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This chapter outlines the basic computational, anatomical, and physiological (CAP) principles underlying upper-limb actions, such as reaching for a cup and grasping it or picking up a key, inserting it into a lock, and turning it.

Introduction

One of the most remarkable aspects of human behavior is the seemingly effortless manner in which everyday activities involving the upper extremities are successfully achieved. This apparent ease, however, masquerades the underlying functions of a truly complex biological system. In their attempts to understand brain functions, neuroscientists have found it useful to seek explanations at several different levels of analysis.¹ This strategy can be particularly useful in our quest to discern how sensorimotor systems respond to brain injury and rehabilitative interventions.

Levels of Analysis

A helpful starting point in analyzing any complex system is to ask what are the problems that this system must solve and why? In the broadest sense, we use our upper extremities to accomplish goal-directed actions—actions that are driven by our motivational states. For instance, our thirst may drive us to seek out a drink. Then, we have to solve the problems of finding a source to quench our thirst and carrying out the actions that allow us to achieve our goal (see Box 1). Our environment may present us with a variety of potential paths from which to select, and achieving each goal may require distinctly different sets of actions that vary in their costs. We might opt to reach out for the cup of water on the table in front of us, rather than walking down the hall to the drinking fountain or locating the change we would need to use the nearby soda machine. Having settled on the water cup, we now face additional choices of how to get it to our mouth. By default, we might opt to use the dominant hand to reach for, grasp, and transport the cup to the mouth. If the preferred

hand is preoccupied with another task (eg, holding a telephone, or shaking hands), we can (at the increased risk of spilling) switch to the nonpreferred side. For an individual with impaired upper-extremity function, the range of potential solutions is obviously restricted, and the costs associated with various goal-directed actions are considerably different. A moderately hemiparetic patient might, for instance, decide to rely exclusively on their less-affected limb. In the moment, this choice may provide a more efficient solution to the problem of getting the cup to the mouth (low immediate costs). Yet the choice to avoid using the impaired limb may have distinctly undesirable longer-term costs that include further weakening of an already compromised system (or learned disuse), eventually leading to a dramatic restriction of the range of available actions (high long-term cost). Conversely, opting to use the affected limb will provide a less efficient solution that is costlier in the short term but that may hold potential for longer-term gains, including improved strength and dexterity. Motivating patients to make such trade-offs consistently can be a major challenge for rehabilitation specialists because costs are also influenced by individuals' emotional and energetic states and also change along with functional status. Strategies such as constraint-induced movement therapy (Pomeroy et al) can be thought of as a way of

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Box 1. Motor goals and apraxia

Actions are normally organized in terms of desired outcomes. To make a cup of coffee requires the organization of a broad range of subgoals such as boiling water, measuring the coffee grounds, and so on. Subgoals in this task need to be sequenced in a sensible order. For example, the water needs to be hot before it is poured. This capacity to organize complex serial behavior is uniquely human. There are multiple cognitive models of how the human brain accomplishes this. At the one extreme are planning models that propose that the brain learns how to set up the subgoals within a logical hierarchy. For example, picking up a spoon is subordinate to scooping the sugar, which is subordinate to making the coffee sweeter. One can readily construct a complex contingency table for getting the entire task organized. At the opposite extreme are associative models that link percepts (a coffee cup) and stereotypical actions (grasp the cup to take a drink). Through experience, we learn the links between these typical motor programs and different situations. It is likely that both these extremes are needed in real life. The system must be able to organize complex sequences of actions in a task space but also perform some of the subgoals such as shaping the hand to fit an object in a direct way. Lesions in the brain can damage the organization of these sequences and lead to deficits of motor action selection known as apraxias. Retraining subgoals via verbal or visual inputs is the basis of the strategy training approach, the only method that has been shown to improve activities of daily living (ADLs) in individuals with apraxia.

artificially rebalancing the costs associated with using the affected versus the less affected limb.

Finally, we can ask how these actions are organized and produced by the brain—what are the biological mechanisms that implement these computational processes? What specific neural mechanisms are involved, and how do they change in response to injury or rehabilitation? Given the central role of manual behaviors in our lives, it should come as no surprise that many regions of the human brain are involved. As will be reviewed below, however, a number of organizing principles have emerged regarding how the brain produces upper-extremity functions. In this chapter, we introduce a conceptual framework for organizing and integrating knowledge gained from studies of functional neuroscience over the past 3 decades that can inform and influence approaches to neurorehabilitation. We refer to this framework as the CAP model because it draws on developments in computational, anatomical, and physiological research.

Computational Principles

Although central to the topic of human actions, our knowledge of the complexities of motivation, intention, and goal formation is relatively sparse. Therefore, we begin our discussion further downstream, with what is currently known about the processes involved in the planning and execution of manual behaviors. We begin by considering some of the processing steps that lead to the generation of a motor command, which is the initial step illustrated in Figure 1. Note that the separation between goal establishment, planning or action selection, and execution relate to the clinical separation between disturbances of motivation (motor neglect, akinetic mutism, others), planning/selection (the apraxias), and execution (hemiparesis) as discussed in the second chapter in this series by Sathian et al.

Computing the Initial Motor Command to the Internal Model and Spinal Cord

One way to appreciate the complexity of upper-extremity functions is to try to program a robot to undertake these behaviors. This exercise is useful in identifying the particular problems that must be solved and in suggesting possible solutions that might also be used by the brain. This task requires solving a number of nontrivial problems. The processes involved in these solutions can be thought of as computations or operations that are performed on incoming information (input) to transform it into output that is useful to the system. For example, an adding machine applies the addition computation to numerical inputs and outputs the sum. As a starting point, consider again the task of reaching for a cup. As a first pass, we can perform a task analysis to decompose this action into 5 basic steps. (1) Assuming that one is motivated to drink and that the cup of water located nearby is the goal, then, a critical first step is to precisely determine the position of the cup in the environment, often through vision. (2) Next, the current state of the system (position of the arm) must be estimated, a process that may draw both on visual and proprioceptive input as well as prediction (a concept that is developed further below). (3) To compute the spatial relationship between the cup and hand, sensory information must be transformed into a common frame of reference. This is analogous to the importance of locating both one's current location and desired destination on a single map when navigating. (4) A plan can then be formed that specifies the direction and distance from the current position of the hand to the cup's location. (5) Finally, motor commands can be issued that cause the hand to reach the cup with sufficient precision to accomplish the goal within a reasonable period of time. These motor commands are generated in the primary motor cortex and then sent to the spinal cord where they activate circuits that generate the final commands to individual muscles. We will return to a more detailed discussion of the motor cortex shortly.

