

Toward a Theory of Apractic Syndromes

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Theoretical development on human motor behavior has occurred largely independently of data on pathological movement disorders. This paper represents an initial attempt to interface findings from studies of apraxia and those of normal motor behavior with a view to formulating a common theoretical framework. Such an integration may ultimately aid in understanding the nature of skill acquisition and provide insights into the organization of motor systems. Three putative theoretical models of movement control are discussed with reference to apractic syndromes. The most commonly accepted view—the hierarchy—possesses properties such as linear transitivity and unidirectionality of information flow that render it inadequate in explaining functional plasticity in the central nervous system. The heterarchy, which incorporates reciprocity of function and circular transitivity, is a more likely candidate but suffers from an inability to regulate the degrees of freedom of the system. Our favored candidate is the coalition model which embodies heterarchical principles, but in addition, offers a solution to the problems of degrees of freedom and context for motor systems. Evidence is reviewed from apraxia of speech and limbs in terms of a coalitional style of control and an experimental approach, consonant with coalitional organization, is developed. We promote the claim that an understanding of apractic behavior—and perhaps motor systems in general—will benefit when clinicians and experimenters embrace a theory of context and constraints rather than a theory of commands as is currently in vogue.

INTRODUCTION

It is an interesting but perhaps distressing feature of science that different areas of study, each bearing a strong potential relationship to the other, can function independently, each in its own oblivion. Except for one or two isolated cases (e.g., Grimm & Nashner, 1978; Roy, 1978) such a situation appears to exist between those who would seek to understand the motor functions of the central nervous system via investigations of

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clinical disorders and those who seek to understand the underlying behavioral processes involved in the acquisition of skill and the control of movement in normal human populations.

The motor behavior area has undergone a good deal of theoretical development in the last decade (e.g., Adams, 1971; Pew, 1974; Schmidt, 1975; Turvey, 1977) but strangely enough with a total disregard for pathologies of movement. The latter, neurologists suggest, have important ramifications for comprehending motor learning and the organization of motor systems (e.g., Geschwind, 1975). The so-called apractic syndromes seem particularly relevant in this regard, for they arise as a result of cerebral insults that interfere with the generation and elaboration of voluntary movement. An analysis of apraxia, therefore, affords a unique opportunity for us to derive important insights into the neural control and coordination of learned movements.

Perhaps a major reason for the absence of a viable interface between the research findings of normal and pathological movement behavior is the absence of a theoretical framework that captures a style of organization appropriate to both. Neither closed-loop nor motor program models—currently popular in the motor behavior area (e.g., Kelso & Stelmach, 1976 for review)—address the problem of controlling a complex system containing multiple degrees of freedom. Thus they are unlikely candidates for an adequate analysis of apractic behavior.

In this paper, we wish to promote a reconceptualization of apraxia based on a perspective on coordinative movement developed primarily by Soviet theorists (e.g. Bernstein, 1967; Gelfand, Gurfinkel, Fomin, & Tsetlin, 1971), and under both theoretical (e.g. Greene, 1972; Turvey, 1977) and empirical (Kelso, Southard, & Goodman, 1979a, 1979b; Nashner, 1976; Nashner & Grimm, 1978) elaboration in this country. In brief, the style of control that we shall propose is *coalitional*; that is, one in which apraxia is viewed, not simply as a breakdown in function of the nervous system itself (cf. Brown, 1972; Hecaen, 1968), but rather as a decomposition of the *synergistic relationships* that hold between the organism and its environment. Current views of apraxia (and indeed motor behavior in general) are based on hierarchical notions of central nervous system organization. This perspective, we shall argue, offers only a limited conceptual framework for analyzing apractic syndromes, being a partial systems approach that fails to account for some important and intriguing phenomena in apraxia. The first part of this paper will be directed toward substantiating this claim and elaborating a coalitional style of control that for us is the *minimal* organization possessing functional integrity (Turvey, Shaw, & Mace, 1978). This leads us, in the second part, to a reinterpretation of the nature of apraxia and consequent proposals for experimentation that may yield significant dividends in the quest for understanding how actions are coordinated and controlled.

Hierarchical Styles of Motor Organization

Let us first consider some commonly accepted organizational concepts of the motor system which we feel warrant careful scrutiny and reexamination. Clearly this is an often-ignored, but important preliminary step since our conceptualization of pathology is likely to correspond to our views of CNS organization. The notion that the motor system is hierarchically organized has a long history that has gained recognition largely because of Hughlings Jackson's (1976) initial observations and insights; it forms the basis for much of our thinking about the nature of skill and the control of movement. There have been numerous recent expressions of the hierarchical viewpoint (e.g., Bruner, 1973; Connolly, 1978) but the basic idea is explicitly defined in Tinbergen's (1950) description of the nervous system as "higher centres controlling a number of centres at a next lower level, each of these in turn controlling a number of lower."

