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Current Status of the Motor Program

Motor program theory has provided physical therapists with one approach to understanding how the brain controls movement. Analogous with computer programs that specify the operations of computer hardware, motor programs are thought to contain commands for muscles that allow movements to occur without the need for continuous peripheral feedback. A review of the physical therapy literature reveals many instances in which motor program theory has been used as a theoretical framework for clinical practice. Yet despite the contribution programming theory has made to the advancement of movement science, the motor program construct is currently under considerable threat. Keele's (1968) original definition no longer seems tenable, given the problems of program storage, motor equivalence, movement flexibility, and context-conditioned variability. The finding that researchers from different disciplines define the motor program in a variety of ways adds difficulty to the task of evaluating the efficacy of the model. A critical appraisal of programming theory and its use in physical therapy suggests that clinicians need to reconsider the usefulness of the motor program model as a basis for movement rehabilitation following brain damage and musculoskeletal disorders. [Morris ME, Summers JJ, Matyas TA, Iansek R. Current status of the motor program. *Phys Ther.* 1994;74:738-752.]

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Whether training motor skills in elite athletes or in patients with orthopedic injuries or brain damage, therapists frequently refer to the motor program when seeking a theoretical framework for clinical practice. Often when patients first attempt a new exercise sequence or motor skill, they rely

heavily on vision and verbal feedback from the physical therapist to monitor performance. Accordingly, their movements are slow and inconsistent. With repeated practice, however, there appears to be a shift toward internal control of movement.¹ Eventually, patients can complete the task quickly

and skillfully in a manner that allows them to attend to changing environmental conditions or secondary tasks. The need to understand the internal mechanisms that govern movement control provided the stimulus for the development of motor program theory. Programming theory argues that skills can be performed automatically due to the presence of motor programs that provide the codes for movement.² Yet there is considerable debate as to the content, structure, and location of these programs.

Origins of the Motor Program

The motor program was defined by Keele as "a set of muscle commands that are structured before a movement sequence begins, and that allows the sequence to be carried out

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Table 1. *Lines of Evidence for the Motor Program*

1. Movement is possible in deafferented subjects
2. Rapid movements cannot be modified by sensory feedback while in progress
3. Studies on anticipatory control in balance and reaching suggest that some movements are "preprogrammed"
4. Electromyographic patterns remain consistent despite blockage of limb movement
5. Reaction time is longer for more complex movements than for simple movements
6. Evidence for central control structures such as central pattern generators

uninfluenced by peripheral feedback."^{3(p387)} The idea of central programs for movement was put forward at a time when many believed that feedback was critical for the regulation of motor skills. "Closed-loop" theories of motor control such as that proposed by Adams⁴ emphasized that somatosensory and proprioceptive feedback was essential for skilled performance, whereas "open-loop" (programming) theories argued that sequences could be prepared in advance of movement and executed without feedback. Closed-loop models became less popular following an accumulation of evidence that some movements could occur without sensory feedback. For example, in 1917, Lashley⁵ described how a man with damage to the dorsal column spinal pathways was able to walk and move his arms, despite the absence of sensation. Animal experiments, such as those by Taub,⁶ have also shown that movements such as reaching and grasping can be maintained following surgical transection of afferent spinal pathways. Patients with tabes dorsalis often lose peripheral feedback from the legs, yet can still walk.⁷ Even though the movement pattern can become irregular, these examples demonstrate that sequences of movement can occur in the absence of sensory feedback. Therefore, it appears that central mechanisms may play a pivotal role in motor control. Advocates of programming theory suggest that motor programs are key central mechanisms that provide the commands for movement.

Support for the Motor Program

Converging lines of research point to the role of motor programs in skilled performance.⁸ This evidence is summarized in Table 1. In addition to studies that show that movement is possible in deafferented individuals,⁹ evidence for the existence of motor programs arises from research on the control of rapid movements such as speaking, piano playing, and typing. These investigations show that, for long-loop reflexes, it usually takes more than 100 milliseconds for sensory feedback signals to reach the cortex, even though the interval between successive movements in such actions is usually less than 100 milliseconds.¹⁰ Therefore, it is unlikely that peripheral feedback alone could control rapid movement sequences while they are in progress. Instead, it seems logical to conclude that rapid movement sequences are structured in advance, or "programmed."^{2,10}

Research on anticipatory postural adjustments also supports the view that some movements are programmed in advance of movement. It is well documented that postural muscles of the trunk, pelvic girdle, and scapula contract before a person lifts an arm in standing.¹¹⁻¹⁴ This is not only the case for asymptomatic subjects, but also for patients with neurological impairments such as stroke¹⁵ and Parkinson's disease.¹⁶ The function of anticipatory postural adjustments is to stabilize the body by minimizing displacement of the center of gravity. That these adjustments occur prior to overt movement provides some suggestion that central

programs provide commands for muscle contraction that are independent of sensory feedback.

