

Voluntary Movement

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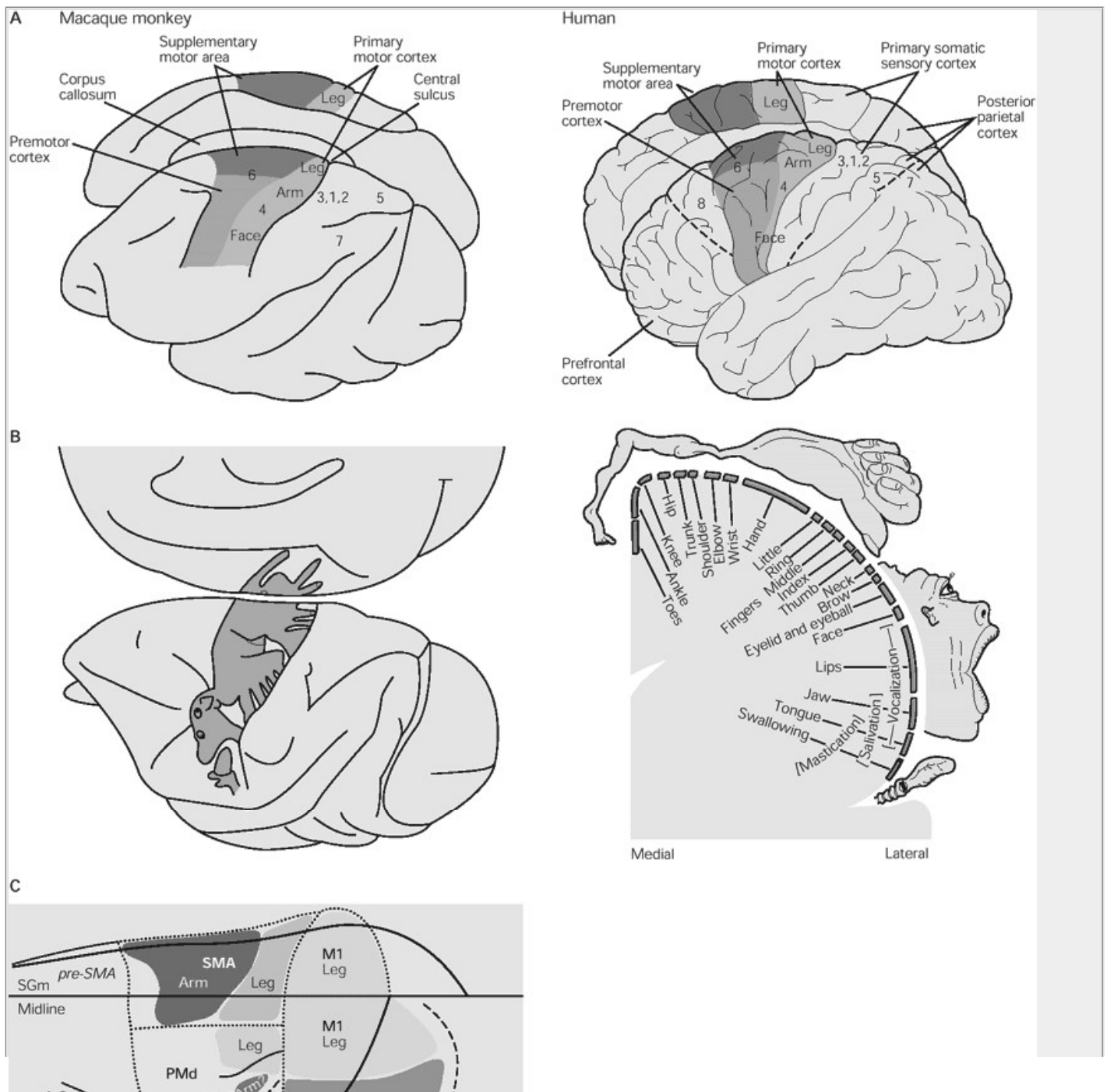
Claude Ghez

IN PREVIOUS CHAPTERS WE saw how spinal and brain stem circuits can organize elementary movement patterns in response to somatosensory, vestibular, and other stimuli. However such reflex actions are relatively stereotyped and the repertory of movements is limited. In this chapter we shall see how the motor areas of the cerebral cortex integrate visual, proprioceptive, and other information to produce the more elaborate voluntary movements that require planning.

Voluntary movements differ from reflexes in several important ways. First, voluntary movements are organized around the performance of a purposeful task. Thus the selection of which joints and body segments will be used for a movement depends on the goal of the movement, whether it is designed to reach for and lift a glass of water or to return a tennis serve. In contrast to the stereotyped relation between response and stimulus, characteristic of reflexes, voluntary movements vary in response to the same stimulus depending on the behavioral task. Second, the effectiveness of voluntary movements improves with experience and learning. Finally, unlike reflexes, voluntary movements are not mere responses to environmental stimuli but can be generated internally. The higher levels of our motor systems can therefore dissociate two aspects of a stimulus—its informational content and its capacity to trigger a movement. In the cortex the informational content of a stimulus signals where to move or what to do, but the occurrence of the stimulus may or may not actually initiate the appropriate movement. In reflexes these aspects of the stimulus are linked.

The motor areas of the cerebral cortex are subdivided into a primary motor area and several premotor areas. Each area contains populations of neurons that project from the cortex to the brain stem and spinal cord.

In this chapter we first describe the organization of the motor areas of the cerebral cortex, showing how they communicate with each other and with primary sensory and association areas. We then examine how these different motor areas control simple and complex aspects of movement.



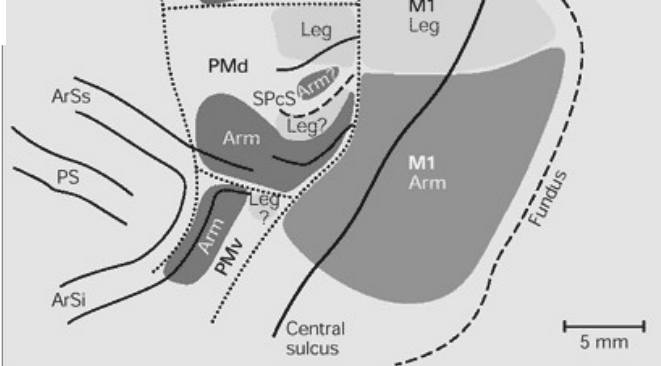


Figure 38-1 Motor cortical areas are organized somato-topically.

A. Brodmann's cytoarchitectural areas in monkeys and humans.

B. Comparison of the somatotopic organization of the primary motor cortex in monkeys and humans. The sequence of representation of body parts is similar. The ankle control area is medial while the face, mouth, and mastication control areas are lateral. The face and fingers in the human motor cortex have much larger representations because of the greater degree of cortical control of these areas. (Left: from Woolsey 1958; right: adapted from Penfield and Rasmussen 1950.)

C. Somatotopic organization of the medial and lateral motor cortex in the monkey, showing the arm and leg representations. (**ArSi**, arcuate sulcus, inferior limb; **ArSs** = arcuate sulcus, superior limb; **CS** = central sulcus; **M1** = primary motor cortex; **PMd** = dorsal premotor area; **PMv** = ventral premotor area; **PS** = precentral sulcus; **SGm** = superior frontal gyrus, medial wall; **SMA** = supplementary motor area; **pre-SMA** = presupplementary motor area; **SPcS** = superior precentral sulcus.) (From Dum and Strick 1996.)