Hierarchical assumptions form the basis for investigations in modern neurophysiology and neurology as well as providing an interpretative backdrop. For example, in answer to the question of where the assembly of "action programs" takes place in the CNS, Brooks (1974) suggests on anatomical grounds that we look to the limbic system for the drive to move and thence to the frontal and parietal cortex for formation of the needed association. From there the output would be channeled via the cerebellum and basal ganglia through the ventrolateral nucleus of thalamus to the motor cortex and then finally to the spinal cord and the muscles. Similarly, in clinical neurology circles, Geschwind (1975) seeks an anatomical (and hierarchical) framework for the analysis of movement organization in response to verbal commands. Since Wernicke's area is responsible for spoken language comprehension, when the subject receives an instruction to execute a right-handed movement "this order is probably transmitted from Wernicke's area though the lower parietal lobe to the left premotor region. The premotor region, in turn, probably controls the precentral motor cortex, which gives rise to the pyramidal tract—a major pathway for motor control—which sends fibers to the spinal cord, where it activates the nerve cells controlling the muscles" (p. 189). These examples clearly illustrate a style of organization that obeys hierarchical principles (or more accurately, linear chaining). Thus the role each element plays in the anatomical chain is fixed and the ordering of dominance relations is immutable.

More recently Roy (1978) has related the presumed hierarchical structure of the nervous system to the functional disorders observed in apraxia. At the top of the hierarchy, damage to frontal and parietal-occipital areas of cortex results in the disordered planning and sequencing of motor acts characteristic of ideational and ideomotor apraxics (Liepmann, 1920). At the next level, lesions in premotor cortex lead to an inability to execute the movement sequence properly (premotor apraxia) even though, ac-

cording to Roy (1978) the patient is still able to plan the motor activity since the frontal areas and the pathways to premotor cortex are preserved. At the lowest level of the hierarchy comes limb-kinetic apraxia—disruption of individual movements within a sequence—which is thought to occur following trauma to the primary areas of the motor cortex.

In all three of the above examples and the last one more particularly, we see an effort to relate the functional organization of the nervous system to its neuroanatomical substrate. But the argument from anatomy does not require presupposing a style of organization that is based on hierarchical principles. Although any characterization of movement must be consonant with anatomical fact, the hierarchical description provides an inadequate representation of both anatomical organization and the functional deficits observed in apractic disturbances. We can buttress this claim on several grounds. Consider first the logic behind attempts to relate apractic behavior to site of brain damage. Its premises are as follows:

(1) Certain lesions in the central nervous system are associated with certain functional deficits.

(2) The effect(s) of the lesion depends on its locus in a neuroanatomically structured hierarchy, i.e., the higher or lower the lesion the greater or lesser the degree of behavioral deficit.

(3) Therefore, the *functional* organization of the system is also hierarchical.

The latter conclusion and consequent claims that data on apractic disturbances "reinforce the need to incorporate features of hierarchical organization into models of motor skill" (Roy, 1978) are based on a curious tautology. Although we are not arguing that structure and function are unrelated, we submit that the conclusion of a functional hierarchy in apractic, and indeed in normal behavior is predicated upon the a priori assumption that the motor system is hierarchically organized.

But the notion that the movement control system is hierarchically organized is subject to more serious flaws. While hierarchical organization offers economy of control as its principal quality, it pays for this attribute dearly. Thus in the conventional view, information in the CNS undergoes continuous transformation into progressively less abstract levels of description as it flows through the system from the "hierarchy" to the peripheral musculature.¹ In this manner, the system may use a single degree of freedom on the central level to regulate many degrees of freedom at the periphery. While an efficient means of reducing the degrees of freedom in a system, hierarchical principles of CNS function obviously

¹ In fairness to Hughlings Jackson, we should emphasize that he was very sensitive indeed to the problem of assuming a simple translation between psychical and physical states and vice versa. The more recent neurological literature—with occasional exceptions (cf. Brown, 1979; Buckingham, 1979)—hardly reflects Jackson's cautions (e.g., Jackson, 1878, in Taylor, 1931, p. 156).

dictate *unidirectionality of information flow* (Davis, 1976). Assuming for example, that two structures x and y are arranged in a hierarchy at two different levels, the higher system x will always command y ; the opposite cannot occur. Furthermore, if x and y are at the same level in the hierarchy, there can be no cross-talk between them (Turvey et al., 1978). In other words, in a hierarchy there is no provision for internal communication within central nervous system networks, yet the evidence for unidirectional pathways is shaky at best (e.g. Brown, 1972; Kelso, 1979; Roland, 1979, for reviews) while the evidence for "feedforward" or "internal feedback" throughout the CNS is virtually unassailable (see Evarts, 1971; Kelso & Stelmach, 1976, for reviews).

A further, and related problem with hierarchical control is that prestige rests with the highest level in the system, i.e., the so-called executive plan or program.² Although this is a tempting approach to conceptualizing apractic disorders (which are after all "higher-order" in nature) it has severe limitations if taken seriously.³ Hierarchies, by definition, dictate that once the superordinate state is lost (say by brain lesions) all subordinate portions governed by it will be left uncontrolled regardless of whether the role of the superordinate state is viewed as excitatory or inhibitory. The absence of excitation or the release from inhibition would render the system unmanageable. In fact, disruption at any level in a hierarchically organized system, either from loss of an element or from the disconnection of elements, affects the functioning of all those levels below it. This shortcoming arises because the relation "is governed by" or "controls" follows the principle of linear transitivity in hierarchical networks.