Support for motor programming is also provided by investigations on the effects of perturbations to rapid movements of the limbs. Wadman et al,¹⁷ for example, observed the effects of mechanically blocking arm movement when subjects were asked to extend the elbow in order to quickly move a lever to a target. Usually during movements of this type, a triphasic pattern of muscle activity is observed. The agonist muscle contracts to initiate the movement, and then the antagonist contracts to decelerate the arm, followed by a second burst of agonist activity to guide the lever to the target. When Wadman and colleagues unexpectedly blocked the movement of the lever, the triphasic muscle activation pattern continued to be exhibited for a period of at least 100 milliseconds after the movement was stopped. The same basic pattern of electromyographic (EMG) activity continued to be recorded for the biceps brachii and triceps brachii muscles, even though somatosensory and proprioceptive feedback was readily available. This finding suggests that the pattern of muscle activation for rapid, goal-directed arm movements is prepared in advance of movement and can be executed for short periods uninfluenced by peripheral feedback.

Additional evidence for the existence of motor programs is provided by investigations on reaction time. Based on the idea that sequences of motor commands need to be organized in the brain prior to movement, reaction time studies measure how long it takes for the person to respond to sensory stimuli. The time from stimulus presentation to movement onset varies according to the complexity of motor commands to be organized. Typically, longer reaction times are seen with more complex movements, presumably because it takes greater time to assemble the appropriate motor program. It is not surprising then that "programming" time has been seen to increase with the number of submove-