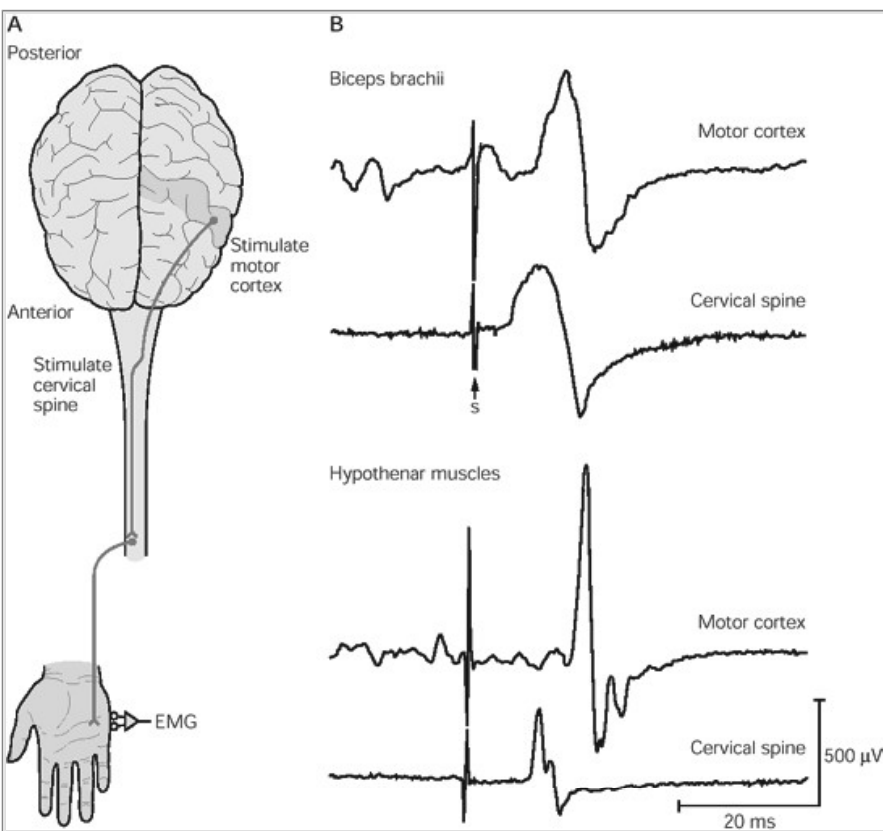


Figure 38-2 The motor cortex can be stimulated directly in awake humans.

A. Magnetic stimulation of the motor cortex or cervical spine produces muscle contraction painlessly. Stimulation of the motor cortex activates the corticospinal fibers and produces a short-latency electromyographic (EMG) response in contralateral muscles.

B. The traces show activation of arm and hand muscles (biceps brachii and hypothenar) when stimulation is applied over the cortex or the cervical spine. The peaks occur earlier from cervical stimulation because the corticospinal impulse has less distance to travel. The point marked **s** is a stimulus artifact, reflecting the application of the magnetic field pulse. (From Rothwell 1994.)

Voluntary Movement Is Organized in the Cortex

The Primary Motor Cortex Controls Simple Features of Movement

The discovery in 1870 that electrical stimulation of different parts of the frontal lobe produces movements of muscles on the opposite side of the body had a major impact on neurological thinking. In the early twentieth century electrical stimulation was used to identify the specific motor effects of discrete sites in the frontal lobe in different species—including primates and humans—and the resulting *motor maps* were correlated with anatomical and clinical observations on the effects of local lesions. The contralateral precentral gyrus (Brodmann's area 4), the region now called the *primary motor cortex*, proved to be the area in which the lowest-intensity stimulation elicited movements. At low intensities the effects of stimuli can be attributed to the activation of neurons near the electrode that are connected to the spinal cord either directly or via only a small number of synapses.

The motor maps produced by these experiments show an orderly arrangement along the gyrus of control areas for the face, digits, hand, arm, trunk, leg, and foot. However, the fingers, hands, and face—which are used in tasks requiring the greatest precision and finest control—have disproportionately large representations in the motor areas of cortex (Figure 38-1), much as the inputs from regions of the body that have important roles in perception predominate in the sensory areas of the cortex. Consistent with the overall somatotopic organization, lesions in arm representation lead to degeneration of myelinated fibers in the cervical cord, while lesions in the leg representation produced degeneration extending all the way to the lumbar spinal cord. These axons arise from specialized large pyramidal neurons in lamina V

named Betz cells after their discoverer.

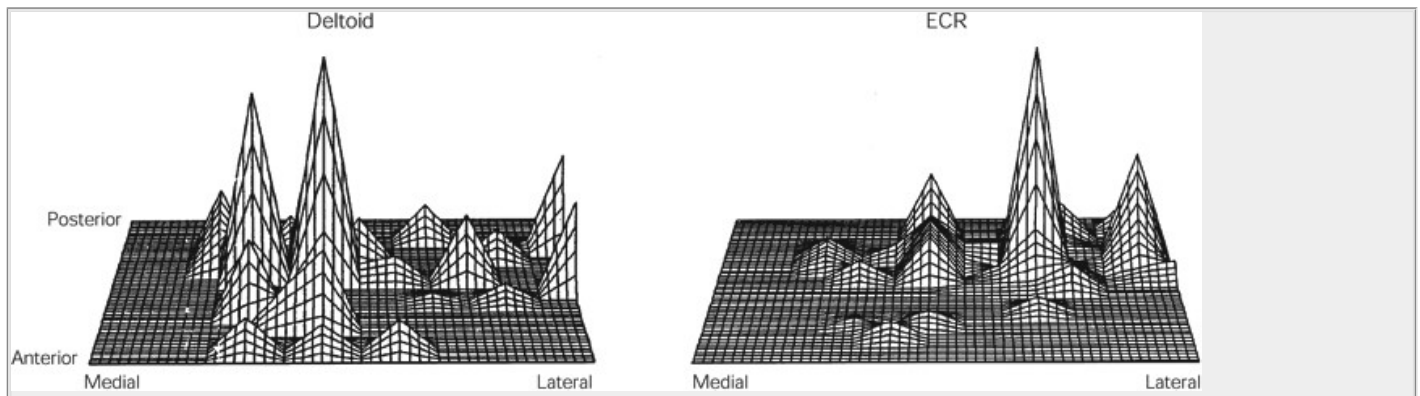


Figure 38-3 Sites controlling an individual muscle are not located together but are distributed over a wide area of motor cortex. Intracortical microstimulation was used to identify sites in monkey primary motor cortex at which low-threshold stimulation evoked electromyographic activity (indicating monosynaptic connections) in a shoulder abduction muscle (middle head of deltoid muscle) and a wrist extensor muscle (extensor carpi radialis; **ECR**). Topographic maps of the identified sites, reveal overlap between shoulder and wrist representations. The maps were constructed based on the inverse of the threshold ($1/\text{threshold}$) in microamperes, with the peaks representing approximately $1/3 \mu\text{A}$ and the valleys $1/40 \mu\text{A}$. (From Humphrey DR, Tanji J. 1991. In: DR Humphrey, HJ Freund (eds.), *Motor Control: Concepts and Issues*, pp 413-443. New York: Wiley.)

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The results of animal experiments done in the early 1900s helped explain the clinical signs in patients produced by traumatic, vascular, and other forms of local damage to the contralateral frontal lobe. They also explained focal epilepsy, which can develop as a result of traumatic injury or tumors. The abrupt rhythmic flexion-extension movements seen in focal seizures resemble the movements produced by electrical stimulation of the primary motor cortex. Indeed, in the nineteenth century, before electroencephalographic recordings were available, John Hughlings Jackson had already pro-posed that seizure activity resulted from paroxysmal increases in local neuronal activity in a limited area of cerebral cortex that corresponds to the primary motor cortex. Focal seizures often start in the fingers and spread proximally down the limb as the focus of discharges spreads from the hand area to adjacent sites controlling more proximal muscles. Clinically this is known as the *Jacksonian march*.

In the past decade it has become possible to stimulate motor cortical areas in alert humans by inducing electrical fields in the brain using rapidly alternating magnetic fields produced by wire coils applied to the scalp. The responses in muscles (eg, of the hand) are recorded with surface electrodes. The motor action potentials are large and have a short latency, consistent with the fact that they are conducted by corticospinal fibers (Figure 38-2). Magnetic stimulation can be used to map the body representation in the primary motor cortex or to perturb processing in other cortical motor areas.

The early mapping experiments stimulating the cortical surface electrically (and more recently magnetically) initially led to the simplistic idea that the primary motor cortex acts as a massive switchboard with a switch controlling individual muscles or small groups of adjacent muscles. More detailed studies, however, using microelectrodes inserted into the depths of the cortex (intracortical microstimulation or ICMS) to stimulate small groups of output neurons indicate that this simple view is incorrect. Whereas the weakest stimuli may evoke the contraction of individual muscles, the same muscles are invariably activated from several separate sites as well, indicating that neurons in several cortical sites project axons to the same target (Figure 38-3).

