshapes of American Sign Language are the most basic possible geometric shapes and probably the easiest to fashion. As noted, the hallmark of the organization is the style of the motor system is the condensing out of behaviors with few degrees of freedom from a mechanical apparatus with many degrees of freedom. Put differently, the organization style necessarily reduces the number of degrees of freedom considerably regulating. It is expected, therefore, that when ever possible the tendency will be toward gestures of drastic cally curtailed free variation. Herein lies a general motoric motivation for the many limitations on signed (2) and spoken forms.

"Naturalness" in linguistics is used in reference to the combination of naturalness, signers/victims and the design of speakers/hearers. The "most compatible" entities between linguistic entities and the design of speech-are unmarked in the formalism. Ideally, a causal explanation of unmarked segments and rules is sought. Some unmarked entities are understandable in terms of fixed constituents. For example, rationalizing the voiced sonorant and the voiceless obstruent as unmarked cases might rest on the observation that, during speech, pressure gradients determine a tendency of the vocal cords to vibrate with the vocal tract open and not to vibrate with the vocal tract closed. It is argued to produce voiceless sonorants and voiced obstruents.

push the limb through each ponte of the trajectory while others would regurgitate hardly any control at all.

THE MACHINE CONCEPTION VS. DYNAMICS

The structure and orderliness of movements are interpreted most generally (as intimated above) through modern-day variants of Descartes' "machine conception." Control of the mechanical degrees of freedom is based upon preestablished arrangements among components (the negative feedback machines of cybernetics) and/or preestablished ordered arrangements of specific instructions (the algorithmic machines of Artificial Intelligence). There are, however, noticeable trends in biology, physiology, and systems theory to question the original apotheosis of feedback (4,32), the reality of set-points or referent signals as causally antecedent to behavior (9,31), and the propriety of formal machine approaches (20,33). It should be underlined that a good many of the properties identified above for the control and coordination of a multivariable system have their origin in the machine conception: Given an artifact of very many variables how might it be regulated? In this conception, many dimensions is a curse, many degrees of freedom a problem.

Dynamics is the commonly touted alternative to Descartes' conception: The regularities - the classifications of degrees of freedom - arise from tendencies in dynamics. That is, forces freely at play among mutually interacting components are configured in the steady-state and in the transitions to steady-state by an underlying geometry of stable arrangements. Dynamics has seemed inappropriate to biology in the past because of its preoccupation with continuous motions in spaces evenly populated with phase points (that is, with linear systems that conserve energy), whereas the problems of biology are expressed as discontinuities in spaces unevenly populated with preferred stabilities (that is, the problems of nonlinear systems that dissipate energy). Contemporary dynamics, represented notably but not completely by Prigogine's (21) Dissipative Structure theory, Iberall's (14) Homeokinetic theory, and Haken's (13) Synergetics, directly address biology and are largely inspired by its problems.

Discussing the structure and orderliness of a complex system in the vocabulary of dynamics is, on first blush, unsatisfactory. In the vocabulary of psychology it is, however, for those disciplines it has seemed that a privileged vocabulary is needed for expressing the complexity of cognitive functions, the vocabulary of nets of associations, and/or computations over representations. The invasion of this domain by physical principles seems in - feasible to most. Nevertheless, contemporary physical theory is carving out an inventory of attributes of complex systems (see (32)) that cannot be ignored, for the physical principles from which these attributes derive are principles yet待定 - number of degrees of freedom. In the dynamics perspective, the energy with their surroundings and they are composed of non-in - tegral related atomistic particulars that stochastically fluctuate. Dissipative structure theory teaches that at certain stages to a critical scale change in, say, energy flux will result in the emergence of a macroscopic structure of few degrees of freedom from the atomistic continuum of many degrees of freedom. Homeokinetic theory teaches that the condition of a free - dom. Homeokinetic theory teaches that the condition of a free - dom, and that a complex system is, first and foremost, an en - semble of nonlinear oscillators.

It suffices to identify two attributes of a complex system as concived in contemporary physics: one is the tendency toward structuralization; the other is the fundamentality of the cycle. Natural complex systems continually of the cycle. Energy with their surroundings and they are composed of matter and matter. Dissipative structure theory teaches that at certain stages to a critical scale change in, say, energy flux will result in the emergence of a macroscopic structure of few degrees of freedom from the atomistic continuum of many degrees of freedom. Homeokinetic theory teaches that the condition of a free - dom. Homeokinetic theory teaches that the condition of a free - dom, and that a complex system is, first and foremost, an en - semble of nonlinear oscillators.

mutually entrained in the fashion of limit-cycle oscillators. The argument for the universality of cyclicity or rhythmicity as a design principle suggests that motoric form (a) is shaped in large part by the physics of weakly coupled oscillators of different periodicities and (b) is most aptly described in terms of a spectrum of stable cyclicities. Homeokinetic theory and its advocacy of "biospectroscopy" (32) predict the discovery of numerous cyclicities and evidence of their mutual entrainment.

From this physical perspective it would have to be the case that speaking and signing, like movement in general, are necessarily rhythmical suggesting, perhaps, that their formational aspects are nontrivially determined by strictures of cyclicity such as mutual synchronization (unilateral or reciprocal adjustments of the frequencies of cycles, whether they be of the same or different magnitudes), superimposition (reciprocal adjustment of the amplitudes of cycles, whether they be of the same or different frequencies), and a relatively small number of preferred (stable) phase relations. With respect to speaking and signing these strictures can be expected to bear on the formation of complex gestures, characterizable as a nesting of events of different periodicities. And the strictures of cyclicity, as treated in Homeokinetic theory, hint at a design distinction between language spoken and signed. The coherency of an ensemble of nonlinear cycles is determined by the longest period over which the major thermodynamic bookkeeping is closed. In speech a good guess is that the bookkeeping is closed over the inspiration-expiration-inspiration cycle, the (variable) period over which the potential energy for laryngeal vibration is stored, dissipated, and restored. In short, the "breath group" (17) identifies a fundamental periodicity in terms of which articulatory cycles of shorter periods cohere. The longest cycle over which the bookkeeping is closed in signing is less obvious and definitely not respirational. This distinction in bookkeeping may not be immaterial to the formational distinctions between spoken and signed languages.

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