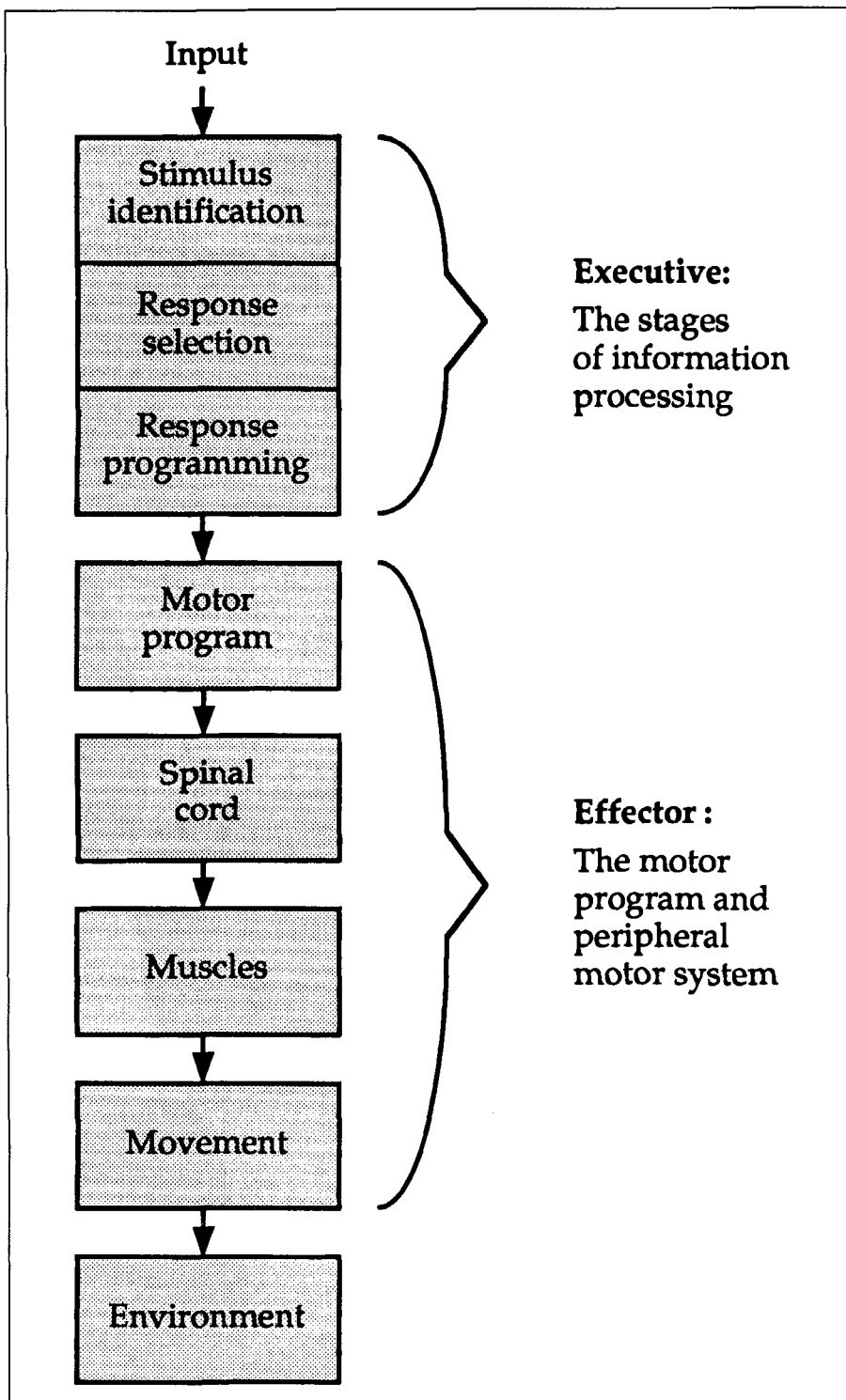


Figure. Model of motor program control. (Reprinted by permission from *Motor Learning and Performance* [p 81] by RA Schmidt, Champaign, Ill: Human Kinetics Publishers Inc. Copyright 1991 by Richard A Schmidt.)

ments in a movement sequence, the movement duration, and increases in timing complexity.^{1,8,10}

Model of Motor Program Control

The Figure shows an example of a program-based model of motor con-

trol as presented by Schmidt.⁸ Essentially, there are two levels in this system. At the executive level, external sensory information and interoceptive signals are mapped onto a reference of correctness based on past experience for goodness of fit.¹⁸ The comparison between incoming information and prior movement knowledge enables the system to determine the appropriate course of action.⁸ In this way, executive functions include strategic planning and goal monitoring. In contrast, the effector system executes the movement commands.⁸ According to Schmidt, the motor program is part of the effector apparatus. After the executive system has evaluated the environment and interpreted internal information, the appropriate response is decided upon and a motor program is called up and run off, to activate muscles subserving postural control or movement.⁸ In this light, the motor program can be seen to be the end result of movement planning.

Where Are Motor Programs Located?

Although the motor program was originally intended as a metaphor to help people to conceptualize the processes involved in planning skilled movements, a more literal interpretation of the concept has emerged in selected areas of the motor behavior literature. Some researchers have taken a fairly literal interpretation of Keele's (1968) definition,³ which affords the motor program the status of a muscle commander. This is illustrated in the following comment by Ghez in relation to motor control of reaching and grasping:

Before we reach out for an object, our nervous system must first select a motor program that specifies (1) the sequence of muscles needed to bring the hand to the desired point in space and (2) how much each muscle must contract.^{19(p494)}

A similar viewpoint is found in Marsden's comments:

To achieve an objective of movement, the subjects requires to assemble the series of motor programs required to

Table 2. Challenges to Keele's (1968) Original Definition of the Motor Program³

1. Sensory feedback refines movement detail
2. The term "commands" assumes a "commander" in the central nervous system
3. Storage problem
4. The problem of infinite regress
5. Problems of movement variability, novelty, and motor equivalence
6. Evidence for distributed organization of movement control system
7. Does not account for movement dynamics, including environmental and biomechanical constraints on action

move in the required direction, at the necessary time, and at the right pace. The individual components of the motor plan may be termed motor programs, each of which involves the activation of appropriate agonists and synergists with adjustment of antagonists and postural fixators.^{20(p134)}

Attempts to identify anatomical correlates of motor programs have led some to suggest that the pre-Rolandic cortical motor areas,²¹⁻²⁵ posterior parietal cortex,²⁶ and basal ganglia²⁷⁻²⁹ play a role in the programming process. Furthermore, it has been argued that the stages of goal specification, motor programming, and execution of final motor commands correspond to the activation of the associative motor cortex, supplementary motor area (SMA), and primary motor cortex, respectively. Single-cell recordings in behaving monkeys and studies on regional blood flow in different areas of the human cerebral cortex during sequential movements suggest that the premotor area plays an important role in the formulation of motor plans in response to environmental cues.²¹⁻²⁵ These motor plans provide a global representation of how sequences of simple movements (or motor programs) are linked together to form complex actions such as dressing, getting out of bed, or playing the piano. The posterior parietal cortex is also considered a site for the assimilation of sensorimotor information necessary for the formulation of motor plans, particularly for visually guided, targeted movements.²⁶ The SMA, however, has a large proportion of neurons active in linking together the submovements of a se-

quence before the commands are finally executed by the primary motor cortex.²³⁻²⁵ As an analogy, the SMA could be thought of as a motor program "buffer" for the temporary holding and execution of motor programs that have been assembled by the premotor cortex and posterior parietal regions. The basal ganglia closely interact with the SMA in the programming process, not by storing the motor programs, but rather by helping to initiate consecutive programs for automatic sequential movements.²⁰