In addition, most stimuli activate several muscles, with muscles rarely being activated individually. This is corroborated by recent anatomical and physiological experiments showing that the terminal distributions of individual corticospinal axons diverge to motor neurons innervating more than one muscle. Instead of a simple switchboard of muscle representations, detailed maps of monkey motor cortex suggest a concentric organization: sites influencing distal muscles are contained at the center of a wider area containing sites that also influence more proximal muscles, while sites in the peripheral ring around this central area influence proximal muscles alone. An implication of this redundancy in muscle representation is that inputs to motor cortex from other cortical areas can combine proximal and distal muscles in different ways in different tasks.

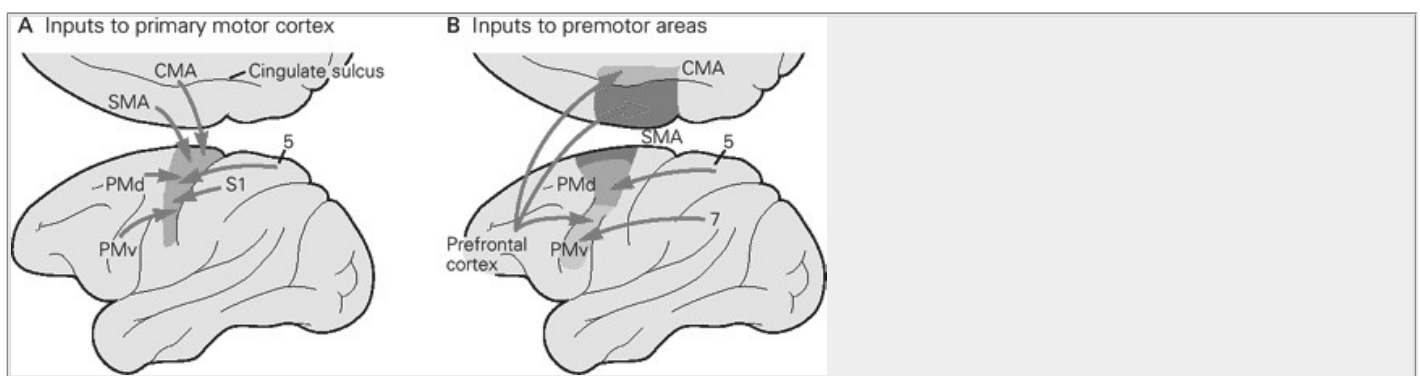


Figure 38-4 The major inputs to the motor cortex in monkeys.

A. The major inputs to the primary motor cortex. (**PMd** = dorsal premotor area; **PMv** = ventral premotor area; **S1** = primary sensory cortex; **SMA** = supplementary motor area.)

B. The major inputs to the premotor areas. Dense interconnections between the premotor areas are not shown here.

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Premotor Cortical Areas Project to the Primary Motor Cortex and Spinal Cord

In the late 1930s it was discovered that movements can also be elicited by direct electrical stimulation of the *premotor areas*, Brodmann's area 6, although the intensity of stimulation necessary to produce movement is greater here than in the primary motor cortex. Brodmann's area 6 lies anterior to the precentral gyrus, on the lateral and medial surfaces of the cortex. Like the primary motor cortex, the premotor areas contain pyramidal (output) neurons in layer V that project to the spinal cord, although the cell bodies are smaller than those in the primary motor cortex.

Recent anatomical studies indicate there are four main premotor areas in primates—two on the lateral convexity and two on the medial convexity. The two on the lateral convexity are the *lateral ventral* and *lateral dorsal premotor areas*. The two in the medial wall of the hemisphere are the *supplementary motor area* and the *cingulate motor areas*, located in the banks of the cingulate sulcus. Similar premotor areas exist in humans, but differences in size and sulcal patterns make it difficult to identify homologous areas with precision.

Motor maps of the face and extremities can be delineated in each premotor area (Figure 38-1C). However, unlike the primary motor cortex, where stimulation typically evokes simple movements of single joints, stimulation of the premotor areas often evokes more complex movements involving multiple joints and resembling natural coordinated hand shaping or reaching movements. Stimulation of the medial parts of area 6, the supplementary motor area, can give rise to bilateral movements, suggesting that this area has a role in coordinating movements on the two sides of the body.

All the premotor areas project to both the primary motor cortex and the spinal cord, although there are fewer projections from the premotor areas to the spinal cord than from the primary motor cortex. In the spinal cord the areas of termination of the premotor and primary motor projections overlap. For example, the corticospinal axons of neurons in the supplementary motor area terminate in motor nuclei innervating digit and hand muscles, as do those of neurons in the hand area in the primary motor cortex. The corticospinal projections from the dorsal premotor area terminate mainly in motor nuclei innervating proximal limb musculature. The existence of these direct mono-synaptic connections suggests that the premotor neurons can control hand movements independently of the primary motor cortex.

Each Cortical Motor Area Receives Unique Cortical and Subcortical Inputs

The primary motor cortex receives somatotopically organized inputs directly from two sources. First, it receives inputs from the primary somatosensory cortex (areas 1, 2, and 3). This means that, like neurons in somatosensory cortex, neurons in the motor cortex have receptive fields in the periphery. For example, some neurons in the motor cortex receive proprioceptive input from the muscles to which they project and many neurons in the hand region of the motor map respond to

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tactile stimuli applied to specific regions of the digits and palms. These so-called *transcortical* circuits are discussed later. Second, the primary motor cortex receives inputs from posterior parietal area 5. Posterior parietal areas 5 and 7 are involved in integrating multiple sensory modalities for motor planning (Figure 38-4A).