But there are data on aphasic and apractic patients that illustrate the transparency of such a view. For example, the abnormally long stretches of jargon speech associated with one form of Wernicke's aphasia have been explained as due to a relatively isolated, and therefore free-running, Broca's area (Geschwind, 1969). But this notion implies a totally random stringing together of elements that is not only an inaccurate description of the grammatical patterns of fluent aphasics, but does not explain why the initial phrase of sentences is often produced correctly (Buckingham & Kertesz, 1974; see also Buckingham, 1979). Similarly, damage to frontal cortex—which typically has superordinate status in the planning of ac-

² We do not feel it necessary to cite references in support of this statement. It is perhaps the most dominant feature of modern motor control theory. Elsewhere we have raised serious questions as to the viability of the concept in natural as opposed to artificial (machine) systems (Kelso, Holt, Kugler, & Turvey, 1980; Kugler, Kelso & Turvey, in press).

³ Of course, it has occurred to us that many who use the term "hierarchy" to reflect the functional organization of the CNS do *not* take the concept seriously. If this is so, then our refutation of the notion—as a scientific enterprise—is probably not to be considered seriously either.

tions (e.g. Luria, 1973; Milner, 1964)—should invariably lead to gross disruption of motor activity if the hierarchical model is valid. Indeed one could think of few better tests of hierarchical organization than to damage the structure thought to contain the "hierarchy";⁴ motor behavior should disintegrate. But this is not the case: so-called "habitual skills" (Luria, 1966; Roy, 1978), while rarely produced in response to clinicians' requests are effectively carried out in the proper context. This finding demands an adequate explanation, but for the time being let us emphasize how damaging it is for hierarchical conceptualizations of motor skills in general, and apraxia in particular. To preserve his/her theory, the hierarchist must provide some rationalization as to why damage to the structure involved in planning all acts (in this case the frontal or parietal-occipital area) has different effects on some acts than on others. At a minimum he/she must provide some basis for distinguishing "planned" and "voluntary" acts from those that are "habitual" or "automatic" (cf. DeRenzi, Pieczuro, & Vignolo, 1966). More important, he/she must provide us with an understanding of why it is certain acts may be performed "given the proper context" (e.g., Roy, 1978; see also Luria, 1966, 1973). Such a rationale does not exist, nor, from our perspective, can it exist within a hierarchical framework. The language of hierarchical systems is one of command not context: if the motor system is hierarchically organized then it is, we would argue, *context independent*.

The broader message then of this analysis is that hierarchies provide no means for explaining the functional plasticity in biological systems. Apractic deficits, for example, as pointed out by Geschwind (1975) are often difficult to detect because of this very factor. Alternative pathways not normally used can be brought into operation following insults to primary brain mechanisms. Conventional (hierarchical) accounts of apraxia assume plasticity. But assumed plasticity is incompatible with hierarchical organization because the ability to recruit reserve or back-up structures violates the linear-transitivity principle, instead favoring *circular* transitivity (Turvey et al., 1978). Circular transitivity is a characteristic of heterarchical organization (McCulloch, 1945), a topic to which we briefly turn next.

Heterarchical Styles of Organization

Heterarchies embody many features that contrast directly with hierarchies: rather than ascribing control to a hierarchy, heterarchies are characterized by *reciprocity* of function. In neurology circles, the concept of

⁴ This language may antagonize some readers. But the language of hierarchical systems, it seems to us, presupposes one-to-one mappings between structure and function. Thus when it is written "The premotor region, in turn, probably controls the precentral motor cortex" (Geschwind, 1975, p. 180) we can only assume that the premotor cortex contains a (or even the) controller.

reciprocity is similar to what Luria (1966) termed "functional pluripotentialism." Thus, in a heterarchical style of organization, a system—by virtue of the reciprocal interconnections amongst its elements—is allowed to assume a variety of roles or functions depending on task demands. Conversely, a particular function may be manifested in a variety of structures; there is no compartmentalization of function in a heterarchy. Accordingly, control may shift—as a consequence of such distributed function capability—to the source of the most important information. These features of heterarchical organization—reciprocity and distributed function—enable a system to exploit redundancy. Duplication of function and the presence of extensive reciprocal interconnections thus reduce the vulnerability of the system to potential insults and help preserve its behavioral stability.

If heterarchical organizations closely approximate a realistic characterization of apractic deficits then attempts to relate functional disorders to locations in the brain or to loss of connections between controlling centers are obviously questionable at best. We can only echo the remarks of Grimm and Nashner (1978) in this regard in their discussion of neurological deficits "*dimensions of the deficit represent the best mix of systems remaining to participate* [emphasis ours]. The characterization of the remanent systems, *their redundancy* [emphasis theirs] and the limitations they impose on performance are necessary before making a functional correlation between a lesion and a motor disturbance" (p. 74).

The above statement nicely captures the heterarchical style of organization and shifts the emphasis away from the common (and we believe ill-founded) preoccupation with directly linking function to specific structures. But this is not to say that a heterarchical style of organization is an entirely satisfactory conceptual framework for understanding apractic deficits. Although offering a well-motivated rejection of the so-called *laws of hierarchical structure* (Luria, 1973)—unidirectionality of information flow, centralization of control, and compartmentalization of function—all of which, strictly speaking, defy the emergence of functional plasticity, heterarchies bring with them a new set of problems. Perhaps the major one is that the heterarchy—by virtue of its free dominance capability and the fact that locus of control is free to reside anywhere in the system—is too flexible. Thus, while a hierarchy is an effective solution to regulating the degrees of freedom of a system (admittedly with serious consequences) a heterarchy has the problem of managing a potentially infinite number of degrees of freedom.