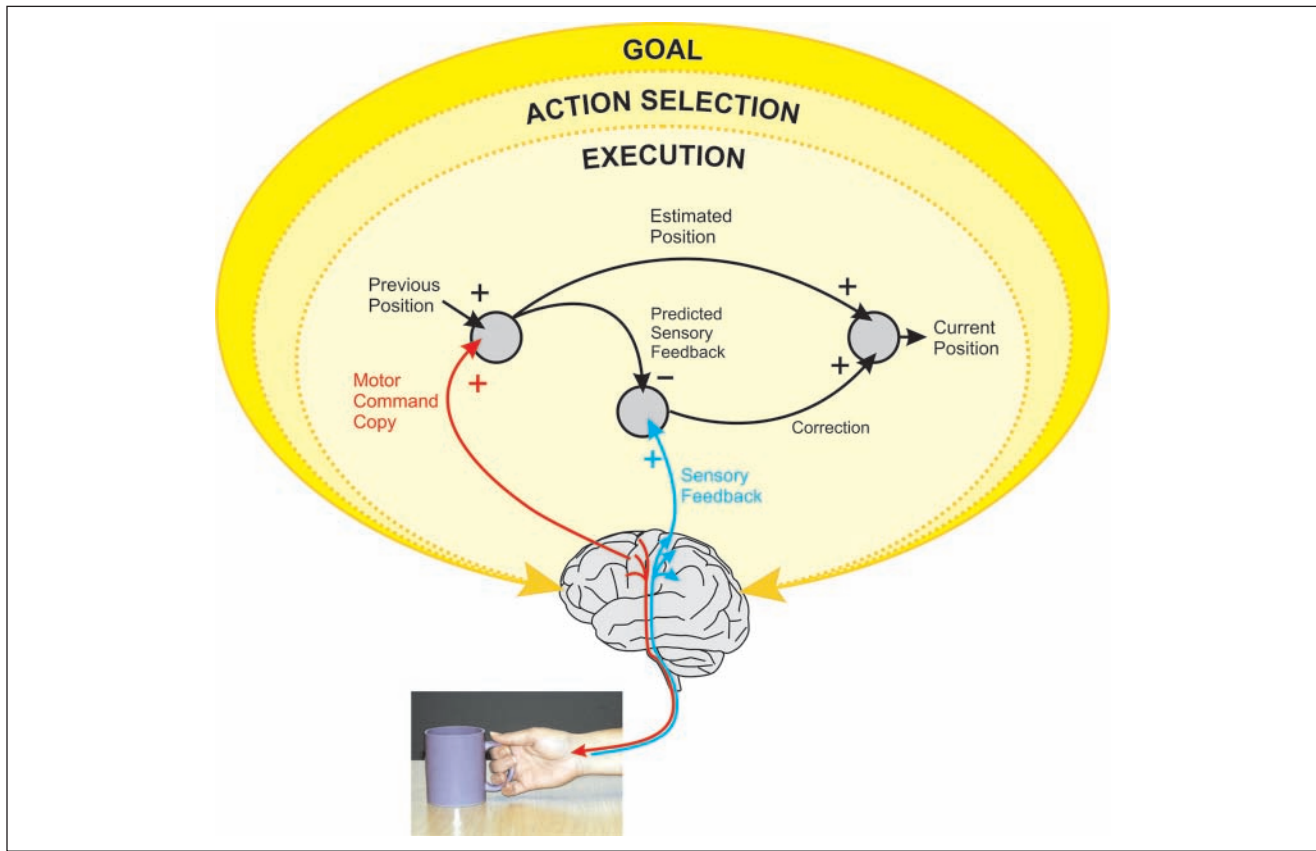


Figure 1. Schematic diagram of the feed-forward and feedback computational processes thought to be involved in the control of movement. This illustrates how feed-forward and feedback control might work together to produce efficient goal-directed movements of the hand. In this simplified model, we assume that the goal has already been established (get a drink) and that the actor has selected the general actions that will be used to achieve this goal (using the right hand to grasp the cup). The inverse model will then generate a motor command (red) based on a description of the goal and the estimated current position of the limb. This efferent command is sent on its way, and a copy serves as an input to the forward model along with the estimated previous position of the limb. The forward model predicts the sensory feedback that should accompany execution of the motor command and estimates changes in the limb's position across time. Of course, execution of the motor command gives rise to actual sensory feedback (blue), and this returning afferent signal is compared with the predictions of the forward model. The resulting error signal can then be used to refine the estimate of the limb's state, and the entire cycle can repeat.

As summarized above, the steps that lead from the motivation to drink to the motor commands to grasp the cup seem rather simple and intuitive. However, it is important to recognize that mechanical properties of the limbs and body introduce a very high level of complexity into this task. The musculoskeletal system possesses a very high degree of redundancy, which means that the number of combinations of joint angles and muscle contractions that can successfully bring the hand to a particular location in space is extremely large. Consequently, an enormous number of different movements can be used to achieve the very same end—that is, grasping the cup. Precisely how the nervous system selects the particular joint and muscle combinations to be used for a given action remain a mystery. Moreover, our system must also cope with relatively long conduction delays in neurons and large amounts of noise. As detailed below, feedback and feed-forward control

mechanisms appear to play important roles in coping with these challenges.

Feedback and Feed-Forward Control

What computational processes are used to generate the motor commands? Computational neuroscientists, robotics experts, and engineers distinguish between 2 general types of control—feedback and feed-forward—each with its own unique advantages and drawbacks. In feedback control, signals that carry information about the discrepancies (error) between the desired movement and the actual sensory consequences associated with its execution are used to generate subsequent motor commands. The performance of systems that rely exclusively on feedback is limited by delays in sensory and motor pathways, which in biological nervous systems can be as long as a few

hundred milliseconds. Although that may not sound like much, delays of this magnitude often approximate the duration of the movements themselves. The consequence is a system that develops large oscillations as it attempts to self-correct. We have all experienced this phenomenon when trying to control the water temperature of an unfamiliar shower located at some distance from the water heater based on perceived temperature alone. You first turn the shower faucet, but after some delay, the temperature is hotter than you wish. You then attempt to adjust the temperature by increasing the flow of cold water, but shortly, the temperature becomes colder than you wish. With some luck, you may be successful on the third trial, but 2 or 3 more iterations may be needed to achieve the perfect mixture. In other words, obtaining the goal will be relatively inefficient and time-consuming. The difficulty here is that the change in water temperature (the consequence) is delayed relative to the time at which your movements occurred. The same thing occurs in the nervous system where, as a result of the time needed for signal transmission, the sensory consequences are delayed relative to our movements. As a result, discrepancies can develop between our motor plans and the actual sensory consequences of our actions. Feed-forward control provides a potential solution to this dilemma.

In feed-forward control, motor commands are generated directly from the goal of the action (eg, grasping the cup) and other internal signals. To achieve a high level of accuracy, feed-forward controllers require learning from experience, just as you will (perhaps following somewhat jolting experiences) eventually learn to rotate the faucet to the exact position necessary to produce the ideal water temperature. Although feed-forward control does not suffer from the delay problem (because there is no need to wait for sensory information), a purely feed-forward approach does require 3 conditions: a perfectly learned controller, a static (ie, not changing) environment, and the absence of noise in the motor command. Because none of these conditions is ever realized in the real world of biological systems, movements resulting from a purely feed-forward motor command will differ from what was planned, and as a consequence, we may fail to grasp the desired cup. By combining both feed-forward and feedback control, however, the nervous system can overcome these challenges and generate a motor command that gets the job done. It is believed that the brain uses feed-forward control to produce fast movements in the face of long delays in neural transmission, whereas feedback control enables correction of these movements when they deviate from the intended goal. Figure 1 presents a schematic of how these 2 types of controllers might work together to control movements of the hand.

Internal Models

An important concept related to feed-forward control is that of the internal model.² Like models of other complex systems, internal models capture important features of the systems

that they mimic (eg, the muscle properties, biomechanics, and dynamics of the arm and hand). However, internal models are implemented in the brain. Feed-forward control relies on 2 flavors of internal models: forward and inverse. Given the motor command, the forward model predicts the sensory consequence of this command, in effect mimicking the movements of the body in parallel with actual movements. A dramatic example of error in a forward model is the weird feeling of lifting an object that we expect to be heavier than it actually is (eg, an empty soda can that is believed to be full). Because forward models are implemented within the brain (see section on functional neuroanatomy below), the sensory consequences of the movements are predicted in advance of the actual sensory feedback that accompanies movement. The reason for this is that actual sensory feedback experiences more significant delays in neural transmission from the peripheral nervous system and spinal cord. Outputs of the forward models, if they are well learned, can thus be used to alleviate the delay problem faced by feedback control. In Figure 1 the forward model is represented by the computations that start with a copy of the motor command and end with a prediction of the estimated position.

An inverse model can be conceptualized as an inverted forward model. Given the desired sensory consequence (grasping the cup), and the current state of the body and environment, the inverse internal model computes the motor command to be sent to the body. For movements to achieve the desired plan, the inverse model must faithfully capture the characteristics of the actual physical systems (muscle properties, arm dynamics, etc) it represents.

There are important clinical implications to the concept of internal models. Internal models must undergo experience-dependent change or learn to accommodate changes associated with alterations that accompany development, senescence, and injury. This ability to adjust, even in the adult brain, is exemplified by amputees who relearn to walk with a prosthetic leg in a matter of days. An even more striking example is the capacity to learn to control, by intention alone, a peripheral device (eg, a mouse). Indeed, some patients who lack the capacity for voluntary movements (eg, those with high-level spinal cord injury and amyotrophic lateral sclerosis), appear to retain motor planning functions. In some patients with stroke and motor deficits, internal models may be damaged but in theory can be relearned.

An interesting possibility to consider is that a well-learned forward model might be used in the mental rehearsal of movements or motor imagery. If you imagine reaching to grasp the cup without actually moving, it is possible that a motor command is generated but is only sent to activate the forward model and not the body. This would result in a prediction of the sensory feedback that would likely accompany the movement but in the complete absence of any actual feedback. Such mental rehearsal has been shown to activate some of the same brain areas as actual movements and may be useful therapeutically

in patients with limited mobility. However, because of the absence of an error signal, it remains uncertain how such activation can be used to tune the motor system. One ought always to consider the importance of sensory feedback in shaping actions and internal models because they provide the signal to update forward models. Accordingly, restoration of motor function is typically more complete in the case of pure motor deficits as compared with combined motor plus sensory deficits.