A different set of arguments that could be put forward in relation to the neural correlates of motor programs is that low-level central pattern generators (CPGs) for movement come very close to Keele's definition of the motor program. Central pattern generators are thought to be oscillators in the spinal cord that generate commands for rhythmical movements such as stepping, walking, chewing, and breathing.³⁰ Like in Keele's definition of the motor program, it is believed that CPGs specify the activation of motoneuron pools to regulate the timing of rhythmical movements such as the swing and stance phases of gait, without the need for peripheral feedback or cortical input (although these inputs can modulate the stepping pattern). This role is illustrated by studies on "fictive" locomotion in cats.³¹ In fictive locomotion, the spinal cord is partially transected to isolate it from the brain and brain stem, and the dorsal roots are severed below the transection.³² The hind-limb muscles are then paralyzed so that feedback from muscles does not influence the activity of the spinal networks.³²

The spinal cord area is therefore functionally isolated from supraspinal and sensory influences. In these conditions, rhythmic bursts of activity corresponding to the phasing of muscle activation for locomotion are still observed in the ventral roots of the spinal cord when it is electrically stimulated or when the animal is placed on a treadmill.³⁰ This observation strongly suggests that there are rhythm generators in the spinal cord that drive the stepping apparatus. Although it has been proposed that CPGs are widespread throughout the nonprimate animal kingdom,^{30,31} the question of whether CPGs exist in primates remains unanswered. Research on the development of stepping movements in infants³³ does, however, provide some support for this proposition.

Given these considerations, Grobstein's³⁴ opinion that CPGs constitute at least part of motor programs seems to be a reasonable one. Yet according to Schmidt,⁸ motor programs involve purposeful, learned actions such as throwing, dancing, or riding a bicycle, whereas CPGs are more concerned with innate, or genetically determined, movements. The discussion of motor programs and their neural representation presented in the physical therapy literature we reviewed has not addressed the possibility that CPGs might comprise a significant component of motor programs. This possibility is not trivial, because the differences between a cortical versus subcortical location and genetic versus learned movement may carry implications for the structuring of rehabilitation programs for patients with movement disorders.

Challenges to Motor Program Control

Criticisms of the motor program concept³⁵ have been raised since its inception in the late 1960s and are summarized in Table 2. One of the main challenges to programming theory concerns the role of peripheral feedback in movement regulation. Taub and Bergman suggested that "once a motor program has been

written in the CNS [central nervous system], the specified behavior, having been initiated, can be performed without any reference to guidance from the periphery."^{36(p173)} Yet, as highlighted by the deafferentation studies, movement accuracy, finesse, and coordination tend to be reduced when sensory feedback is precluded. Because feedback does have an effect on the fine details of movement, some critics have questioned the validity of Keele's concept of the motor program.³⁷ A closer examination of Keele's original definition, however, reveals that even though motor programs may *allow* sequences to be performed without sensory feedback, they do not *require* movements to be unaffected by feedback, as Rosenbaum³² has already pointed out.

Current models of motor programming emphasize that both peripheral and central mechanisms interact to govern skilled performance.³⁸ Quite clearly there are some important conditions in which sensory feedback works in conjunction with open-loop mechanisms to help regulate performance. One example is when the performance environment changes unexpectedly, as is the case with a sudden perturbation. When movements are disturbed, sensory feedback eventually provides information to the CNS about the mismatch between the movement goal and its outcome. Even though sensory feedback is relatively slow to reach the cortex, its availability permits adjustment of movements scheduled for subsequent trials.³⁹ Therefore, feedback can play an important monitoring role. This point was illustrated by the recent research of Abbs and Winstein,³⁸ which showed that feedback can modify a range of movements, including ballistic movements.

Peripheral feedback is also useful when the effector apparatus fails to adequately implement motor commands. Lough⁴⁰ made the observation that some patients with cerebrovascular accidents are unable to overcome hypertonicity during tasks such as reaching and thus cannot consistently achieve their movement goals. As a

consequence, they rely on visual feedback to monitor and guide performance. Although feedback-based control of this type is very slow and places heavy demands on attention, it still ultimately helps to refine movement behavior.

One of the main questions raised in recent critiques of programming theory relates to *what* the motor program actually specifies. In his original definition, Keele³ proposed that motor programs specify commands that allow muscles to be activated with optimum timing, phasing, and force to produce the desired movement sequence. *Muscle commands*, according to Schmidt's impulse timing model, are

... a series of pulses of activation, delivered to the musculature at the proper time and graded in duration and intensity so that the resulting muscular forces are sufficient to control the limbs.^{39(p261)}

However, the idea that the brain controls movement via motor programs that contain commands for muscle activity has been questioned from a number of standpoints. The primary concern appears to be one of storage. It is not clear how the CNS could possibly store all of the motor programs required to specify every muscle in the human body for the variety of observed movements. One-to-one mapping between motor programs and muscles would require a vast storage capacity. Mulder and Hultsijn,⁴¹ among others, have suggested that higher CNS centers cannot be charged with specifying all of the possible details of movement.