The degrees of freedom problem is not trivial (cf. Bernstein, 1967), belonging as it does to the class of "non-deterministic polynomial-time complete" problems (Lewis & Papdimitrios, 1978). More simply, the time necessary to regulate a set of independent variables increases as an exponential function of the number of variables to be regulated. Thus for

any living system the cost (in time) of controlling a large number of degrees of freedom would outweigh the benefits of heterarchical organization. If coordinated movement is to follow heterarchical principles, the number of degrees of freedom to be controlled individually must be reduced. The question arises as to how this may be accomplished. One possibility is that a reduction of the degrees of freedom occurs when a set of variables are linked to form self-regulating autonomous subsystems (cf. Greene, 1972). Wherever the locus of control at any given moment, regulation of the entire subsystem entails only one degree of freedom. Moreover, it makes no sense for variables to be randomly linked to form biologically and behaviorally irrelevant subsystems. Rather there must be a principled basis for constraining variables into appropriate functional units. A good candidate from which such constraints may arise and one that is motivated by descriptions of apraxia is the situational context within which an act is performed. Given this hypothesis the traditional dichotomy between "habitual" or "automatic" acts and "planned" or "voluntary" acts becomes less tenable. For us then, understanding how a heterarchical system operates entails understanding how a system may be contextually constrained. We feel that the issue of context has been skirted too long in explanations of apractic behavior. What follows is an attempt to conceptualize the notion of "context of constraint" as it applies to the functioning of the nervous system (or, more appropriately animals and humans), and to promote an experimental approach that is consonant with it.

What Does it Mean for a System to be Contextually Constrained?

The meaning of a particular action cannot be explained by a narrow concentration upon the physical movement in isolation. The meaning is given by the *context* of the action, or complex of actions, of which it can be observed to form a part. Precisely the same physical movements may have quite different meanings, i.e. it may be different actions in different contexts. (Best, 1978 p. 220)

A popular way of conceptualizing "context of constraint" is in terms of the activation of a motor image or plan (which itself may be either hierarchical or heterarchical) in the rather restricted sense of a stimulus activating a response. Geschwind (1975), for example, considers a verbal command as an inadequate stimulus for a patient with destruction of the anterior four-fifths of the corpus callosum in that the experimenter's verbal command cannot reach the patient's right hemisphere. Hence, the verbal stimulus cannot initiate correct responses by the patient's left limbs. In contrast, an object placed in the patient's left hand constitutes a visual stimulus to the right hemisphere which can evoke the correct movement response. In both cases the movement is considered functionally equivalent regardless of whether it occurs as the response to a verbal or a visual

stimulus. By considering verbal commands and situational context as stimuli for functionally equivalent movements, motor apraxias, so it seems, can be understood as a breakdown of the stimulus-response relations that normally hold.

Notice that in this view the relationship between the object (the stimulus) and the actor (the response) is not truly interactive but rather is unidirectional, being characterized by an immutable, hierarchical dominance relation. In order to be effective, the stimulus must activate the response via pathways that are responsible for the interpretation of verbal or visual information or by the motor system itself.

We wish to support an alternative theoretical perspective—based on work by Bransford, McCarrell, Franks, and Nitsch (1977)—in which a movement (or any event) is not defined independent of the context in which it occurs. In this view, in response to questions like "Who wants to go with me?" "How many oranges do you have?" and "How high can you reach?" the gesture of an outstretched hand with all five fingers extended has very different meanings. In short, the hand gesture is *not* functionally equivalent in different contexts.

In our view, the significance of a movement, and its functional role, are integral to the process of linking free variables into coordinated subsystems. Just as the situational context provides boundary conditions or constraints on the possible meaning of the movement, so also do the possible meanings of the movement provide boundary conditions on the movements' dynamic forms. We will examine this notion later in more detail.

Coalitional Styles of Organization

Our view of organization, in which actions cannot be considered independent of their context, is captured by what may be termed a coalition (see Turvey *et al.*, 1978, for detailed discussion). We have gone to some length in attempting to establish that heterarchical and hierarchical notions consider, in effect, only part of the total system that defines the movement. In contrast, a coalitional framework stresses the mutual compatibility or fit between the individual and the environment. While a coalitional style of control embodies the advantageous characteristics of heterarchies, namely free dominance, reciprocity and distributed function, it possesses the additional control advantage of effectively reducing the degrees of freedom of the system.⁵ Thus, unlike heterarchies where en-

⁵ There is a fourth feature of heterarchies embodied by the concept of coalition that is beyond the scope of this discussion, namely the notion of *emergent properties*. This is a general but often-ignored characteristic of complex systems that illustrates the transparency of views that implicitly or explicitly postulate one-to-one mappings between structure and function. As Davis (1976) points out in his discussion of neural-network properties, a novel function may reflect the interaction of cells with different properties. For example, oscilla-

vironmental variables are potentially indifferent to the organism and vice versa (hence magnifying the degrees-of-freedom problem), in coalitions the environment is just as thoroughly organized as the organism and is specific to it (Gibson, 1977; Turvey et al., 1978). Thus, as Turvey et al. (1978) point out, neither member of the synergy is properly constrained without the other, nor may the total system be defined without their closure. From our perspective then, reduction of the degrees of freedom is accomplished by the contextual framework that operates as a constraint on possible movements. Accordingly, the interaction between the individual and the context or environment must be an adaptive one whose fit is functionally defined by the particular behavioral goal. As a consequence, the *significance* of this interaction must be an important variable in the coalitional system. If we are correct in claiming that a coalition represents the minimal organization that possesses functional integrity, then apractic deficits may be more properly viewed as a breakdown in the synergistic relationship between the individual and the environment as defined by the behavioral goal.