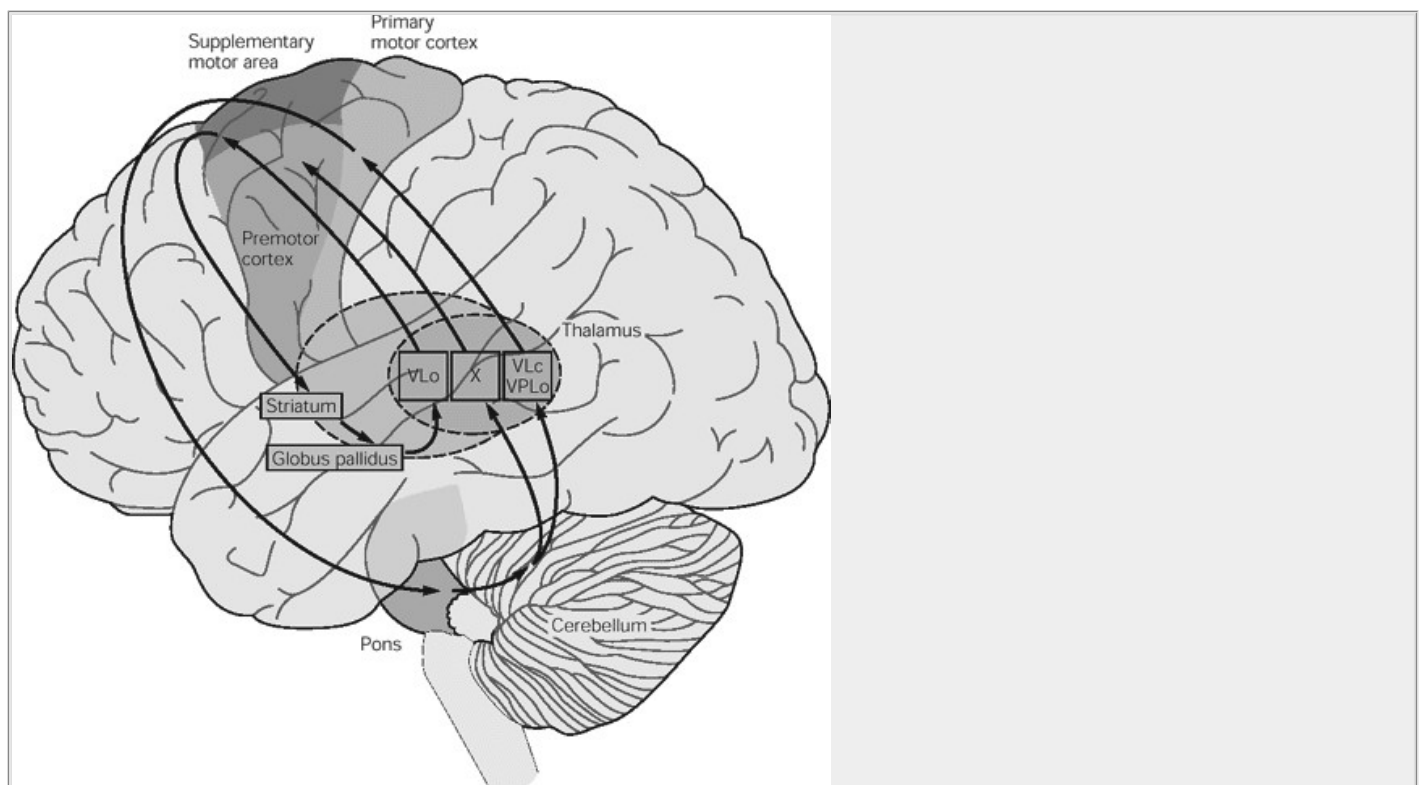


Figure 38-5 The motor cortex receives inputs from the cerebellum via the thalamus. **VLo** and **VLc** = oral (rostral) and caudal portions of the ventrolateral nucleus; **VPLo** = oral portion of the ventral posterolateral nucleus; **X** = nucleus X.

The premotor areas receive major inputs from areas 5 and 7 as well as from area 46 in the prefrontal cortex (Figure 38-4B). Each premotor area has its own pattern of inputs from distinct locations in areas 5 and 7. Area 46 projects mainly to the ventral premotor area and is important in working memory; it is thought to store information about the location of objects in space only long enough to guide a movement. There are also dense connections between the premotor areas themselves. These connections are thought to allow working memory to influence specific aspects of motor planning that are mediated by the different premotor subregions.

The premotor areas and primary motor cortex also receive input from the basal ganglia and cerebellum via different sets of nuclei in the ventrolateral thalamus (Figure 38-5). The basal ganglia and cerebellum do not project directly to the spinal cord.

An important feature of the relationship between cortical areas and subcortical structures is the reciprocal nature of their connections. Each cortical motor area appears to have a unique pattern of cortical and subcortical input. Thus there are many cortico-subcortical loops, each one making a different contribution to a motor behavior (Chapter 43).

The Somatotopic Organization of the Motor Cortex Is Plastic

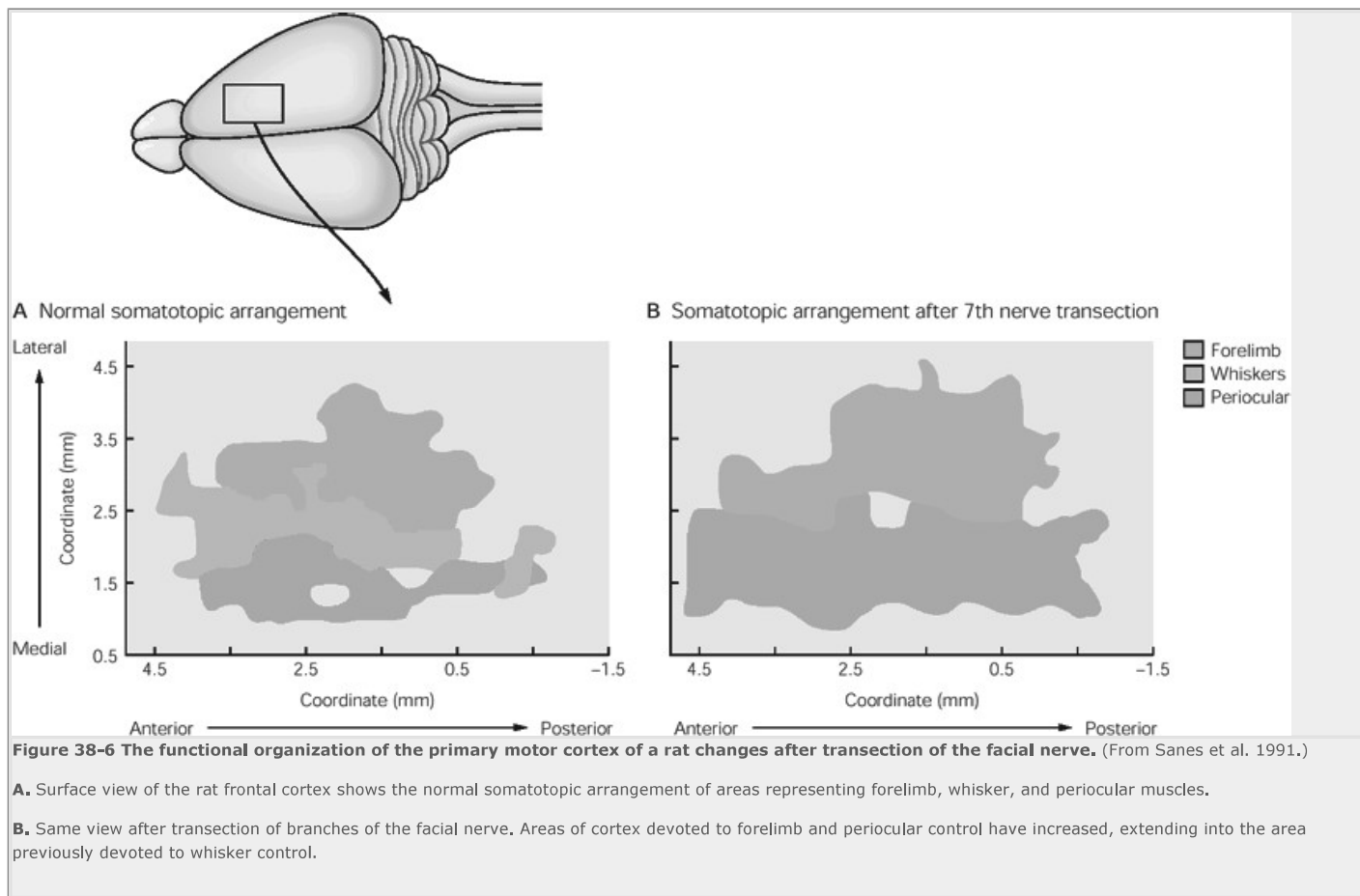
The somatotopic organization of the motor cortex is not fixed but can be altered during motor learning and following injury. This plasticity has been demonstrated in many experiments and clinical studies. In one study using mature rats the representation of the whiskers in the primary motor cortex was first mapped using intracortical microstimulation. The whiskers were then denervated. Electrical stimulation of the cortical region that had caused whisker movement subsequently produced forelimb movement (Figure 38-6). This shift in functionality may be due to facilitation of preexisting circuits in the whisker region that are connected to the forelimb. The change can take place in just a few hours. The loss of sensory inputs from the whiskers into the motor area is thought to trigger the reorganization. This indicates that neurons influencing facial musculature are more widely distributed than is revealed by local electrical stimulation at any given point in time.

The idea that the organization of at least some mature

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motor circuits in the cortex can change depending on sensory or motor activity holds important promise for the rehabilitation of patients who have had strokes and other

forms of brain injury. Evidence in favor of this possibility has recently been obtained in animal experiments. In one such experiment, a small cortical artery was occluded in squirrel monkeys to destroy a portion of the population of cells in the primary motor cortex controlling the hand and digits. The animals lost the ability to retrieve food pellets from the smallest of a series of wells, and with time the area of hand representation around the lesion shrank.