We conclude this section with a brief discussion of noise—variation in neural activity that is not carrying information about the task. Noise in the motor system is known, at least in part, to be signal dependent: that is, the greater the motor signal, the greater the noise. Therefore, the faster you reach for the cup, the greater the uncertainty in the final position of your hand. It has been proposed that the nervous system minimizes movement variability by generating smoothly varying motor commands; this reduces the need for brusque accelerations and decelerations in activity and minimizes the amplitude of the noise generated. The presence of noise in the motor command, however, contributes to the inaccuracy of purely feed-forward movements, and visual and proprioceptive feedback signals are often critical for correcting for these inevitable deviations.

Principles of Functional Anatomy

Having established a computational framework consisting of various processing components that are critical to upper-extremity control, we now turn our attention to what is currently known about how these functions are implemented in the brain.³ Despite the complex and distributed nature of the brain systems involved in upper-extremity functions, it is possible to distinguish several principles of functional organization within the cerebral cortex and in the descending pathways to the spinal cord that have direct relevance to understanding the effects of brain injury. Although there are many ways to slice the pie, we have identified 6 principles that we find are of particular relevance. Generalizations about the relationship between processes and brain anatomy always come at the cost of some details. However, they can be very helpful in capturing the larger organizing principles and are useful for interpreting clinical syndromes and planning treatment for functional restoration.

An important caveat is that most of the information we have about anatomical connections and the response of neurons in different circuitries comes from studies in nonhuman primates, but there is increasing evidence from functional neuroimaging that a similar organization exists in humans.

Principle I: Anatomical Gradients in the Parietal and Premotor Cortices

Anatomical connections are organized in the brain according to patterns or trends that relate to function. These patterns do

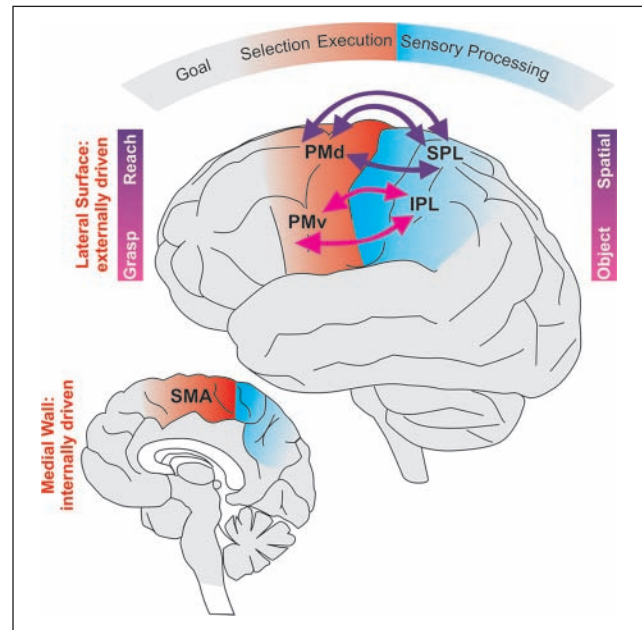


Figure 2. Parieto-premotor connections: 2 largely separate streams form extensive interconnections between the motor areas of the frontal lobe (red) and areas of the parietal lobe (blue). Arrows indicate parallel parietofrontal circuits. Regions of the superior parietal lobule (SPL) are interconnected with the dorsal premotor cortex (PMd). Areas in the inferior parietal lobule (IPL) are densely interconnected with the ventral premotor cortex (PMv). The premotor areas on the lateral surface of the brain tend to be more active for the planning of actions driven by external stimuli. Conversely, the premotor areas on the medial wall of the hemispheres like the supplementary motor area (SMA) are particularly involved in the planning of actions determined by internal drives.

not change abruptly between different regions but gradually. Three main organizational principles have been identified in the cortical areas involved in motor planning and control, and these have important functional implications for understanding the brain mechanisms of action.

From Goal to Action: Anterior-to-Posterior Gradient in the Frontal Lobe. The neural processes that are involved in moving from an action's intended goal (eg, grasping the cup) to generation of a motor command can be mapped onto an anatomical gradient running along the anterior–posterior axis of the frontal lobe (Figure 2). The goal emerges from motivational influences on the activity of associative areas in the prefrontal cortex located at the very front of the brain (gray). Prefrontal regions receive inputs from areas like the amygdala, hypothalamus, and the ventral striatum that code primary impulses like fear, hunger, and reward. Goals are translated into action selection, for example, reach for a cup to drink, and into more specific movement plans and execution for moving the arm and shaping the hand in the right posture. The premotor areas (red), located more posteriorly in the

frontal lobe, are pivotal for action selection and serve as the interface between the prefrontal and parietal (blue) association areas and the primary motor cortex.

One organizational principle is that the more abstract and time-removed processes (eg, action selection and planning) tend to involve more anterior areas of the frontal cortex, whereas increasingly more specific and immediate requirements for movement execution are represented more posteriorly in the frontal lobe. It is important to recognize that it is an oversimplification, however, to assume that the computations performed in the frontal lobe occur in a strictly serial (step-by-step) fashion as information moves along the anterior–posterior gradient. On the contrary, like most brain systems, the regions of the frontal lobe form a highly interconnected network, and this enables a parallel flow of information through the system. It might be helpful to think of the system less as a superhighway and more as the complex grid of city streets.

From Sensory to Motor and Back: Parallel Parieto-Frontal Circuits. A second organizational principle is the existence of parallel pathways that reciprocally interconnect distinct regions of the parietal and premotor cortices (see Figure 2). Earlier, we introduced the idea that our ability to prepare and control goal-directed actions depends on visual information about the external scene and somatosensory (and also often visual) information regarding the state of our body (Figure 1): Where is the cup in the environment, and how is this location related to the current state of the hand?

The posterior parietal areas are important for coding the location of the stimulus (eg, the cup) and forming an estimate of the body's state, for example, the relative position of the gaze, trunk, arm, and hand in relation to the stimulus prior to the movement. The right parietal cortex is particularly important for representing the spatial aspects of movements, whereas the left appears to be more heavily involved in planning familiar actions. Information from parietal areas flows into premotor regions in the frontal lobe where information about stimulus and body position is combined with goal representations. Put differently, parietofrontal circuits participate in the transformation of sensory information into motor commands (sensory-to-motor transformations). The parietal cortex is also critical for adjusting these estimates based on incoming information during the movement (sensory feedback; compare Figures 1 and 2).

Although it is often taught that sensory processing for action is accomplished in parietal areas and that motor signals originate in frontal regions, this is not correct. As illustrated in Figure 2, these regions are in fact reciprocally interconnected, and both frontal and parietal areas are endowed with motor and sensory properties. Because of this reciprocity, areas within parietofrontal circuits not only transform sensory input in the motor programs for specific goal-directed movements but are also directly involved in motor plan selection. Furthermore, as alluded to earlier, parietal regions are involved in calculating the sensory effects of an intended movement (motor-to-sensory

transformations). As shown in Figure 1, intended movements generate predicted sensory feedback, which is a key component of the forward plan. It is important to highlight that this basic computational, anatomical, and physiological architecture is replicated several times in different parietofrontal circuits, each specialized for a different body part and/or set of movements, as described in the following sections.

Superior parietal lobule to dorsal premotor cortex (SPL-PMd). Circuits connecting these regions of the cortex appear to be important for the control of goal-directed upper-limb movements on the basis of visual and/or proprioceptive feedback (Figure 2). In SPL, there are some areas (eg, PE) that are activated only by stimulation of the joints and skin, whereas other areas (eg, MIP, V6A) also receive input arising primarily from peripheral vision (ie, extrafoveal visual space). The former nonvisual processing areas are linked with a sector of the PMd involved in reaching movements, whereas the latter visual processing centers are connected with a different sector of PMd that contributes to both reaching and grasping movements. These latter regions monitor visual and somatosensory feedback to ensure that the trajectory of the arm and shape of the hand is appropriate for achieving the desired goal (eg, stably grasping the cup). If not, then this information is critical in specifying any corrective adjustments that might be necessary (see Figure 1). Patients with damage in this circuit may suffer from optic ataxia, a disturbance in which movements of the upper extremity are inaccurate when trying to make contact with visual objects (see accompanying chapter by Sathian et al).