Another issue of contention stems from Keele's use of the term "muscle command." The word "command" invokes the notion of a commander, in charge of receiving sensory information then issuing instructions for movement. The question then arises: What type of CNS structure could possibly provide the dual executive functions of receiving information and allocating commands for particular movements? Also, if the commander were to decide independently on an

appropriate course of action, it would have to be an intelligent or knowing agent. If the commander carries out instructions from a higher authority, however, then one must question where they come from. This last problem could be seen to become one of *infinite regress*. As stated by Turvey et al, "When trying to explain how it is that a person can, for instance, play tennis, you do not want in your explanation a person inside the head playing tennis."^{42(p243)}

Another problem with the term "muscle commands" relates to what is known as "context-conditioned variability."⁴² This term refers to the finding that the manner in which muscles are activated changes according to the context in which movement occurs. Consider the action of arm muscles when the elbow is flexed from neutral to 90 degrees when a patient is lying on his or her back with the shoulder positioned in 90 degrees of flexion. If the patient flexes the elbow slowly from neutral to 90 degrees, the triceps brachii muscle contracts eccentrically to control the movement. If the patient is asked to flex the elbow at the same speed but against resistance, however, the triceps brachii muscle is not activated. The biceps brachii muscle contracts to flex the elbow. The same kinematic movement pattern is produced by different muscle groups, according to the task demands. Keele's original definition³ does not accommodate this finding, nor does it embrace the related issue of *motor equivalence*, which Hughes and Abbs described as "the capacity of a motor system to achieve the same end-product with considerable variation in the individual components that contribute to them."^{43(p199)} For example, people can continue to speak reasonably clearly when they have a pipe in their mouth, are eating, have paralyzed chest muscles, wear orthodontic braces, or have lost their teeth.⁴⁴ Moreover, the movement system can usually achieve functional goals such as speaking or reaching to grasp a cup despite sudden perturbations.

A further consideration is the issue of movement novelty. The system contains many degrees of freedom, which permits flexibility in the way we perform tasks. Even with simple movements, there are subtle changes in performance from trial to trial. At the extreme, every movement could be seen as a novel movement even though fundamental characteristics of an action remain stable from one performance to the next. Yet, in programming theory, it is not clear how new movements can be performed when no motor program exists to specify how the muscles should contract. The lack of an adequate explanation for the problems of movement novelty and motor equivalence could be seen as an inherent weakness of traditional programming theory.

The Generalized Motor Program

In an attempt to address the limitations of traditional programming theory, Keele⁴⁵ modified his earlier definition of the motor program from a set of muscle commands for movement to an abstract representation for movement. Schmidt's concept of the "generalized motor program" (GMP),⁴⁶ which encompassed the abstract representations of a movement plan and was therefore effector, size, and speed independent, reinforced this newer conceptualization of the model.

Generalized motor programs can be thought of as algorithms that define classes of action, such as reaching, walking, and writing. (Algorithms are sets of equations that specify the computations for eliciting a particular response.) Close examination of movement patterns reveals invariant features for particular classes of action. This point was demonstrated in a handwriting study by Raibert.⁴⁷ When Raibert analyzed writing performed with the dominant and non-dominant hands, the foot, and an immobilized hand, he noted that a particular style containing characteristic features was apparent for all conditions. This finding suggested that a fundamental or abstract pattern was

stored in long-term memory that enabled consistent features to be reproduced regardless of the speed of movement, size of words, muscles, or limbs used. It seemed feasible that these invariant features be coded in a GMP.

For a specific movement to be executed in a given environmental context, variables need to be assigned to the generalized program. These variables (commonly termed "parameters" in the motor control literature) define exactly how the motor program is expressed on a particular occasion. In relation to the handwriting example, application of a size variable could lead to small, regular, or large letters according to the value assigned. Other variables of GMPs that have been indicated in experimental research include overall duration, overall force, and muscle selection variables.³⁹

The GMP or abstract representation of movement comes some way toward tackling the movement novelty and variability problems discussed previously. By setting different variables for an abstract program, a wide variety of movements can be produced. Specific movements, therefore, need not have been performed previously. Only the general action pattern has to be learned. The GMP also helps to alleviate the problem of storage. Rather than storing memories for every possible movement sequence, only key programs for classes of action require representation, which would further assist with the storage problem.