Some animals were retrained and others not. The changes in the cortical maps of hand and forearm representation were strikingly different in the two groups. In animals that had not practiced using the hand and relied only on proximal muscle control, all areas of hand and forearm representation were lost. The neurons outside the lesion did not die but elbow and shoulder areas expanded into the remaining (undamaged) hand area. In animals that practiced using their hand daily, the undamaged cortex controlling the hand and digit expanded into adjacent undamaged cortex previously occupied by neurons controlling the elbow and shoulder. These animals fully recovered the ability to retrieve pellets after 3 or 4 weeks. This result emphasizes the importance of practice in sensorimotor tasks for rehabilitation following stroke and other focal brain damage.

As noted in the introduction, a characteristic feature of voluntary movements is that they improve with practice. This may be associated with cortical reorganization. In one study striking changes were found in the motor cortex in human subjects after practice of a single motor task. Subjects were asked to practice a finger opposition task for about 20 minutes every day, touching the thumb to the tip of each finger in a specific repeating sequence. As one can readily appreciate, at first this task was performed slowly and hesitatingly. However, as with typing or playing the piano, speed and accuracy increased with each successive day of practice until the performance learning curve reached asymptote in about 3 weeks. Functional magnetic resonance imaging (MRI) scans revealed that the area of cortex activated during performance of the trained sequence was larger than that activated during a novel untrained sequence (Figure 38-7)

It is important to emphasize that subjects performed both the novel and learned sequences at the same rate. This is crucial in order to exclude the possibility that the differences in activation are simply due to differences in the speed of finger movements. Moreover,

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practice with one finger sequence did not facilitate performance of a new sequence nor did it transfer to the untrained hand. (Hand areas are unique in that they are not connected across the corpus callosum.) Such experience-dependent change in the primary motor cortex is likely to be important for the acquisition and retention of other motor skills.

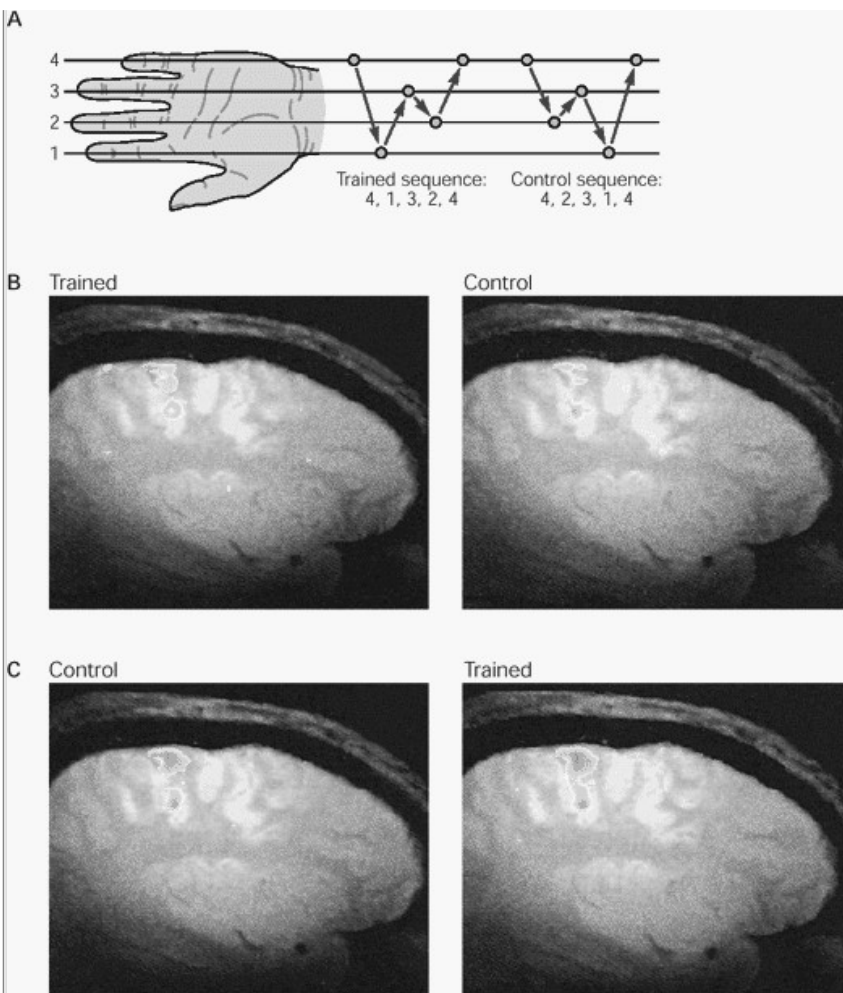


Figure 38-7 As a movement becomes more practiced, it is represented more extensively in primary motor cortex.

A. Human subjects performed two finger-opposition tasks, touching the thumb to each fingertip in the sequences shown. Digits are numbered 1 through 4. Both the practiced and the novel sequence were performed at a fixed, slow rate of two component movements per second.

B. Functional MRI scans show the area in the primary motor cortex activated during the performance of a finger-opposition sequence that had been practiced daily for 3 weeks (**left**) followed by a novel sequence (**right**). The area of activation is larger when the practiced sequence is performed. The experimenters interpret the increased area of metabolic activity as indicating that long-term practice results in a specific and more extensive representation of the trained sequence of movements in the primary motor cortex.

C. In another trial the practiced sequence followed the novel sequence, yet the area of activation in the primary motor cortex during the learned sequence is still larger. Thus the extent of activation is not merely an effect of the order in which the tasks were performed. (From Karni et al 1995.)

Corticospinal Axons Influence Spinal Motor Neurons Through Direct and Indirect Connections

Corticospinal neurons make powerful and direct excitatory connections with alpha motor neurons in the spinal cord. A unique feature of the corticospinal synapse is that successive cortical stimuli produce progressively larger excitatory postsynaptic potentials in spinal motor neurons. This potentiating connection is one of the mechanisms that permit monkeys to perform individual movements of the digits, including the grasping of small objects (Figure 38-8A) and to isolate movement of proximal joints. This ability is lost permanently after sectioning the pyramidal tracts in the medulla (Figure 38-8B) or after ablating the hand-control area of the motor cortex.

Corticospinal fibers also terminate on interneurons in the spinal cord, which in turn project to alpha motor neurons. These indirect connections with motor neurons regulate a larger number of muscles than do the direct connections and so may contribute to the organization of multijointed movements such as reaching and walking.

Sectioning the medullary pyramidal tracts, which interrupts the projection of corticospinal axons from the primary motor cortex and premotor areas, produces contralateral weakness in monkeys. But the animals recover after a period of months, leaving only deficits in speed of movement and in the rate of force development. These deficits can be attributed to interruption of the projections from the primary motor cortex because

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similar deficits arise from lesions in primary motor cortex but not from lesions in premotor areas. Animals with pyramidal tract lesions climb, jump, and appear generally normal. Their partial recovery is possible because cortical commands have indirect access to spinal motor neurons through the descending systems of the brain stem (Chapter 33). Nevertheless, individuated movements of the digits are lost permanently, and the wrist, elbow, and shoulder become linked in extensor or flexor synergies.

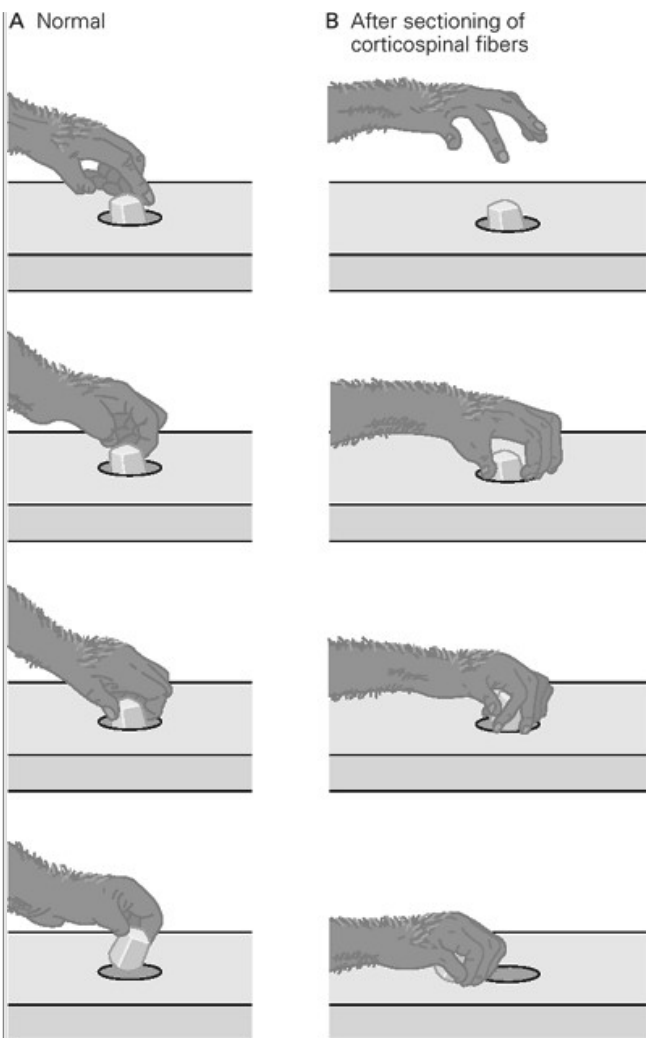


Figure 38-8 Direct corticospinal control of motor neurons is necessary for fine control of the digits.