To summarize, we view the role of informational support or context in a system as providing boundary constraints on the specifics of an action. Our definition of context is very broad and may be applied to both coarse-grain and fine-grain analyses of the nature of control. Accordingly, the significance of a movement as well as the specifics of the movement, are a function of the coordinative relationship between any particular movement and a set of contextual boundary constraints. Verbal commands, imitation, and even object use, in our view, leave too many degrees of freedom unconstrained. Context, defined globally and locally, provides boundary conditions that specify exactly how the degrees of freedom of meaning and movement must be constrained. Let us illustrate how this may be the case.

Various forms of apraxia (e.g., ideational, ideomotor, constructional) may be characterized broadly as disorders in which the meanings of objects and events are disrupted. We have seen that the meaning of an act in the absence of an appropriate contextual framework is quite different from the meaning of an act embedded in a particular context, even though the kinematic details may be superficially the same and analyzed as such by the clinician/experimenter. The kinematic sequence exhibited by an apractic patient pretending to hammer a nail in a clinical setting is not functionally equivalent to the (possibly identical) kinematic sequence that

tion in a motor network may emerge as a property of the system even though no single neuron within the network has the capacity of endogenous oscillation. The broader point of course is that no analysis of the system in terms of its parts or the arrangements between them will account for emergent phenomena occurring at high levels of organization (cf. Koestler, 1969). Such a view, which we endorse, forces consideration of the total system (expressed as a coalition) in any analysis of movement disorders.

occurs when actually hanging a picture. The former is extrinsically specified and applies to only a single part of the system, namely the patient. The latter is specified as a function of the interactions within the total system; the significance, or meaning is an intrinsic feature of the whole act.

Evidence in Support of Coalitional Control: Toward an Experimental Reanalysis of Apraxia

Thus far we have argued that given appropriate context the organization of an act is *uniquely specified*. We would like to examine some experimental evidence supportive of the notion that contextual constraints serve to specify precisely the parameters of the motor system. This we believe forces a novel, but principled approach to the experimental analysis of apraxia. Key insights into this problem are provided by Belen'kii, Gurfinkel, and Pal'tsev's (1967) demonstration that during the reaction time period for arm movement, the muscles of the trunk and lower limbs undergo a highly patterned and specific series of changes. Note that these muscles are unrelated to those actually involved in the volitional act but characteristically change prior to any actual limb movement. Nevertheless, the postural changes that occur depend on the requirements of the intended limb movement such that those changes specific to raising a leg cannot be identical to those changes specific to raising an arm. The requirements of the intended movement specify the necessary postural adjustments, thereby reducing the number of control decisions required. In other words, the boundary constraints applied to the postural organization minimize what Bernstein (1967) called "the degrees of freedom problem." In the Belen'kii et al. experiment, the complex of postural adjustments is uniquely specified by the nature of the upcoming movement.

We also see from the Belen'kii et al. study that the relationship between postural adjustments and the specific limb movement is not one of immutable, unidirectional dominance. The requirements of the limb movement do not simply impose boundary constraints on the postural mechanisms. While the latter are indeed specific to a movement, e.g., lifting an arm, they in turn *preclude* the occurrence of a number of other possible activities, e.g., lifting a leg. As Fowler (1977) points out, an individual in this state of "feedforward" ~~is~~ constrained to produce one of a limited class of acts. The postural context provides boundary conditions on what movements are possible while specifics of the intended movement constrain the postural organization. Hence, the relationship between postural adjustments and limb movement must be viewed as at least reciprocal.

It remains to appreciate an additional variable in the relationship between postural adjustments and limb movements before necessarily describing the style of control as coalitional. We have seen how specifics of

the intended movement bias the postural system. Nevertheless, the particular movement comprises only part of the contextual framework for postural adjustments: the nature of the support surface must also constrain such modifications. Those changes appropriate for lifting an arm when the individual is on solid terrain are inappropriate for lifting the arm when she/he is in the water. Only the coalitional style of control then captures the coordinative constraints that exist between the individual, the activity, and the environment.