Nevertheless, there are two possible criticisms of the earlier versions of GMP theory. First, the search for invariance in movement has yielded conflicting findings, and it is still not clear which aspects of movement remain stable across conditions. In particular, quite a few articles have recently challenged the hypothesis of relative timing invariance, which provided the foundation for GMP theory.⁴⁸⁻⁵¹ The second criticism is that the earliest versions of the theory failed to adequately take into account how the biomechanics of movement

and the context in which the movement is performed constrain motor behavior. Recent studies indicate that much of the movement we produce is "for free," as a result of factors such as gravity, momentum, and the elastic properties of soft tissue, rather than being specified by a higher order structure such as a motor program.⁵² Along these lines, a direct challenge to the motor program is the dynamical systems viewpoint.⁵³⁻⁶⁰ Although a detailed description or critique of the dynamical approach is beyond the scope of this article, this approach will be briefly introduced as an alternative way of conceptualizing how movement is controlled.

The Dynamical Systems Approach

Advocates of the dynamical approach argue that motor program theory places too much emphasis on brain computations for movement and insufficient emphasis on the dynamics of motor control. Their view is that movement is not prespecified by centrally located programs. Rather, characteristics such as the timing, force, and amplitude of movement are emergent properties of the dynamics of the motor system as it interacts with the environment. As an example, consider the control of the timing of cyclical limb movements such as finger tapping. Whereas programming theorists might argue for the existence of a "central clock" or temporal codes within motor programs that control the tapping rhythm, those advocating a dynamical viewpoint suggest that the timing is a consequence of the natural frequency of oscillation of the limbs. The frequency of oscillation is dictated by *coordinative structures*,⁵² defined by Tuller and colleagues as "groups of muscles often spanning several joints which are constrained to act as a single functional unit for a given task."^{58(p253)} Coordinative structures are not "hard wired"; rather, they self-assemble according to task demands. The direct coupling between perception and action constrains the manner in which the coordinative structures are assembled. Thus, in-

stead of being controlled by a higher order executive, movement is seen to result from a self-organizing motor control system that receives multiple inputs across many levels.⁵⁶⁻⁵⁸ The reviews by Meijer and Roth⁵⁵ and Turvey⁵⁴ provide more detailed accounts of these concepts.

The dynamical viewpoint has drawn attention to the point that not all aspects of motor behavior need to be controlled by a central representation for movement, and from this point of view has made a valuable contribution to motor control research. This viewpoint, however, has yet to address some key issues in movement control. For example, in assuming that physical-mechanical factors and environmental constraints "drive" the nervous system, the dynamical approach still fails to explain the persistence of motor output commands when there is no movement. The continuance of the triphasic muscle activation pattern for movements that have been blocked and the persistence of neural activation in fictive locomotion provide good examples of this limitation. Moreover, it is difficult to reconcile the idea that there are no central representations for movement with the range of diverse and highly skilled movements that humans can perform at will and from memory. That humans can *intentionally* move in a particular way suggests that there is some form of central representation for movement that can be accessed by an "intelligent" brain.

A recent analysis of the motor behavior literature by Abernethy and Sparrow⁶¹ revealed that there is currently a paradigm shift away from motor program theory toward a dynamical approach. It could be argued, however, that these two paradigms are not necessarily mutually exclusive. The dynamical approach attempts to describe the neural, gravitational, and musculoskeletal mechanisms that regulate movement. As such, we see it not as a theory of motor control but rather as a descriptive tool. The information processing viewpoint (which is the branch of psychology in which programming theory is embedded)

places considerable emphasis on the notion of executive and central representations of movement in the brain that enable a person to act intentionally. Thinking of an integrated model that captures both cognitive and dynamical elements is possible. Some adherents to the dynamical approach have discussed *cognitive constraints* on action, which help to establish the intentional elements of a particular movement.⁶² Similarly, most information processing theorists now acknowledge that some aspects of movement control result from the biomechanics of the effector apparatus, including the mechanical properties of muscles. The new attitude is reflected in the following statement by Marteniuk:

There are undoubtedly biomechanical factors that constrain movement control processes and that can account for a substantial part of coordinated movement. However, there are also brain mechanisms, potentially complimentary to the biomechanical factors, that take part in planning and control processes, and that account also for a proportion of the coordination process. Neglecting one approach at the expense of the other will not solve the complex problem of understanding how coordinated movement occurs.^{63(p115)}

This balanced approach appears to signal the direction for future research and is an important evolution in the most recent versions of motor program theory.⁶⁴⁻⁶⁹

Levels of Control

A remaining issue to be addressed by motor program theory is whether the nervous system controls movement via hierarchical or distributed processes. The traditional viewpoint was that motor programs operated within a hierarchical structure, as depicted in the Figure. It was thought that movement goals were coded in the frontal and parietal association cortices, that motor programming occurred in the SMA, and that the final commands for movement were executed by the motor cortex and corticospinal pathways.