Inferior parietal lobule to ventral premotor cortex (IPL-PMv). These regions of the brain are connected by at least 3 separate circuits. The first connects the ventral intraparietal areas (VIP) and a division of the PMv (known as PMvc or area F4). This circuit is involved in actions such as feeding or avoiding objects approaching the face. These actions involve objects in the environment or within our work space that eventually make contact with our body and that are coded both by visual and somatosensory information. The VIP is located in the depths of the intraparietal sulcus (IPS), a deep fold that separates the IPL and SPL (Figure 2). Neurons in VIP become active during tactile stimulation of different body parts, particularly the face. Some of them are bimodal (ie, they respond to both vision and touch) and increase their activity when moving visual objects come within reach. The interconnected PMvc (or F4) also contains bimodal neurons that respond to tactile stimulation of the face, arm, or body and to visual stimulation from objects introduced in the peripersonal space near the tactile receptive field (RF). Furthermore, in this area, there are neurons showing increased responses during the execution of reaching and approaching/avoidance movements directed toward objects.

A second circuit in the IPL transforms objects' visual features into appropriate grasping postures. If, for instance, you want to pick up the water cup by the rim when cleaning up the table, its visual attributes (shape, orientation, size, etc) are

transformed into a precision grip. However, visual features may be transformed into a power grip if your intention is to grasp a large water glass and take a drink. This visual-to-motor transformation is accomplished in a circuit connecting the anterior part of the IPS (AIP) and an area located in the rostral part of the PMv (known as F5 or PMvr). Neurons in both areas show increased activity when target objects (eg, the water cup) are grasped and manipulated. In some cases, this is true regardless of whether grasping involves the hands, mouth, or even a tool. That is, some of these neurons appear to be concerned with the act of grasping independent of the effector used. AIP also contains visual neurons that increase their activity when individuals observe graspable objects of specific sizes, shapes, or orientations. By contrast, PMvr (area F5) contains neurons that show selective changes in activity when performing specific types of grasps (eg, precision vs power). Patients with damage in this circuit have problems shaping their hands to grasp objects (see accompanying chapter by Sathian et al).

A third circuit links the IPL (area PFG) with areas PMvr (F5) and the cortical area 44. In the left hemisphere, this latter region may be the precursor of what in humans is classically defined as Broca's speech production center. Of considerable relevance to those working in rehabilitation is evidence indicating that the parietal node of this circuit receives visual information about motor acts performed by other individuals. There is a growing body of evidence that we may achieve an understanding of others' actions by matching them with our own internal motor representations (probably stored in the frontal node of this circuit). What is interesting is that this circuit shows increased activity not only when we observe others' actions but also when we attempt to imitate them. Because of these joint properties, such cells have been named *mirror neurons*. As discussed in Pomeroy et al in the third chapter, there have been some recent attempts to develop rehabilitative interventions based on the effects of action observation on motor system activity.

Internally Versus Externally Cued Movements: Medial-to-Lateral Gradient in Premotor Areas. A third gradient of functional organization can be defined along the medial-lateral dimension of the premotor areas (Figure 2). Premotor areas on the medial wall are particularly involved in the planning and generation of internally guided actions like imagining oneself playing a musical piece from memory. They also participate in initiating voluntary movements that are not driven by sensory stimuli such as walking, speaking, or pointing. Premotor areas on the lateral surface of the cerebral cortex are particularly active for actions made in response to sensory stimuli, like braking at a red traffic light, and object-oriented actions, like grasping a cup to get a drink (Figure 1). As with the anterior-posterior gradient, this functional distinction is also relative. It has nevertheless proven important to evaluate whether patients have more problems planning internally versus externally driven movements. Motivational syndromes (eg, abulia, akinetic mutism, or motor neglect) may be attributable to difficulties with more internally driven actions, whereas deficits of motor planning in response to

sensory stimuli (eg, optic ataxia) may reflect more a problem with externally driven actions. Rehabilitation protocols might be devised that tap into one or the other mechanism.

Principle II: Overlapping Synergies in the Primary Motor Cortex

Several principles of functional organization within the primary motor cortex are relevant to rehabilitation. Zones within the primary motor cortex that project to the spinal cord are organized topographically by body segments such as the hand, face, or foot—a feature called somatotopy (see Box 2). A less clearly differentiated somatotopic organization is also found in the premotor areas. The coarse segmental somatotopy of the primary motor cortex masks its fine-grained organization. Cells connected to motoneurons controlling a particular muscle are widely distributed within a patch of cortex representing that particular body part and intermingled with other cells influencing the activity of different muscles within the same segment (eg, the hand or face). This is an important difference with the primary sensory cortex where, for example, regions receiving inputs from individual digits can be identified within the hand map. Also, neurons in the primary motor cortex typically influence the activity of several muscles that may act at different joints. The activity of a single neuron in the primary motor cortex may produce a mixture of facilitation and suppression of the activity of its target muscles. This organization suggests that the primary motor cortex represents overlapping synergies (coordinated patterns) of muscle activations rather than individual muscles or movements. It is interesting to note that recent electrical stimulation studies of the motor cortex indicate that these muscle synergies are not random, but they resemble simple mini-actions (eg, grimacing or withdrawal) of naturalistic, more complex actions. This is directly relevant to understanding why rehabilitation strategies just based on training non-goal-directed movements may be less effective than training based on task-specific exercises. A further discussion of this point is found in Pomeroy et al in this issue.

The primary motor cortex makes the most direct and powerful connections with spinal motor neurons controlling the distal muscles of the hand. However, as will be discussed below (Principle V), in truth, multiple movement-related cortical areas project onto the spinal cord either directly or indirectly through the brainstem. Direct connections to motor neurons are essential for the fractionation of movements such as those seen in the independent keystrokes performed by a typist (see Case A in the accompanying chapter by Sathian et al). The primary motor cortex is particularly concerned with the precise patterning of muscle activity. It may achieve this patterning by selective recruitment and weighing of synergies. This also contributes to the fine control of force (eg, at the fingertips when grasping). Clinically, testing fine finger movements, especially those involving fractionation of movements at 1 joint, for example, wiggling the distal phalanx of your thumb, strongly relies on the primary motor cortex.

Box 2. Somatotopy in the motor cortex

The somatotopic organization of the motor cortex reflects the somatosensory input that a patch of cortex receives and the group of muscles that its output influences. At the macroscopic level, the primary motor cortex contains an orderly representation of body segments along the central fissure and precentral gyrus illustrated by Figure 3A. The lower extremity, the upper limb, and the face are represented in sequence from superior–medial to inferior–lateral regions. A similar arrangement is found in the postcentral somatosensory cortex. The body representation appears distorted because larger areas of the brain control the most dextrous (and sensitive) body parts like the fingers and mouth. Lesions affecting a small part of the primary motor cortex impair the function of the corresponding body segment but spare the function of other segments represented at distant sites. Like the primary motor cortex, all premotor areas are somatotopically organized to some degree. The somatotopic organization of the primary motor cortex appears more detailed than that of the premotor areas. This is partly a result of the large size of the primary motor cortex, which allows a better resolution of separate representations with exploratory techniques such as electrical stimulation. For example, a pulse stimulation at a site in the hand representation (yellow arrow) might cause a small deviation at the wrist (Figure 3B). More complex gestures can be evoked from longer trains of stimulation that activate a larger network. In the primary motor cortex, the topography of representations decays from the segmental level to that of its constitutive parts. For example, within the representation of the upper limb, regions of the cortex that control the musculature of the shoulder or elbow partially overlap with regions that control the wrist and fingers. This overlap is one reason why a cortical lesion rarely impairs the function of individual joints in isolation. At the level of small groups of cells or single neurons projecting to the spinal cord, it becomes apparent that the representation of individual muscles is diffused over a large expanse of cortex and intermixed with other muscle representations. In addition, cortical neurons projecting to the spinal cord typically influence the activity of multiple muscles sometimes acting at different joints. Thus, the coarse somatotopy masks the distributed and mosaic-like nature of the organization of the motor cortex that is present on a fine scale.

Principle III: Critical Role of the Cerebellum in Motor and Cognitive Predictions

While the cerebral cortex often grabs most of the attention, many critical aspects of movement control are performed by structures that are positioned below the cerebral hemispheres—hence

subcortical. There are several structures of which the most important are the cerebellum and the basal ganglia (BG).

A common circuit throughout the cerebellum. Let us first consider the cerebellum, or “small brain” in Latin, which contains about 50% of all neurons in the brain despite occupying only 10% of its volume. A first important, and rather surprising, fact is that despite the large number of cells, the cerebellum contains a very simple anatomical circuitry that is the same throughout its cortex. The cerebellum receives input from the spinal cord and the cerebral cortex via the mossy fibers that in turn project to numerous and tiny granule cells in the cerebellar cortex (Figure 4A). The axons of the granule cells (called parallel fibers because of their long T-shape parallel to the surface of the cerebellar cortex) in turn project to the Purkinje cells, the sole output cell out of the cerebellar cortex. The Purkinje cells, which inhibit the deep cerebellar neurons, also receive major inputs from the climbing fibers. The latter are the axons of a group of neurons within the brainstem nucleus called the inferior olive, a nucleus known to carry error signals in relation to the execution of movements. The deep cerebellar neurons do not project to the spinal cord directly but instead send large projections to the brainstem and to the cerebral cortex via the thalamus (Figure 5).