The so-called "lower-level" adjustments that normally occur prior to voluntary movement warrant, in our mind, much more detailed examination. Conceivably, some apractic disturbances result from brain insults that disrupt the complex of supraspinal influences on progressive changes in brainstem and spinal organization. Kots (1977), among others, has examined the changes in spinal organization before and during voluntary movement by testing the excitability of spinal motoneuronal pools. A monosynaptic Hoffman reflex is elicited by direct electrical stimulation of an afferent nerve. The strength of the reflex provides the information from which one can infer the state of excitability, or gain in the motoneuronal pool. On the basis of empirical evidence, Kots has divided the complex of spinal (and presumably brainstem) changes into three basic processes: pretuning, tuning and triggering. Pretuning occurs prior to the signal to move and extends throughout the latent period of the movement. It involves a "background" increase in the reflex excitability of all motoneuron pools and is generally associated with postural adjustments in anticipation of a movement. The pretuning process is associated with supraspinal processes, in that pretuning is absent from the agonist motoneuron pool during the latent period of an elicited reflex movement.

Changes in the spinal apparatus specific to the future movement are described by the processes of tuning and triggering. Approximately 50 to 60 msec prior to the onset of electromyographic activity in the agonist of the impending movement, there is a smooth and progressive tuning increase in the reflex excitability of the motoneuron pool of the agonist. During the last 25 to 30 msec of this interval, the "fast" motoneurons of the agonist show a sharp increase in reflex excitability simultaneous with a depression of the inhibitory interneuronal system acting on the motoneuronal pool of the future agonist (triggering).

Are impairments of these processes evident in apractic disorders? In patients with cortically localized pyramidal lesions, the background pretuning change in the motoneuron pool of a paralyzed muscle is absent during any attempt to move the paralyzed limb. However, a small background increase in reflex excitability of the same motoneuronal pool occurs during the latent period of voluntary movement of the healthy limb (Kots, 1977). These observations suggest separate supraspinal

mechanisms for changes specific to the limb to be moved and those changes having more global consequences.

An observation by Geschwind (1975) may be relevant here. He observed that axial movements involving bilateral actions of the eyes, neck, or trunk are often executed correctly by apractic patients in response to a verbal command. In contrast, movements of individual limbs, or of the lips, tongue or larynx cannot be produced. He attributes this to the availability of a nonpyramidal motor system which, while capable of elegantly executing axial movements, can only roughly perform discrete movements of individual limbs.

In the current perspective, we do not wish to dichotomize "pyramidal" and "nonpyramidal" motor command systems but rather prefer to consider the possibility of selective impairment of cerebral influences on spinal and brainstem organization.

As we see it, the chief function of changes in spinal organization is to provide the postural context in which a limited class of movements may occur. Thus preservation of axial movements by apractic patients, but not movements of individual limbs, may reflect selective impairment of cortical influences on "tuning" and "triggering" changes in spinal organization.

Available evidence does not run counter to the notion of "nonpyramidal" axial movements. The pyramidal pathways are known to have a selective facilitatory effect on "fast" motoneurons (Preston and Whitlock, 1963). "Fast" and "slow" motoneurons show an increase in reflex excitability during tuning whereas during the triggering process a sharp and selective increase in reflex excitability of only "fast" motoneurons occurs. Hence, the pyramidal pathways may influence the tuning and triggering processes directly, or via nonpyramidal mechanisms. In fact, tuning and triggering are abolished by lesions of the corticospinal system. We believe, however, that classifying movements as the consequences of "pyramidal" or "nonpyramidal" motor commands has less explanatory power than considering movements as arising from pretuning, tuning, or triggering changes in spinal or brainstem organization.

One means of testing this hypothesis is to determine whether the sequence of changes in reflex excitability in the apractic limb during the latent period prior to movement, as well as the sequence of postural adjustments specific to the movement, differ radically from the changes known to occur in the normal limb. The same technique may be used in apraxia of speech. Reflex changes specific to speech gestures have been recorded from the orbicularis oris muscle during bilabial movements for the syllable /pa/ (Netsell and Abbs, 1975; McClean, 1978; McClean, Folkins, and Larson, 1978). Empirical testing of persons with apraxia of speech may reveal whether or not these reflex changes specific to normal speech gestures are maintained.

If the notion of boundary conditions on a movement is viable, then more extensive biasing, or pretuning (feedforward) adjustments must precede a movement that is not within a context than precede a movement that is more fully specified by its context. Consequently, in patients with apraxia of speech, the first movement of an articulatory sequence may be the most difficult to produce because the feedforward adjustments of brainstem organization that delimit the class of speech movements must be established. In fact, Shankweiler and Harris (1966), Shankweiler, Harris, and Taylor (1968) and Trost and Canter (1974) found that errors in apractic speech occur more frequently on initial sounds than on the same sound in a medial or terminal position. This analysis may also apply to the so-called ideomotor and frontal apraxias, in which patients have difficulty initiating a movement sequence. Moreover, the nature of the biasing adjustment that occurs is a function of the entire act, not simply of the initial segment. Some evidence for this notion is implied by a series of experiments by Sternberg, Monsell, Knoll, and Wright (1978). Normal subjects were provided a list of one or more monosyllabic words, and told, on the occurrence of a signal light, to begin reciting the list as quickly as possible. Interestingly, the latency from the signal to the onset of the speaker's response increased linearly with the number of words in the list. Although not interpreted in this way by Sternberg et al., these data suggest to us that the necessary feedforward biasing is a function of the entire sequence of movements. This paradigm may be exploited to explore the progressive biasing of the motor apparatus in patients with apractic disorders. If apractic deficits result from impairment of the feedforward adjustments that would normally precede a movement sequence then we might not expect patients to maintain a linear relationship between latency to initiate a movement sequence and the number of segments in the sequence. If a linear function is obtained, we would expect the slope of the function to be greater than the slope obtained in a normal subject population. In other words, the effect of adding elements to a movement sequence should be more detrimental to apractic patients than to normal subjects. Preliminary evidence for the latter prediction comes from work by Mateer and Kimura (1977) who observed that complex sequences of movements are more likely to uncover apractic deficits than are single motor tasks.