Recent commentaries by Requin⁷⁰ and Alexander et al⁷¹ suggest that one-to-one mapping between stages of information processing and precisely located regions of the brain is becoming increasingly incompatible with what is now known about the functional architecture of the brain. There is growing evidence that central representations for action planning and control are widely distributed in neural networks that overlap throughout a large portion of the brain and that are flexibly interconnected.⁷⁰ For example, neurons coded for the same behavioral function are found throughout several different regions of the brain.⁷⁰⁻⁷² It is also now apparent that single neurons can be involved in implementing different functions, according to the context in which they are activated.⁷³ In addition, the control of movement variables such as movement direction has been found to result from the recruitment of large populations of neurons (which may have different individual functions) rather than one-to-one mapping between neurons coded for a given function and a particular muscle.⁷⁴

Alexander and colleagues⁷¹ also point out that the architecture of the brain shows massive parallel connections between the motor areas of the cortex, the basal ganglia, and the cerebellum, in addition to connections that are in series. A system that contains a predominance of parallel pathways is unlikely to restrict its operations to serial, analytic processing, as suggested by traditional motor programming models. Such an approach would considerably underutilize available capacities and would be slower than parallel processing. More importantly, if the brain uses sequential analytic processes, then there should be evidence of specialization for these transformations in some of the brain circuits. Such evidence, according to Alexander and colleagues,⁷¹ has not been forthcoming.

There remains the possibility that motor programs may not be stored in set regions of the brain such as the premotor cortex and supplementary area and executed according to a

sequential process, but may be distributed over a number of levels. In line with recent evidence that indicates concurrent, distributed processing of sensorimotor transformations, the prevailing view is that the motor program is a multilevel system that enables abstract representations of actions to be elaborated into their more specific components at lower levels.^{1,69} Accordingly, the program may simply coordinate the interaction between submovements for a particular task and delegate the role of specifying the fine details of movement to lower levels, including the brain stem and spinal cord. Such an executive function considerably reduces the computational burden on the CNS, thereby helping to alleviate the storage problem. The notion of motor programs that utilize distributed and parallel processing also links more closely with what is known about the neural architecture of the brain.⁷⁵ Rosenbaum's³² current definition is in agreement with this broader role. He has described the motor program simply as "a functional state that allows particular movements, or classes of movements, to occur."^{32(p109)} The most recent definition by Keele et al⁴⁵ followed suit. They defined the motor program as representing the orders of actions, rather than their specific elements, and therefore concluded that it was a plan.

The trend toward defining motor programs in more abstract terms could be seen to come at the expense of predictive capacity. Some critics argue that it is now time to question the predictions that can be derived from a model that is couched in terms such as "functional state" or "plan." Added to this, the distinction between the executive and the motor program (Figure) becomes more blurred when the motor program is assigned the role of a regulator or coordinator of lower level systems. These issues need to be resolved if programming theory is to withstand challenges from alternative models of motor control, such as neural network theory or the dynamical systems approach.

A Problem of Semantics?

Difficulties in defining the motor program and deriving the practical implications of programming theory have arisen, in part, due to semantics. From its inception, the "motor program" was intended to be a metaphor or "black box" that helped to explain aspects of skilled movement such as planning and central representations for particular actions. Yet, over the years, some have attempted to make literal applications of the concept. A growing number of researchers^{37,55,71,76,77} have indicated that this literal interpretation can no longer be sustained, given recent knowledge on neural control of movement. Although a metaphoric use of the term "motor programming" might still help to loosely describe cognitive processes involved in movement planning without specifying the neural correlates,⁷⁷ the continued use of the term is likely to lead to further confusion in the motor behavior literature, particularly as researchers from different disciplines define the motor program in a variety of ways. The issue is not whether central representations for movement exist in the CNS, rather whether the motor program construct provides a viable model of these representations.

Physical Therapy and the Motor Program

A review of the physical therapy literature over the last decade reveals that programming theory has had considerable impact on the formulation of key questions in movement rehabilitation. The interest in motor program theory as a basis for physical intervention is reflected by the many references to the motor program (engram) concept in standard physical therapy texts as well as refereed journals.^{60,78-90} In most instances, this literature reflects Keele's original definition of the motor program, which is seen as a "muscle command" center that enables performance of coordinated sequences of movement without continuous reliance on sensory feedback.³

Although motor control theorists have rarely discussed programming theory in relation to motor impairments or movement rehabilitation, physical therapists have made use of the motor program concept to place therapeutic practice within a theoretical framework. This appears to be particularly the case in neurological rehabilitation. For example, in relation to the treatment of people with Parkinson's disease, Schenkman recently advised that

The breakdown in motor planning and programming that has been associated with Parkinson's disease dictates that physical therapy for the disease should specifically incorporate the repetitive practice of functional activities that require simultaneous sequencing of different motor programs.^{88(p174)}