In summary the cerebellar cortex (Purkinje cells) is in the optimal position to compare different kinds of signals: signals from the cerebral cortex related to the planning of movement, feedback signals about limb position from the spinal cord, and error signals during movement execution. The output of the cerebellum in turn modulates the cerebral cortex and the brainstem. It is interesting to note that although traditionally the cerebellum is considered a structure for monitoring and correcting ongoing movements, a number of recent studies show that cerebellar neurons respond in anticipation of a movement rather than during execution as previously believed (see section of forward models). This fact has important implications for understanding its functions, as described below.

Another important fact is that the cerebellum is amenable to learning. Granule cell/Purkinje cell synapses are plastic and are modified when the parallel fiber inputs fire at approximately the same time as the climbing fiber inputs, that is, when the input from the cerebral cortex or spinal cord is synchronized with that from the inferior olive. The inferior olive is thought to tune the cerebellar output such that the movements become more accurate with practice (by virtue of more precise predictions) or are better adapted to new environmental conditions (such as the sudden introduction of a force field). It is likely that this mechanism may also be critical in adaptation to control of an upper extremity whose functions have been impaired by stroke or degenerative disease.

The functional-anatomical organization of the cerebellum. Despite regularity in its circuitry, it is important not to think of the cerebellum as a homogeneous structure. Different parts of the cerebellum through their input/output connections with different parts of the cerebral cortex contribute in different ways to brain functions. The phylogenetically oldest part of

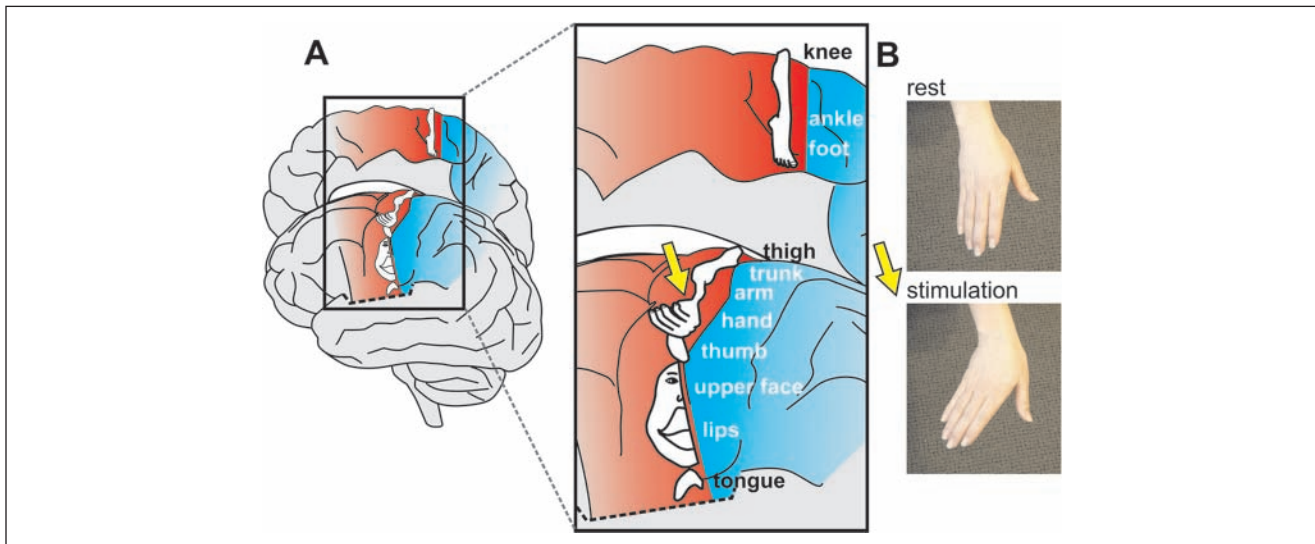


Figure 3. A schematic representation of the sensory homunculus; see Box 2.

the cerebellum is the vestibulocerebellum located anteriorly, just behind and lateral to the brainstem. This part is strongly connected with the vestibular nuclei, and it is important for balance and interactions between the eyes, head, and body. The spinocerebellum, so called because of its massive input from the spinal cord, involves the vermis, central and dorsal part of the cerebellum, and the intermediate cerebellum located between the vermis and the cerebellar hemispheres. This region contains maps of the body, is strongly connected with motor and premotor cortices, and is important for coordination of balance and gait as well as movements of the trunk and proximal limbs (Figure 4B). Phylogenetically, the most recent portion, the neocerebellum or lateral cerebellum, includes the cerebellar hemispheres. These have greatly expanded in primates in parallel with the development of the frontal, temporal, and parietal cortices, regions involved in sensory and cognitive functions. The neocerebellum is important for the coordination of hand movements (grip and manipulation) as well as of cognitive functions. Recent studies suggest a lateralization of function. Consistent with its preferential connections to the left hemisphere language regions, the right neocerebellum appears to be specialized for verbal selection and working memory, whereas the left neocerebellum (connected with the right cerebral hemisphere) may be more involved in spatial working memory and nonverbal reasoning.

Motor and cognitive function of the cerebellum: prediction and internal models. The role of the cerebellum in motor control is still not fully understood despite more than half a century of theories and experiments. The dominant idea has been that the cerebellum participates in motor feedback and error correction; however, more recent findings indicate that it is critically involved in the prediction of sensory consequences of motor commands, as discussed earlier (see Figure 1).⁴

The cerebellum presumably acts in concert with the parietal cortex where information about the state of the body (eg, trunk and limb positions) as well as information about spatial environment are stored. It appears to be ideally suited to acquire new, and adapt existing, internal models. Indeed, experimental evidence suggests that the cerebellum acquires both forward and inverse models. Lesions of the cerebellum prevent adaptation to environmental changes, probably because the internal models cannot be modified via the errors between intended and realized movements. For instance, patients with ataxia caused by cerebellar disease or profound loss of proprioception from large-fiber sensory neuropathy are unable to properly anticipate interaction torques—they cannot send predictive signals that correct for errors before they occur. Consequently, trajectories are curved, lack smoothness, and overshoot the target. Cerebellar patients also have trouble performing over-arm throws—they seem unable to coordinate opening of the hand and release of the ball at the right point along the arm's trajectory, which is required to make an accurate throw. In both reaching and throwing, the abnormalities arise because the patients do not seem to have the ability to anticipate forces acting at the joints and, therefore, how the limb position will change over time. These deficits in anticipation prevent cerebellar patients from learning novel actions. Multiple studies have shown that this is indeed the case: patients with cerebellar damage, either from stroke or neurodegenerative disease, are impaired in their ability to adapt to prisms, visuomotor rotations, and force fields.

In summary, the cerebellum provides predictive state estimates that allow feed-forward coordination between agonist and antagonist muscles and between limb segments in anticipation of the movement. This accounts for its early recruitment in the planning phase of a movement. Similar predictions are

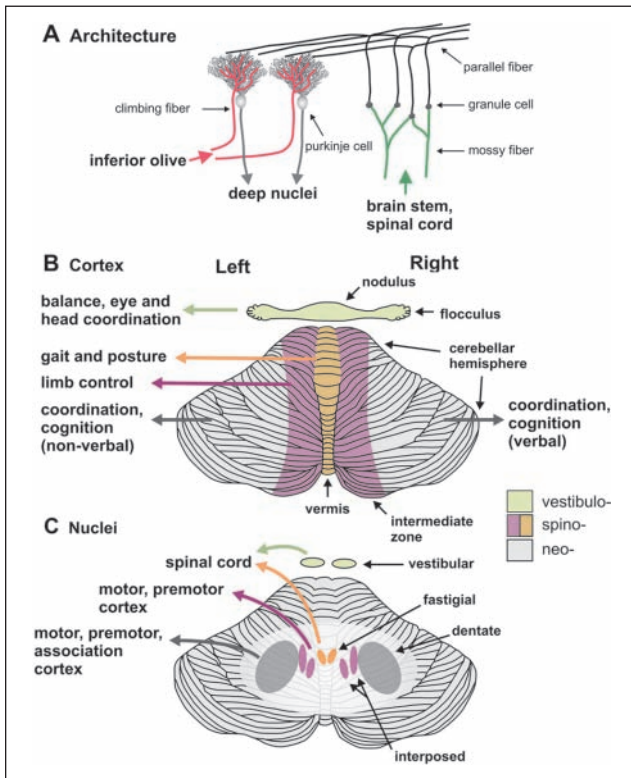


Figure 4. Anatomical and functional organization of the cerebellum: (A) The cellular architecture of the cerebellar cortex is uniform through the structure. Purkinje cells are the sole output of the cerebellar cortex and project to the deep nuclei. They receive input on their extensive arborization from a beam of parallel fibers from granule cells and a single climbing fiber from the inferior olive. Cortical and some spinal inputs are relayed by the brain stem nuclei that give rise to the mossy fibers. (B) The 3 functional divisions of the cerebellum correspond to 3 anatomical segments known as the vestibulocerebellum, the spinocerebellum (or paleocerebellum), and the neocerebellum. The vestibulocerebellum, located near the brain stem, is illustrated separately on top because it would be hidden from this point of view in its actual position. (C) Each segment of the cerebellar cortex projects to a specific nucleus buried deep within the cerebellum (see also Figure 5). Outputs from the deep nuclei influence the spinal apparatus and many cortical areas.

likely to occur in more cognitive functions such as verbal selection or nonverbal decisions that also require anticipation of sensory consequences.