We have suggested that disturbances in "tuning" may be manifest in certain apractic disorders although the data base is very limited indeed. Moreover, if some forms of apraxia involve a selective disruption of supraspinal biasing influences on lower levels, further predictions are possible as to exactly what specific aspects of motor output should be altered. It has been argued here and elsewhere (Bernstein, 1967; Easton, 1972; Greene, 1972; Kelso, Holt, Kugler, and Turvey, 1980, Turvey et al., 1978), that for coordination to occur the free variables in a complex

system must be organized into collectives (Gelfand, Gurfinkel, Tsetlin, and Shik, 1971), or coordinative structures. Such collectives or neuromuscular linkages are created when interneuronal pools in the brainstem and spinal cord are selectively facilitated and inhibited (Bratzlavsky, 1976; Greene, 1972; Gurfinkel, Kots, Pal'tsev, and Fel'dman, 1971). As a consequence of these tunings or biasings aggregates of neuromuscular variables are constrained to act as functional units, units which may be marshalled temporarily and expressly for the purpose of accomplishing a particular behavioral goal.

Such functional units are thought to govern the spatiotemporal interactions among body parts and may be parameterized in several ways (cf. Boylls, Note 1). One form of parameterization is the *structural* prescription defined as a set of qualitative ratios of activities in the linked muscles, that apply over time, independent of absolute activity levels. On the other hand, the *metrical* prescription of a coordinative structure specifies the absolute level of activity in linked muscles. The latter may be viewed as a scalar quantity that multiplies the activities of all muscles in the linkage. This view receives strong support from Orlovskii's (1972) data showing that cerebellar stimulation during cat locomotion affects only the magnitude of muscle contraction leaving unchanged both the period duration and the timings of periods relative to the step cycle. This indeed is the principal characteristic of a coordinative structure. Namely, when a group of muscles is constrained to act as a unit some temporal relationship is preserved invariantly over changes in the magnitude of activity (Turvey, et al., 1978).

Experimental evidence of invariant temporal relationships in normal movement must act as the reference for judging whether or not temporal relationships in apractic movements are disturbed. Moreover, whether or not the distinction between structural and metrical specification is preserved in normal and apractic movements is open to experimental test (cf. Grimm & Nashner, 1978). A series of experiments involving the coordinative use of both hands, and hence the concerted working of both hemispheres, illustrates these concepts rather well (Kelso et al., 1979a, 1979b). The results suggest that in the coordination of complex movements some temporal relationships are preserved over metrical changes. Moreover, the role of context, both fine- and coarse-grain is apparent.

The question that precipitated the Kelso et al. studies was a simple one. Suppose an individual is asked to produce movements of the upper limbs toward targets, with the movements varying in amplitude and precision requirements, how will she/he respond? Kelso et al. used the well-established relationship between movement duration, movement amplitude and target demands (Fitts, 1954) to create such a situation. The key aspect of the Fitts' formulation is that movement time depends on the ratio of movement amplitude to movement precision.

Consider a one-handed movement condition in which the target size is large and the amplitude is small (termed easy) relative to a condition in which the target size is small and the movement amplitude is large (termed difficult). Movement time in the former case will obviously be much shorter in duration. But when these conditions are combined for both hands, the hand producing a short movement to an easy target does not arrive earlier than its more difficult counterpart, as Fitts' Law might predict. Rather, when subjects were asked to strike targets of varying difficulty as quickly and as accurately as possible, they responded with virtually simultaneous movements of the two hands. Moreover, the limb moving to the easy target did not hover over the target or "wait" for its difficult counterpart but rather moved at quite different speed. In fact, the limbs under easy-difficult target conditions reached peak velocity and peak acceleration at practically the same time during the movements. Thus, although different spatial demands on the two limbs affected the magnitude of forces produced by each hand, the absolute timing and the segmental durations of parts of the movement—the timing *relations* of the limb movements—appeared to be an invariant consequence of the two limbs being organized as a functional unit.

An additional experiment explored more directly the influence of contextual constraints in the environment on the dynamics of the functional unit (Kelso, Putnam, & Goodman, Note 2). The subject was required to move both hands to separate targets, but one hand was required to move over an obstruction. Under these conditions the movement of the other, unobstructed hand described an arc, showing the influence of the obstruction on the functional unit. Again, the velocity and acceleration patterns of the two limbs were not independent but rather possessed highly similar characteristics.

We may interpret the contextual constraints provided by the size of the targets, and by the obstruction, as constraining the degrees of freedom of the unit, rather than the individual limb. The synchronous velocity and acceleration patterns of the two limbs suggest a strong interaction between the limbs and are not conducive to an independent programming view. Moreover, the effect of target size is on the functional *unit*, again suggesting that the coalitional perspective may better represent the style of the control than hierarchies or heterarchies.

