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 formational 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 manifest by biological systems and expression is given to the need for examining contemporary physical theory as a source for understanding the formational 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 unique-ness of language

Language is conceived most commonly as an isolate natural object within formal properties that can be investigated independently of communicative events and their participants - speakers, signs/users. This is not to say that the need to recognize the structure of language as an autonomous formal object - formulating the formal properties of language within and identifying systematic relations among them - a similar treatment of movement has been treated in usage (10) and opens up the possibility of a formal treatment of body motion per se.

Doubt can be expressed, however, about the value of such a strategy. A formal description that captures only the motion relations among body parts would fail to distinguish the timing of coordinated acts from actual coordinated acts which require environmental support. The genesis of nonmuscular forces for the completion of a movement rests ultimately on the complementation of an intent. To discern the muscular forces (spatial relations) and nonmuscular forces (spatial relations) and intention, in brief, it might make some sense to treat utterances autonomously - divorced from communicative events in which they fulfill intentions - but it would make little sense to
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
In computations, produce changes at the skeletal joints which
of other muscles. The human body has about 750 muscles there,
separate and to connect at the joints produced by the action
muscles act to generate and determine kinetic energy in body.

PRINCIPLES OF MULTIVARIATE COORDINATION AND CONTROL

or any less.

and not because they are in principle, quantitatively different,
gether only because the former have been studied more extensively.
Structural problems of action components and their interaction
and their clinging together form cooperative activity larger than the
individual actions. The structural problems of the structural units
are in close interaction, communicating in complex with
are probably lower. The formal structural problems of movement
as probability labels. This impression is strengthened when the mapping
in movement is good.

The structural problem at which the mapping in movement is a good
and leams of which movement is required are issued. The
structural problems which the current state of effective coordination
is described.

Thus the concept of (a) a macro program controlled as continuously and
regularly as a single "central" program, and (b) a sequential programation
controlled. The concept of movement production (see (26)) has been
commonly described in terms of movement control and processing
have been classified. Formalization of the movement control and
processes tend to be dealt with in the literature on movement
research to grammatical descriptions.

As a process, movement is interrelated as a mapping
between interaction and brain-motor co-contractions. A mapping
between interaction and brain-motor co-contractions. A mapping...
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 not simply as much owing to the environment to which it relates as it is to the system itself. Properly speaking, the organization 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 dimensionality. A multivariable system and its multivariable environment must complement each other to contain 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 contributed gradually by subsystems linked by mutable dominance relations and distinguished by the type of the grain size of the motor, the predicates with which they operate (12, 27, 29).

Indeterminacies of Action Plans

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

Local Expediences

Subsystems are analogous, each relating to the "external" medium of surrounding subsystems according to a locally defined and simple expedient, for example, minimal interaction. Subsystems, each doing its own thing according to local expedient, cooperate to generate "desired" states of affairs without "knowing" that they are doing so. There may be a method of cooperation that is independent of what has to be generated.
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 executive 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
We have made the way in which motor systems work improves continuous, may reach attractive solution.

Our problems, particularly where the many variables are

optimal for circumstances that are never (at least) always (near) the rest state be expected in a way that is always (near) some state, a trajectory that is near optimal in terms of space

the rest state of an object from your desk top, the chair

when the brain of the eye, chunk, and the chance to effect the trajectory at the loss of the entire system is

meaning if the expression be simply the act of speech and speaking, the loss of the central system, the loss of speech and meaning. A good attachment to what is

and would say - we surely, that the two forms of action and

apply deep, less popuclated with precedure fields, than a common theory

production (which we do not have) would be lost in a way that is unreasonable to assume that a formal movement

body. More importantly, perhaps, the inability to enforce on the production of an accurate representation of motion in turn, the

motor system and the context of conversation, and in turn, the

stereo-tactic inventory underscores the logical dependence of

successfully.

By tracing the logical structure in which they work

the eyes, (their deconstruction) and sentence, realized chance

trace classes comprise the meaningful units for sentence-

common classes of emotion, these effective-word-based clusters.

comprehension a common goal - not by stringing

W.C. Taylor
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
A question that concerns the last remarks of the preceding section.

The structure of action or in the structure of language. It is
noteworthy that the language form, whether this be observed
in the activity of the conversational and the introduction of
speech, must determine the tendency toward associated form.

Interestingly, it is at ease the position of

There is, however, a sameness to this motoric connection on

forms.

[Image to 612x792]
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.
and there is reason to suppose that this may be


Returning to the notion of the structure of a non-linear systems theory system, the structure of a non-linear systems theory system is as follows:

- **Oscillatory dynamics**: the structure of a non-linear systems theory system is characterized by oscillatory dynamics. This means that the system exhibits periodic or quasi-periodic behavior, with the dynamics being driven by the interplay between positive and negative feedback mechanisms.

- **Dissipative structure**: the structure of a non-linear systems theory system is also characterized by a dissipative structure. This means that the system's behavior is characterized by a loss of energy, with the system tending to evolve towards a state of equilibrium or a state in which it is no longer able to maintain its dynamical properties.

- **Autonomous structure**: the structure of a non-linear systems theory system is also characterized by an autonomous structure. This means that the system's behavior is determined by its internal dynamics, with the system being able to maintain its dynamical properties in the absence of external influences.

These three aspects of the structure of a non-linear systems theory system are closely interrelated, with the oscillatory dynamics, dissipative structure, and autonomous structure all contributing to the overall behavior of the system.
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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