**Principle IV: Basal Ganglia—
Movement Selection and Reward**

As illustrated in Figure 5, the BG are a set of nuclei located in the center of the brain adjacent to the thalamus. These nuclei receive inputs from a broad expanse of the frontal and parietal cortices, as discussed earlier, that extend beyond the classic motor areas.⁵ Within the BG, there is a complex

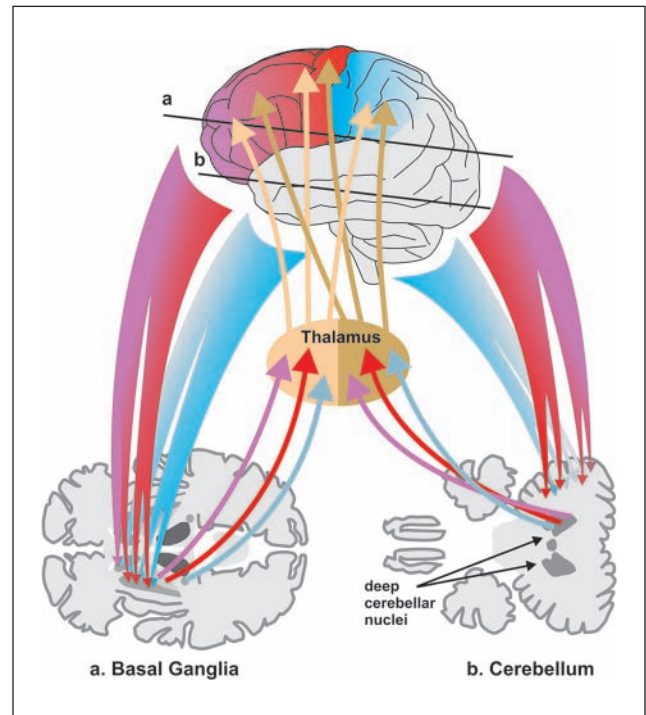


Figure 5. Corticostriate and corticocerebellar loops. Two subcortical structures, the basal ganglia (or striatum) and the cerebellum, participate in action control through multiple loops with the cortex. Cortical projections to the subcortical structures are illustrated on the bottom in transverse sections through the brain at the level of the basal ganglia (a) and cerebellum (b). Both structures receive massive inputs from wide areas of the cortex. Inputs from associative and sensorimotor areas terminate in partially segregated regions in the basal ganglia and cerebellum. Similarly, separate output streams from associative and sensorimotor territories of the basal ganglia and cerebellum are directed back to the originating areas in the frontal lobe with an intermediate synapse in the thalamus. Projections back to the parietal lobe are directed to only parts of the posterior parietal cortex, notably the inferior parietal lobule. Brain sections adapted with permission from the Talairach daemon (<http://www.talairach.org>, Lancaster JL, Woldorff MG, Parsons LM, et al. Automated Talairach atlas labels for functional brain mapping. *Hum Brain Mapp.* 2000;10:120-131).

network of excitatory and inhibitory pathways that modulate information propagation. The main output nucleus sends inhibitory projections to the thalamus. The thalamus in turn sends excitatory projections back to the cortex. This inhibitory output to the thalamus has been used to explain some of the motor features observed in certain movement disorders. Hypokinetic movement disorders, such as Parkinson’s disease, are caused in part by excessive BG output, leading to inhibition of the thalamus and a lack of cortical recruitment to initiate or appropriately scale movements. In contrast, hyperkinetic movement disorders such as Huntington’s chorea or drug-induced dyskinesias are caused by a loss of

BG output, a lack of thalamic inhibition, and the release of cortically derived movements.

An important organizational principle is the existence of segregated BG-cortical loops through the BG (Figure 5). For example, a projection into the BG from the prefrontal cortex will stay segregated from a projection arising in the premotor cortex. This segregation will persist through the thalamus and back to the originating cortex. This anatomical pattern suggests that the BG are not designed for mixing information between different cortical areas. Instead, the anatomy suggests that the BG are involved in modifying local areas of the cortex. Within the premotor and motor cortex loops of the BG, there is strong evidence that the network is necessary for the scaling of force, amplitude, and acceleration of both simple and complex movements. Abnormalities in these loops help explain the bradykinesia observed in Parkinson's disease.

In sum, there are several cortico-BG loops (motor, oculomotor, executive, and motivational), each involving different regions in the prefrontal cortex and segregated regions in the BG. This explains why lesions in the BG can give rise to cortical deficits such as aphasia, neglect, and akinetic mutism.

A second essential role of the BG is in reward-mediated learning. The BG have the highest density of dopamine-containing neurons in the brain. These neurons fire in anticipation of an upcoming reward. Pathology of reward circuits can lead to increased reward-seeking behavior, as in drug addiction. Reward circuits may also be needed for normal skill learning as well as motor recovery after brain injury. Finally, harkening back to our discussion of computational principles, it has been proposed that the BG are needed for automatically selecting one motor program from among many possible alternatives. An example would include choosing among all the actions taken in the morning prior to work that are given no thought, such as dressing, brushing, eating, and so on. An important caveat is that there is little evidence that motor skills such as dressing, brushing, or eating are actually "stored" in the BG. Rather, the BG may be used to release these behaviors given the proper environmental cues. There is also evidence that the BG interact with the prefrontal cortex for the selection of novel, not habitual, actions.

Principle V: Parallel Pathways From the Cortex to the Spinal Cord—Alternative Routes for Motor Commands

Having discussed both cortical and subcortical contributions to upper-extremity functions, we are now in a position to consider the variety of ways in which motor commands reach the body.

Multiple cortical areas output to the cord. An important, and often overlooked, fact is that the corticospinal tract, the main output pathway from the cortex, is not limited to descending fibers from the primary motor cortex but includes a number

of parallel pathways to the brainstem and spinal cord that originate in premotor and even parietal cortices.⁶ As we will see, this has important implications for the prognosis and treatment of patients with motor deficits. The large majority of projections to the spinal cord come from the frontal lobe (80%). These include, but are not limited to, projections from the primary motor cortex (Figure 6A). In fact, when considered together, 6 premotor areas actually make a larger contribution (60%) to the corticospinal projections from the frontal lobe than the primary motor cortex (40%). The rest of the corticospinal system originates from the SPL (20%). All considered, a substantial chunk of the cerebral cortex has the capacity to influence muscle activity through direct input into the spinal machinery (a topic discussed in detail shortly).

As reviewed earlier, outputs from the primary motor cortex are involved in the control of the distal musculature of the hand, whereas outputs from the superior parietal cortex and some premotor areas are more involved in guiding limb movements in space (kinematics). Still other descending pathways (eg, from the brainstem) are more involved in the maintenance of posture and whole-limb movements.

The multiple descending pathways from the brain convey largely parallel signals that shape the activity of spinal networks for movement generation and control. Some signals establish the functional set in anticipation of movement execution; that is, they prepare the appropriate segmental networks in the spinal cord for the upcoming job. Other signals regulate the activity of axial and proximal muscles for postural support and appropriate limb positioning, and still other signals trigger the sequence of muscle activity to accomplish the goal.