A. A monkey is able to pick up a food morsel from a small well using the index finger and thumb.

B. After bilateral sectioning of the pyramidal tract the monkey can only remove food from the well by grabbing with the whole hand. (From Lawrence DG, Kuypers HGJM, 1968. The functional organization of the motor system in the monkey. *Brain* XCI.)

Corticospinal projections also have inhibitory effects on spinal motor neurons. Direct recordings in monkeys and indirect evidence from reflex testing in humans indicate that corticospinal inhibition is mediated by the Ia inhibitory interneuron, the same interneuron responsible for the reciprocal inhibition of stretch reflexes (Figure 38-9). Because these spinal interneurons receive peripheral inputs and are able to respond directly to ongoing changes in somatic sensory input, the higher centers of the brain are freed from the need to manage all the details of movements and instead can use the spinal circuits as components of more complex behaviors, much like the subroutines of a computer program.

The Primary Motor Cortex Executes Movements and Adapts Them to New Conditions

Activity in Individual Neurons of the Primary Motor Cortex Is Related to Muscle Force

To understand how cortical motor areas contribute to movement it is necessary to study how individual neurons are modulated in natural motor behaviors. This became possible in the 1960s when Edward Evarts succeeded in correlating the activity of single neurons with specific motor behaviors in active monkeys. Evarts found that activity in individual neurons in the primary motor cortex is modulated when monkeys either flex or extend the individual joints of their contralateral limbs. Individual neurons are maximally activated during movement of a particular joint and particular direction of movement. The changes in neuronal activity begin some 100 ms or more before the onset of movement.

In a classic experiment Evarts showed that, during wrist flexion, the firing of primary motor cortex neurons varied with the amount of force the animal had to exert to move its hand, not with the amplitude of the hand's displacement (Figure 38-10). The activity of these cortical neurons therefore appears to signal the direction and amplitude of muscle force required to produce a movement rather than the actual displacement of the joint.

Jun Tanji and Evarts found another, more surprising property of some primary motor cortex neurons. In these cells the baseline discharge changed while the animal waited for a signal to move in a predetermined direction. For example, a cell would change its level of baseline activity when a green light instructed the animal that an extension movement was to be made at a later signal (an instructed delay task). This pattern of activity was termed *set related* because it reflected the animal's

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preparation—or *preparatory set*—to respond to a later stimulus. These discharges demonstrated that the intent to perform a movement alters the firing pattern of neurons in the primary motor cortex hundreds of milliseconds before the movement takes place.

Simple correlations of neuronal activity and behavior do not prove causality. Movement or set-related neurons might be concerned with early changes in postural muscle activity or some other process, rather than with the voluntary movement. The most common (and often the only possible) approach to relating neuronal activity to a specific behavior is to exclude confounding sources of correlation. However, in the case of primary motor cortex neurons, what is really needed is a way to know for sure whether activity that precedes a voluntary movement directly influences the muscles used in the movement. Only after a direct influence has been established can the relationship of these cells' activity to specific aspects of the movement be addressed meaningfully

A major advance in this direction was made in the mid-1970s by Eberhard Fetz and co-workers, who used the spike-triggered averaging technique (Box 38-1) to identify neurons in the primary motor cortex that project directly to motor neurons, called *corticomotoneuronal* (CM) cells. They found that individual CM cells project monosynaptically to more than one motor nucleus and sometimes to muscles controlling different joints. Thus, muscles are not mapped one-to-one in cortical output neurons. Most of the neurons recorded by Fetz have phasic patterns of activity, firing most briskly during the dynamic phase of movement and settling down to a

lower tonic rate when a steady force is reached (Figure 38-12A). For almost all neurons there is a range over which force is related linearly to firing rate. Often, however, this range is quite small, and maximal firing is achieved for relatively small forces.

Direction of Movement Is Encoded by Populations of Cortical Neurons

Most movements involve multiple joints and require sequential and temporally precise activation of multiple muscles. This raises the question of whether cells in motor cortex directly control the specific spatiotemporal patterns of muscle activation or do they encode more global features of the movement such as its direction, extent, or joint angle changes?

This was examined by Apostolos Georgopoulos, who trained monkeys to move a joystick toward visual targets located in different directions and recorded the associated changes in activity in the primary motor cortex. All neurons fired briskly before and during movements in a broad range of directions (Figure 38-13A)