It is apparent that timing relationships among limbs normally are preserved over changes in the absolute levels of activity in individual muscles. A close examination of the dynamics of apractic motor output may reveal whether these timing relations are disturbed. Recently, Grimm and Nashner (1978) have made a cogent case for such an approach to what they term "program disorders" of which the apraxias constitute one type. While we are obviously averse to categorizing the apraxias as "program disorders" we are sympathetic with their view that "all such disorders

engender distortions in their structural and metrical prescription which are *measurable defects*" [emphasis ours (p. 72)]. Such remarks remind us also of Geschwind's (1975) recognition that he "had often accepted as normal, movements that were in fact poorly executed." He goes on to express a lack of surprise "if some apparently correct response were proved abnormal by more exacting techniques" (p. 194). We feel that the time is ripe for a more precise approach to problems of apraxia within the presently proposed theoretical (coalitional) framework. A detailed movement analysis of apractic disturbances may prove highly informative relative to disruption of spatiotemporal control. We do not feel content with experimental efforts that examine global task situations in the hope of revealing greater performance deficits in apractic than nonapractic subjects (e.g., Heilman, Schwartz, & Geschwind, 1975). While such studies provide interesting facts about the nature of apraxia, product scores such as time on target on a pursuit rotor task tell us nothing about the motor process itself. Distortions in the structural and metrical prescriptions can only be detected by detailed analysis of the dynamics of movement.

Further evidence for this type of approach comes from recent work on apraxia of speech in which fiberoptic measurements of velar movements were obtained from an apractic speaker (Itoh, Sasanuma, & Ushijima, 1977). When the intended target phoneme /n/ was replaced by /d/ the velum continued to descend for a period of time, that is, the pattern of velar lowering specific to a nasal sound was preserved. This appears indicative of poor temporal coordination between velar lowering for /n/ and tongue-tip movement for alveolar closure. Thus, the phonetic change is not an error in selection of the target sound (or meaning element) but results from a breakdown of the tight temporal patterning of movement of two or more articulators. Kent, Carney, and Severeid (1974) in their cinefluorographic study of tongue and velar movements, provide additional evidence that articulatory movements are organized as functional units so that for a given rate of speaking the relative timing of movements of the tongue, lips, velum, and jaw is systematically patterned. This timing pattern of tongue, lips, and velar movements for normal production of a nasal sound may be disrupted in the speech of an apractic patient (Itoh, Sasanuma, Hirose, Yoshioka, & Ushijima, 1978).

Disturbances of temporal coordination in apraxia of speech have also been suggested by Freeman, Sands, and Harris (1978) and Sands, Freeman, and Harris (1978), who found that their apractic speaker produced a large number of errors on the voicing dimension. As discussed by Lisker and Abramson (1964, 1967), the voicing contrast results from a tight temporal relationship between laryngeal and upper articulator events. Freeman et al. (1978) measured voice onset time for initial stop productions of an apractic speaker and found that the discrete temporal

categories for voiced and voiceless stop consonants produced by normal speakers were not preserved in apractic speech.

It appears that apraxia of speech may be characterized, at least in part, by a disruption of the normally invariant timing relations among articulators. To date, however, there have been no investigations of the effect of metrical changes on apractic speech, or even on apractic movements in general. Metrical changes do not exist in isolation but rather specify values for parameters of a structural organization. In the experiments of Kelso et al., the spatial demands of any one target affected the movement of both limbs. (In the terminology used here, the spatial demands specify values for parameters of the functional unit which includes both limbs.) In another sense, however, the metrical specification provides the background context for the structural organization in that the form of an action and its meaning depend on the metrical specification. Running is not functionally equivalent to walking, although their structural organizations may be identical.

These arguments underscore the broad concept of context that we are proposing. Orlovskii's (1972) data, and indeed the general concept of tuning, show coordinative structures to be the context which gives the supraspinal information meaning. Identical supraspinal signals will have different consequences, or significances for the individual depending on the background context (coordinative structure organization) of the spinal cord or brainstem (cf. Aizerman and Andreeva, 1968; Greene, 1972). Conversely, the realization of a spinal or brainstem organization is affected by the supraspinal signals. Only a coalitional organization could provide an interpretative backdrop for this view.

As we have seen, the relationship that exists between the individual and the environment is specific to the behavioral goal and constrains the movement dynamics. Any analysis in which the motor system is considered to the exclusion of the functional setting must fall short of attaining an adequate specification of apractic coordination. Moreover, the data we have discussed here portray some general principles about how movements are controlled and coordinated and what an account of apraxia might entail.

Obviously our motivation has been to provide a conceptual framework (admittedly incomplete) and to promote ways of approaching the problems of apraxia rather than to point to specific neuronal mechanisms that may be tied (in some, by no means clear manner) to behavioral deficits. For those who find this displeasing we would echo Greene's concerns about motor systems research—of which the pathologies constitute a chunk—that the time has come to "know less and to understand more" (in Boylls, Note 1, p. 9). An understanding of apractic behavior (and perhaps motor systems in general) will not come, we believe, until the possibility is recognized that any claim about what a given piece of the

nervous system tells another piece "is not the same as what a given piece of the nervous system tells the animal" (Shaw and Turvey, in press). More emphatically, our bias promotes a shift from a theory and language of commands to a theory and language of context.

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