Descending signals and aspects of motor performance may be disrupted by either cortical lesions that interfere with specific computations (see case B in the chapter by Sathian et al), or by white matter lesions that block the results of these computations from reaching the spinal cord (see case A in Sathian et al). White matter fibers coming from the cortex (the corona radiata) bundle together near the middle of the brain to form the internal capsule (Figure 6B) and continue on to the spinal cord. Interruption of these long fiber tracts deprives the spinal cord of its normal cortical input (see case A). Functional recovery after a cortical or fiber tract lesion often involves a shift in the balance of function to intact motor areas of the same or opposite hemisphere that retain access to the spinal cord. The 2 hemispheres are heavily interconnected, and each has a small number of fibers (10%) that reach the spinal cord on the same side of the body (ie, uncrossed pathways). As a result, motor areas in the right hemisphere can influence the activity of muscles on the right side of the body that have lost their dominant input from the left hemisphere, for example. Another route is through connections to brainstem regions that in turn connect to the spinal cord.

Brainstem–spinal pathways: additional routes from the brain to the spinal cord. Though often overlooked, the organization of pathways that project from the brainstem to the spinal cord

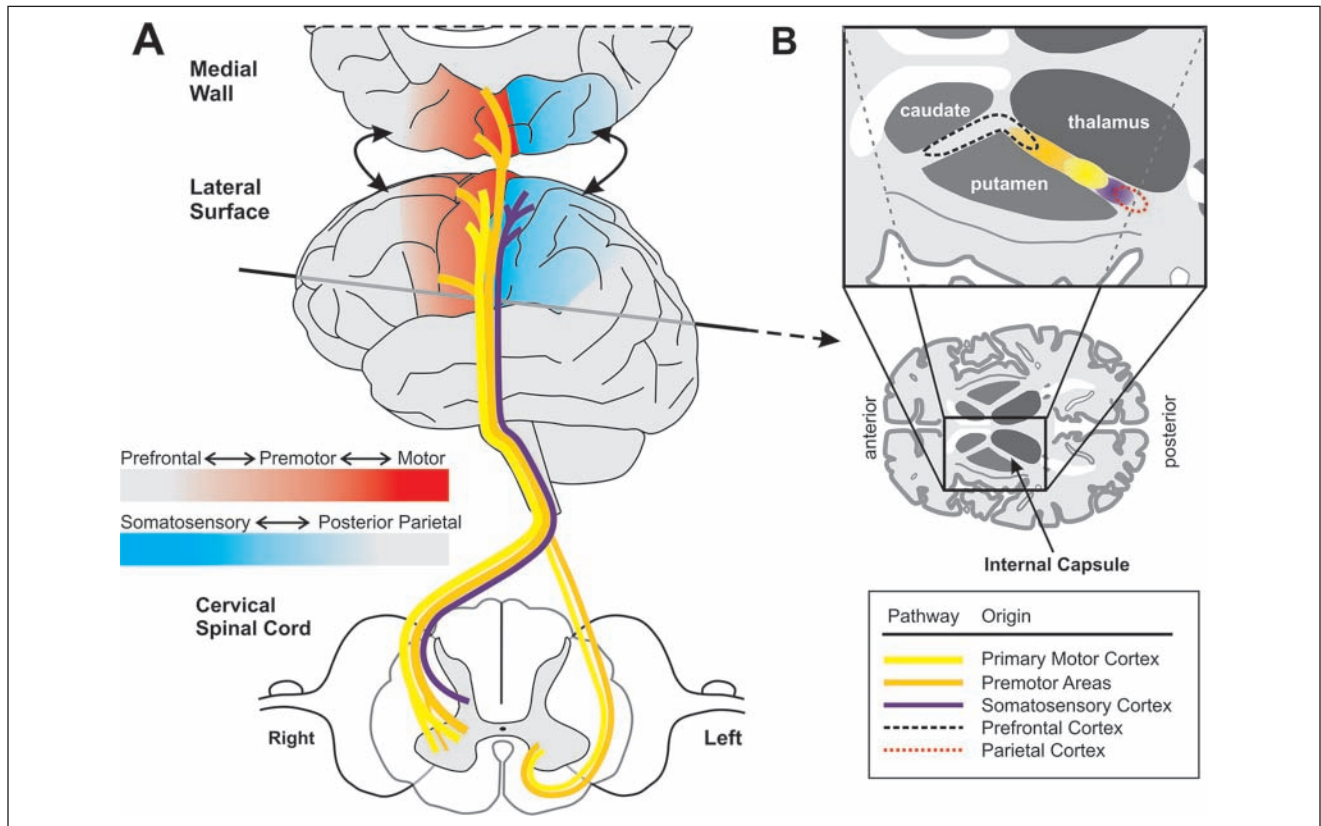


Figure 6. Descending pathways to the spinal cord: (A) Large portions of the frontal and parietal lobes contribute to the corticospinal system. In addition, several pathways to the spinal cord originate from brainstem nuclei. All pathways can influence muscle activity by acting on the rich network of spinal interneurons. Fibers from the primary motor cortex and premotor areas terminate in or near the ventral horn on the opposite side of the body. This pathway controls the activity of limb muscles by activating motoneurons directly or through local interneurons. A small contingent of fibers innervates the ventral horn on the same side of the body. This pathway is primarily involved in the control of proximal muscles. Fibers originating from the parietal cortex terminate mainly in the dorsal horn of the spinal cord. These fibers can influence muscle activity only through spinal interneurons. (B) Descending fibers from the cortex form the internal capsule on their way to the spinal cord or other lower brain structures. The anterior limb of the internal capsule arises from anterior parts of the frontal lobe (prefrontal cortex). Fibers originating from the premotor areas, the primary motor cortex and parietal regions occupy successively more posterior locations (with partial overlap) in the posterior limb of the internal capsule. Because of this arrangement, lesions affecting parts of the internal capsule may block descending influences from particular cortical areas and may have differential effects on motor and cognitive functions. Brain section adapted with permission from the Talairach daemon (<http://www.talairach.org>, Lancaster JL, Woldorff MG, Parsons LM, et al. Automated Talairach atlas labels for functional brain mapping. *Hum Brain Mapp.* 2000;10:120-131).

has important implications for recovery of functions following brain injury. Notably, these pathways provide additional avenues for a diversity of regions within the contralesional and ipsilesional hemispheres to influence movements of the affected upper extremity.

Several motor pathways originate in the brainstem and project to the spinal cord (Figure 7). The largest of these are the reticulospinal tracts (RSTs) that arise from cells in the pons and medulla. The axons of the latter lie close to the corticospinal tract in the lateral columns of the spinal cord, whereas axons from the pons run in the ventromedial portion of the cord. Their terminations are mainly onto interneurons in the spinal gray matter, which then activate spinal motor neurons; however, direct monosynaptic inputs to motor

neurons also exist. There are extensive inputs to the RSTs from wide areas of the cerebral cortex, including the primary and all premotor areas of the cortex, many of which are branches from corticospinal axons that traverse this region on their way to the spinal cord. Other inputs come from spinal afferents and from the fastigial nucleus of the cerebellum.

It is important to note that reticulospinal neurons are thought to receive input from both hemispheres; they then project ipsilaterally or bilaterally to the spinal cord. This organization, which is quite different from the predominantly crossed corticospinal projection, has an important implication for functional recovery. Specifically, it means that after a hemispheric stroke, the nonstroke hemisphere has intact projections to both sides of the spinal cord via the RST and hence

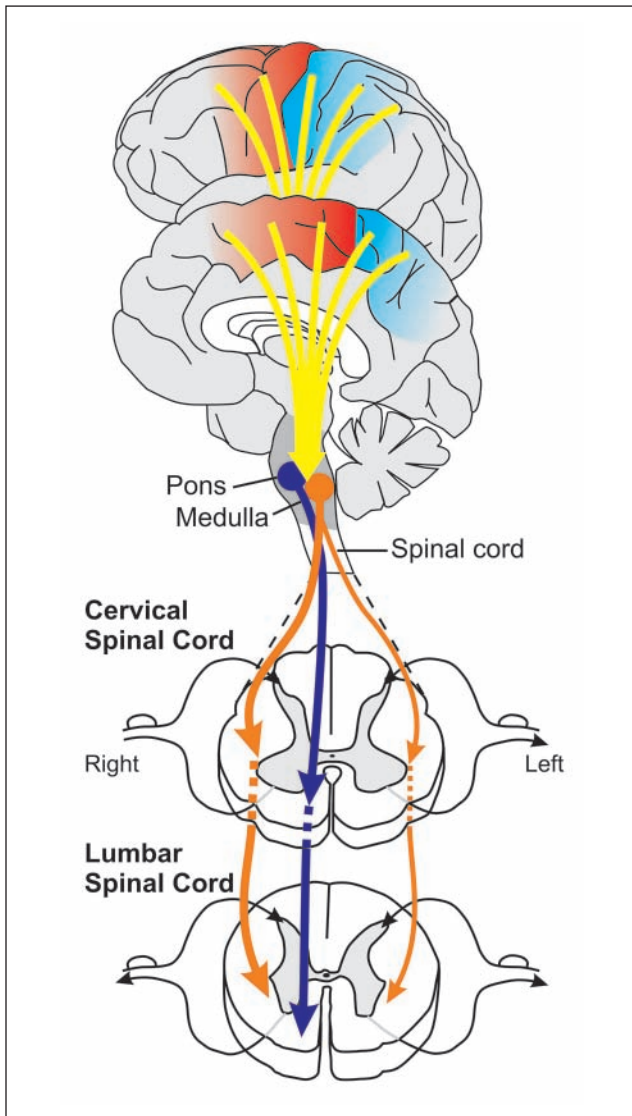


Figure 7. The reticulospinal tract: large regions of the cortex project to groups of nuclei in the brain stem where several pathways to the spinal cord originate. The reticulospinal tract is composed of the pontine (blue) and medullary (orange) divisions, which originate from nuclei located in the pons and medulla, respectively. The reticulospinal tract differs from the corticospinal tract (see Figure 6) in the larger cortical territory that contributes to it and the course and termination of fibers in the spinal cord.