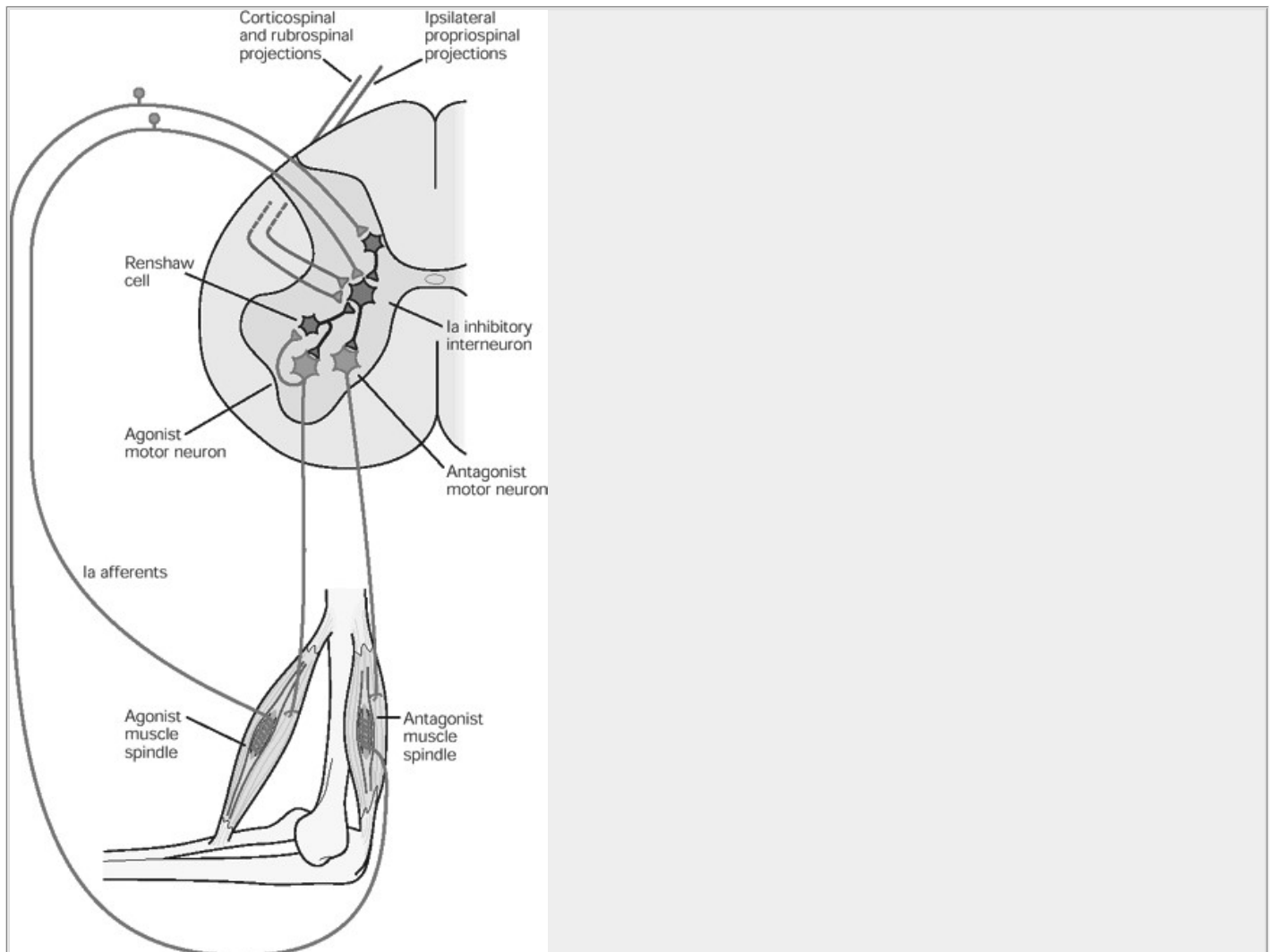


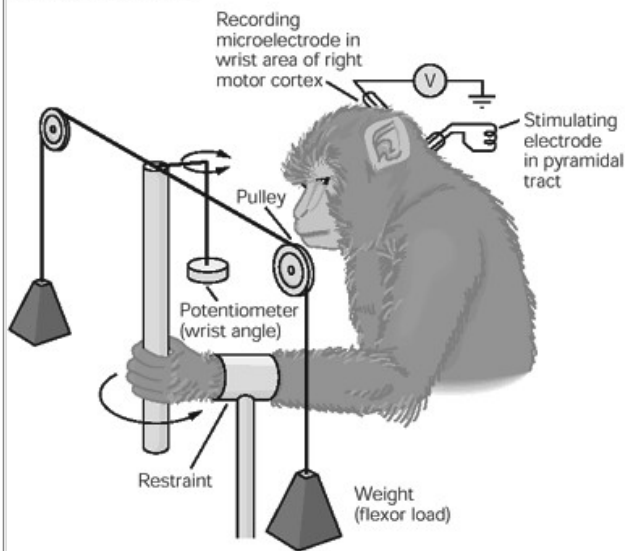
Figure 38-9 The Ia inhibitory interneuron in the spinal cord sends inhibitory signals to antagonist motor neurons when muscle spindles in the agonist muscle are activated. The interneuron receives complex excitatory and inhibitory inputs, including direct input from the motor cortex. These direct cortical connections allow the motor cortex to use reflex circuits as components of complex movements, thereby simplifying the motor cortical program. (Based on Lundberg, 1979.)

How can movement direction be coded precisely by neurons that are so broadly tuned? Georgopoulos proposed that movement in a particular direction is determined not by the action of single neurons but by the net action of a large population of neurons. He suggested that the contribution of each neuron to movement in a particular direction be represented as a vector whose length indicates the level of activity during movement

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in that direction. The contributions of individual cells could then be added vectorially to produce a *population vector*. In fact, the directions of such computed population vectors closely match the directions of movement (Figure 38-13B).

Experimental setup



Records of behavior and cell activity

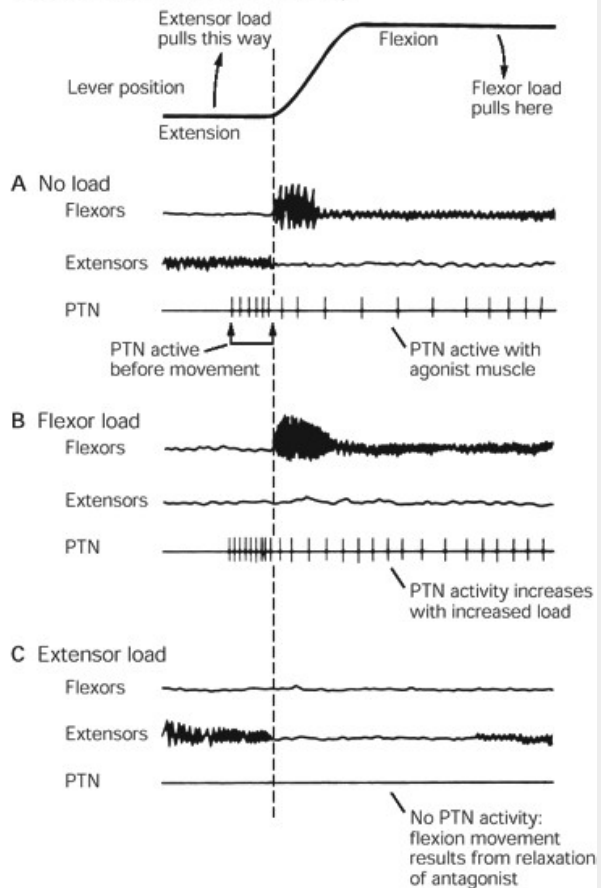


Figure 38-10 Activity in a corticospinal axon correlates with the direction and amplitude of muscle force rather than the direction of displacement. Records shown here were made while a monkey flexed its wrist under three load conditions. In each set of traces the **top trace** indicates the activity in a corticospinal neuron and the **bottom trace** wrist position, with upward deviation being flexion. When no load was applied (**A**) the neuron fired before and during flexion. When a load-opposing flexion was applied, activity in the neuron increased (**B**). When a load-assisting flexion was applied, the neuron fell silent (**C**). In all three conditions the wrist displacement was the same but the neuronal activity changed as the load changed. Thus the firing of the corticospinal neuron in this experiment is related to the force exerted during a movement and not to the displacement of the wrist. (From [Evarts 1968](#).)

The directionally tuned neurons described by Georgopoulos are modulated strongly by the presence of external loads during reaching movements in a given direction, and this modulation depends on the force required to displace the limb. A cell's firing rate increases if a load opposes movement of the arm in the cell's preferred direction; it decreases if the load pulls the arm in the cell's preferred direction ([Figure 38-14](#)). This dependence of firing rate on load suggests that the activity of neurons in the primary motor cortex varies with the direction of forces as well as with movement direction during reaching with the whole arm. This force coding is similar to that for single-joint movements, discussed earlier.

Together these various studies show that motor cortex activity signals not only "lower level" movement parameters, such as muscle forces, but also "higher level" parameters related to the trajectory of the hand during reaching. This feature of motor cortex neurons distinguishes them from alpha motor neurons.

Box 38-1 Postspike Facilitation of Muscle Activity

Recording from cortical neurons in awake animals and relating the neuronal activity to movement parameters has led to significant insights about cortical control of movement. However, studies of this type are limited by their inability to identify functional connections between cortical neurons and the motor neurons of target muscles. This becomes possible with a technique developed by Ebehard Fetz and his colleagues called spike-triggered averaging (STA).

Cortical motor neurons with direct excitatory synaptic connections to motor neurons produce individual EPSPs with a fixed latency. Any one EPSP is unlikely to fully depolarize a motor neuron but it transiently increases the probability the motor neuron will fire by bringing it closer to threshold. The EMG profile is the sum of spike trains of a population of motor units within a muscle and is a reliable indicator of the firing of spinal motor neurons. By averaging the EMG profile over thousands of discharges of one cortical neuron, the effect of a single cortical neuron on an EMG profile can be ascertained. This averaging subtracts out random associations of cortical neuronal firing and motor unit discharge; the signal-to-noise ratio improves with the number of discharges used to compile the average.

[Figure 38-11](#) shows the relation of the discharge of a single cortical neuron to an extension movement of the wrist. A cumulative average over 2000 discharges of the cortical neuron reveals a clear peak in the EMG profile beginning at a latency of 6 ms. This transient increase is called *postspike facilitation* and its short latency is interpreted as evidence of an underlying synaptic connection between the cortical neuron and the motor neurons.