Implicit within this statement is the idea that motor programs are stored in the nervous system, and that physical therapy can "activate" such programs in patients with movement disorders. Both of these assumptions, however, remain speculative and are clouded by the lack of consensus as to what is meant by the term "motor program." If the prevailing view is taken, that the motor program is no more than a "black box" in which movements are planned within a multilevel system, then perhaps it makes little sense for clinicians to speculate about how these programs can be triggered in order to elicit skilled movements. Yet a more literal interpretation of the motor program as a set of muscle commands or algorithms is difficult to reconcile with the problems of motor equivalence, movement novelty, program storage, and context-conditioned variability. Clearly, physical therapists are faced with a dilemma as to the validity of applying motor program theory to movement rehabilitation procedures.

In one sense, physical therapists are confronted with this type of dilemma whenever they apply motor control theory to clinical practice. Even with the newer models of movement control such as the dynamical approach, there is little objective evidence to suggest, at this point, that the assump-

tions are valid. The ultimate test of the usefulness of motor control models as a basis for physical therapy practice will be clinical research, and, until clinical trials have been conducted, therapists will need to remain cautious when they apply any motor control theory to practice.

Nevertheless, it is still important for physical therapists to examine the assumptions that they hold about how movements are controlled, because these assumptions structure the way in which we formulate key questions related to the assessment and treatment of movement disorders. Horak⁹¹ highlighted this point in a recent review of motor control models underlying posture rehabilitation in children, as did Gordon⁸⁷ in relation to methods of rehabilitation for patients with stroke. Whereas clinicians who hold a motor programming viewpoint might ask questions about how physical therapy can be implemented to facilitate the smooth retrieval and execution of motor programs for a given movement sequence, clinicians who take a dynamical systems approach might ask how the task dynamics can be structured to enhance performance, for example, by carefully structuring the training environment or by teaching the patient strategies for optimizing the biomechanics of the movement. From a neural network perspective, the emphasis would be on identifying the neural constraints on action and exploring ways in which the CNS can be assisted to utilize alternative neural connections to help overcome movement disorders. By regularly examining our underlying assumptions about motor control and by adapting our approach as more robust models evolve, physical therapists might be better placed to devise and implement effective strategies for movement rehabilitation. This would seem to be particularly the case if an informed approach is coupled with the physical therapists' expertise in observing, measuring, and documenting the outcome of specific interventions for movement disorders.

Finally, in considering the ways in which motor program theory might inform physical therapy practice, it is useful to delimit the processes associated with motor control from those involved in motor skill learning. One of the key roles of physical therapy is to assist patients with brain damage or musculoskeletal disorders to acquire the capability for moving in a more skillful or functional way. We believe that, to date, motor control theories have offered little insight into the processes associated with skill acquisition. In contrast, the field of motor skill learning has centered on practical issues such as the value of feedback, specific types of practice, and different practice schedules for movement training.^{92,93} There have already been clinical trials that have investigated the efficacy of methods for promoting motor skill learning in skilled athletes,^{94,95} individuals with brain impairment,⁹⁶⁻¹⁰⁰ and people with musculoskeletal disorders,¹⁰¹ and some of these methods have been incorporated into movement rehabilitation programs.^{102,103} From a practical viewpoint, it could even be argued that the literature on motor skill learning currently provides more direct applications for physical therapy practice than motor control paradigms such as motor program theory.

Conclusions

A historical overview of the motor program highlighted the changing applications and definitions surrounding its use during the last 25 years. Although the motor program still enjoys the status afforded by a literal interpretation in some disciplines, the weight of evidence suggests that it is now difficult to sustain such interpretations. Currently, there is a return to the use of the term "motor program" simply as a metaphor to describe cognitive processes in movement planning. As such, there may be limited potential for determining the anatomical correlates of motor programs. In reference to motor control research, Summers recently suggested that

... in view of the lack of consensus as to what exactly is a motor program and whether it is a metaphoric or literal term, ... continued use of the term may actually impede progress in the field.^{77(p800)}

Ultimately, physical therapists will need to decide whether the motor program construct still provides a useful framework for clinical practice.

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Invited Commentary

Since Keele's seminal paper¹ in 1968, the term "motor program" has become part of the vocabulary of theorists in motor control and motor learning, and, as Morris et al point out, the term has also become widespread in the clinical literature. Unfortunately,

despite considerable theoretical development in the concept of a motor program (reviewed nicely by Morris et al), the term is still frequently used in its original formulation. That is, it is used to imply that when we learn a movement skill, we learn a specific set

of muscle contractions. As Morris et al demonstrate, this assumption is simply untenable. Even small changes in the context in which an action takes place will radically affect the magnitudes and timing of muscle contractions necessary to carry out the act, and even