has the potential to contribute to recovery of movement in the paretic side. In addition, the area of the cortex that supplies the RST is larger than the region of origin of the corticospinal tract (see discussion above), so that strokes that may totally interrupt the hemispheric output to the CST do not interrupt all descending input to the spinal cord from the stroke hemisphere. In many species, the rubrospinal tract is another important pathway to the spinal cord and receives a

strong input from sensorimotor areas of the cortex. However, in humans, it is thought that the rubrospinal tract is very small and that its function has been taken over by the enlarged corticospinal tract.

To get an idea of the functional contribution to movement provided by the reticulospinal systems, Lawrence and Kuypers made bilateral lesions of the corticospinal tract in monkeys. After a period of recovery, the monkeys showed remarkably normal motor behavior. The animals could feed, play with littermates, and climb the bars of their cages with little difficulty. The only problems came in performing independent finger movements such as the pinch grip. An additional lesion in the rubrospinal tract showed that there was a further impairment in hand grip, but the monkeys could still climb the bars of their cage, walk, feed, and maintain balance with no difficulty. The implication is that all these functions were maintained via activity in the RSTs. Indeed, animals in which the RSTs were sectioned fared very poorly; they could not maintain balance or feed and had to be cared for daily by staff. These experiments indicate the potential role of the activity of RSTs in isolation.

In the intact human, it is thought that the descending tracts cooperate in virtually all movements. Consider again our example of reaching for the water cup. In this scenario, the RST output provides a level of background activity on which is superimposed detailed patterning of the CST projection, enabling individuated use of the fingers in coordination with the rest of the upper limb. Experiments in cats suggest an important role of the RST in gait, and recordings of RST activity in monkeys suggest an important role in reaching movements.

Principle VI: The Complex Roles of the Spinal Cord—Shaping the Consequences of the Motor Command

Although some descending commands from the CST have monosynaptic connections with (particularly) distal hand motor neurons, the majority of both CST and RST projections synapse on the interneurons of the intermediate zone of the spinal gray matter. It is critical to appreciate that the spinal gray matter is not a passive conduit for cortical inputs to reach motor neurons; it is a complex piece of computational circuitry where descending commands interact with sensory reflex pathways before producing movement.⁷ Essentially, the descending inputs can set the excitability of reflex pathways and modulate their effectiveness during different types of movement. In turn, the reflex inputs can modulate the descending motor commands to muscle.

The final processing of the motor command occurs at the motor neurons themselves. Although often thought of as summing synaptic inputs to reach a firing threshold, these neurons have several active membrane properties that allow them to adjust the “gain” of the input–output relation. Plateau

potentials have been described in cat motor neurons that are caused by the activation of persistent inward Na^+ and Ca^{2+} currents. They are activated when the neuron is depolarized beyond a certain potential. Their effect is to maintain the depolarization even when the original driving input is no longer present. In this way, they can effectively amplify the action of synaptic inputs and produce sustained firing of motor neurons in the absence of large inputs.

Reflex pathways. Descriptions of reflex pathways can be found in many textbooks. Here, it is interesting to ask how much of the excitatory drive during muscle contraction is provided by reflex inputs versus descending signals from the cortex. Experiments with peripheral anesthesia suggest that in leg muscles, about 30% to 40% of the force output during a volitional contraction is supported by reflex inputs. This means that without reflex support, maximum voluntary strength is reduced by 40%; conversely, a good deal more descending drive is needed to start off a contraction in the first place. Not all this support need necessarily occur through sensory interactions at the spinal cord, although in simple tests of muscle strength, this is thought to be the case. Reduced sensory input to the brain may also contribute.

The converse question is what happens to spinal circuitry when deprived of supraspinal motor input, as in the case of cortical or subcortical stroke or high-level spinal cord injury? With a complete spinal transection, there is a sudden loss of all descending excitation to the spinal circuits, and they become unable to respond to any sensory inputs with a reflex output (spinal shock). However, over time, there are adjustments in the excitability of neural circuits that gradually raise excitability so that responses can occur again, although no longer under the control of central commands. One factor that might contribute to the gradual adaptation to loss of descending drive is an increase in the role of plateau potentials; indeed, by increasing motor neuronal excitability, they may contribute to muscle spasms that can often be easily triggered in spinal cord patients.

Conclusions

The CAP model described in this chapter highlights the main computational, physiological, and anatomical principles that we can use to think about movement in the healthy brain and in patients with movement deficits secondary to brain injuries. It is important to have in mind a few key simplifying principles. The goal or desire of moving originates in the more anterior part of the frontal (or prefrontal) cortex from signals that relate to internal states (hunger, thirst, fear, motivation, memory, etc). This initial goal is transformed into an intention to move one or more body parts. We know that signals related to the intention or motor plan are maintained in specific circuits—some for moving the eyes and others for moving the head or the arm—that involve premotor and posterior parietal cortices. Accordingly, damage to anterior (and medial)

prefrontal regions impair the goal, giving rise to problems with initiation such as abulia, whereas lesions in the premotor and posterior parietal cortices give rise to problems with intention and motor plans, or apraxias.

Movements are furthermore context dependent, and different regions are recruited depending on whether the movement is guided by sensory information, as when reaching for an object, and/or by internal information, as when we “search” for food when hungry. Most movements involve both sensory and internally driven plans. As we get closer to the actual execution of the movement, motor plans code the actual combination of body parts to be moved. For example, in the motor cortex, moving the hand activates a different subregion of the motor cortex than that activated while speaking or walking. This segregation of body parts in the cortex, or somatotopy, is present not only in the primary motor cortex but also in other parts of the cortex, the cerebellum, and in the organization of descending fibers to the spinal cord. Notably, not all descending motor fibers come from the primary motor cortex. Other premotor and parietal regions directly project to the spinal cord and brainstem.

Whereas the traditional view is that the motor cortex generates the commands to activate the spinal cord and that signals from the spinal cord are relayed back to the cortex to control the movement (feedback), an important and novel concept is that motor control involves both feedback and feed-forward control. Parallel to the generation of the descending motor signal, a copy (like a backup on your computer) travels to sensory regions “anticipating” where the body part will be at the end of the movement. This “forward model” is important to accommodate sensory changes induced by the movement itself. For example, in the absence of a forward model of an intended eye movement, our retinal image would appear to jump every time we move the eyes. Instead, this mechanism allows rapid calculation of the retinal displacement produced by the movement and enables us to accommodate for it. Forward models are also essential for smooth movements and fill the time before feedback sensory signals from the peripheral receptors activated by the movement itself (cutaneous, joint, and tendons) return to the cortex. When the forward model is broken, as in the case of cerebellar injuries, movements are very irregular (ataxic) because they primarily depend on the sensory feedback.

Another important aspect of movement is the association with reward and habits. Useful actions tend to be more common and are carried out more automatically. In contrast, novel tasks require more control and need to be reinforced to become habitual. The BG are important for integrating reward with action and also for shifting from one action to another. Lesions in the BG lead to rigidity both in movement and cognition. Finally, although we think of the cortex as the structure generating all the movements, in reality, many postures and movements are controlled unconsciously by the brainstem and the

spinal cord via sensorimotor reflexes. The brainstem and spinal cord are sophisticated devices that hold our body upright, maintain common postures in our limb segments, and allow us to walk. They also determine the level of excitability of our muscles through the interaction with the cortex.

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