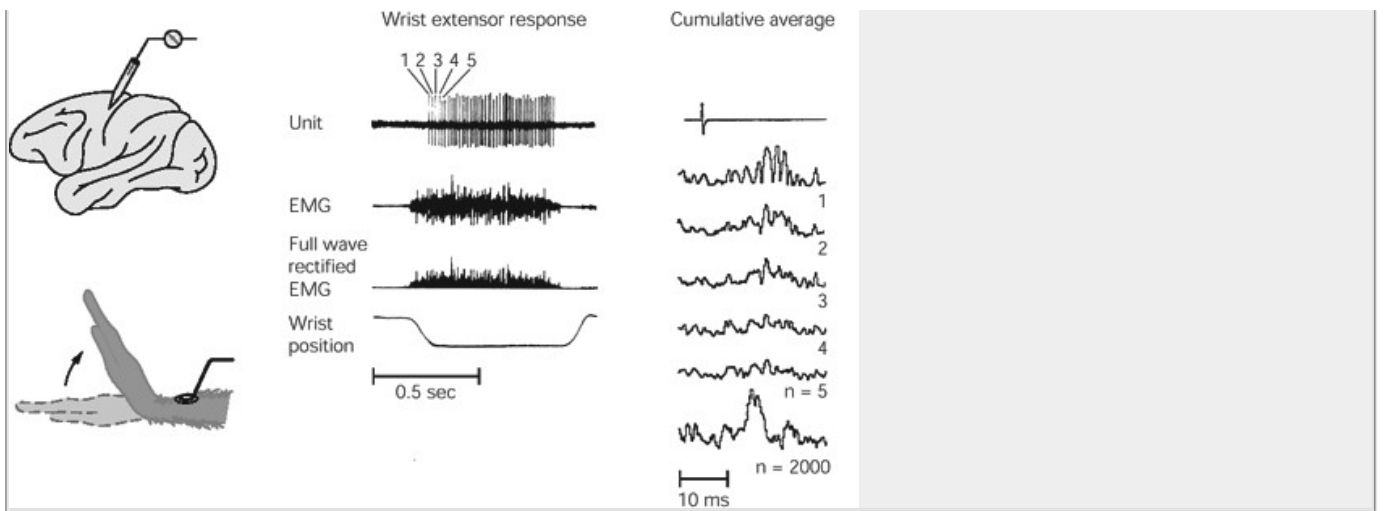


Figure 38-11 Spike-triggered averaging can detect the effects of a single cortical neuron on motor units. The records on the left show discharges of a cortical cell and normal and rectified EMG activity of one agonist muscle associated with wrist extension. From these records 30 μ s segments of EMG activity associated with each cortical spike were averaged. The cumulative average of EMG segments associated with the first five spikes are shown on the right. No clear effect can be seen after averaging over only five spikes, but at 2000 spikes postspike facilitation can clearly be seen. (From Fetz and Cheney 1980.)

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Neurons in the Primary Motor Cortex Are Activated Directly by Peripheral Stimulation Under Particular Conditions

The simplest behaviors controlled by the primary motor cortex are those elicited directly by sensory stimuli. Motor cortical neurons receive strong sensory inputs from the limb whose muscles they control. When a standing human subject pulls on a handle, the sudden postural perturbation elicits a rapid counter-response in the stretched muscle at a latency shorter than a simple reaction time but longer than for a spinal reflex. However, this counter-response happens only when the person is told to resist. Such rapid motor adjustments are mediated mainly by relatively simple transcortical pathways through which somatosensory inputs reach the primary motor cortex directly via projections from the thalamus or primary sensory cortex. This transcortical pathway provides a degree of flexibility to rapid responses that is unavailable in spinal reflexes. These long-loop or transcortical responses are selectively increased in several movement disorders, such as Parkinson disease and myoclonus, while spinal reflexes remain normal.

Individual Movement of Digits Is Controlled by Patterns of Activity in a Population of Cortical Neurons

As noted earlier, anatomical studies and lesion experiments have suggested that the primary motor cortex

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plays a special role in producing individuated movement of the digits in primates.

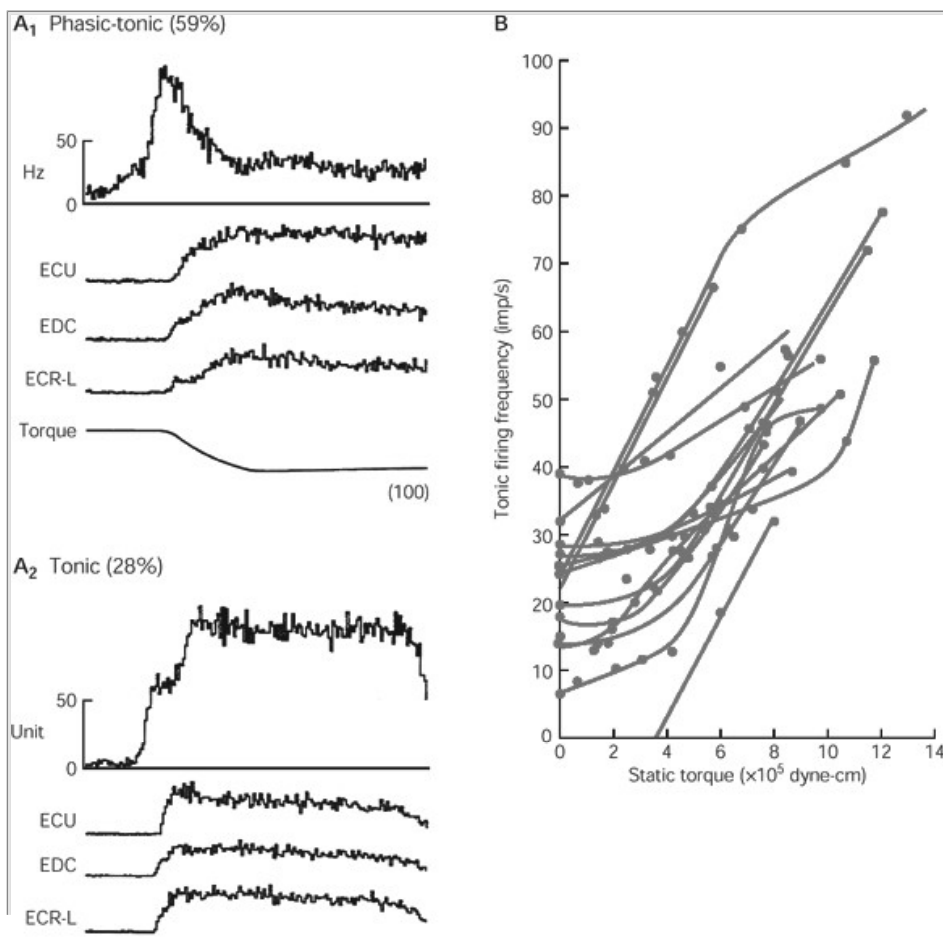




Figure 38-12 There is a direct relationship between the firing rate of motor cortical cells and force generation. (From Fetz EE and Cheney 1980.)

A. Two types of motor cortical neurons, phasic-tonic and tonic, are predominant in the primary motor cortex. Each has a characteristic response pattern during isometric wrist torques in which the torque level is reached and held. (Similar patterns are seen for torques accompanied by wrist displacement.) **1.** Phasic-tonic cell activity begins with a dynamic burst during the initial increase in torque and then decreases to a steady level when torque is maintained. **2.** Tonic cell activity follows the rise in torque and remains at a high level.

B. In both cell types activity increases with torque. The plot shows the relation between tonic firing rate, (impulses per second) and static torque during wrist extension.

Although individual neurons fire maximally when a particular finger is moved, these neurons are dispersed throughout the hand control area of primary motor cortex (Figure 35-15). The manner in which such activity is coordinated to produce a finger movement is analogous to the population coding that underlies reaching movements.

This observation is not surprising, since the digits are biomechanically coupled by common tendons and thus are not anatomically independent of each other. Moving a single digit alone requires activating and inhibiting muscles acting on all the digits. Current evidence indicates that each corticomotoneuronal (CM) cell influences activity in a small group of target muscles. Very few of these cells have been found that control only a single muscle. Even CM cells involved in individuated

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finger movements have axons that diverge to more than one motor nucleus in the spinal cord. In addition, as noted earlier, the same target muscle may be influenced by CM cells that are dispersed throughout the hand representation. The cells activated will depend on the task in which the muscle is used.

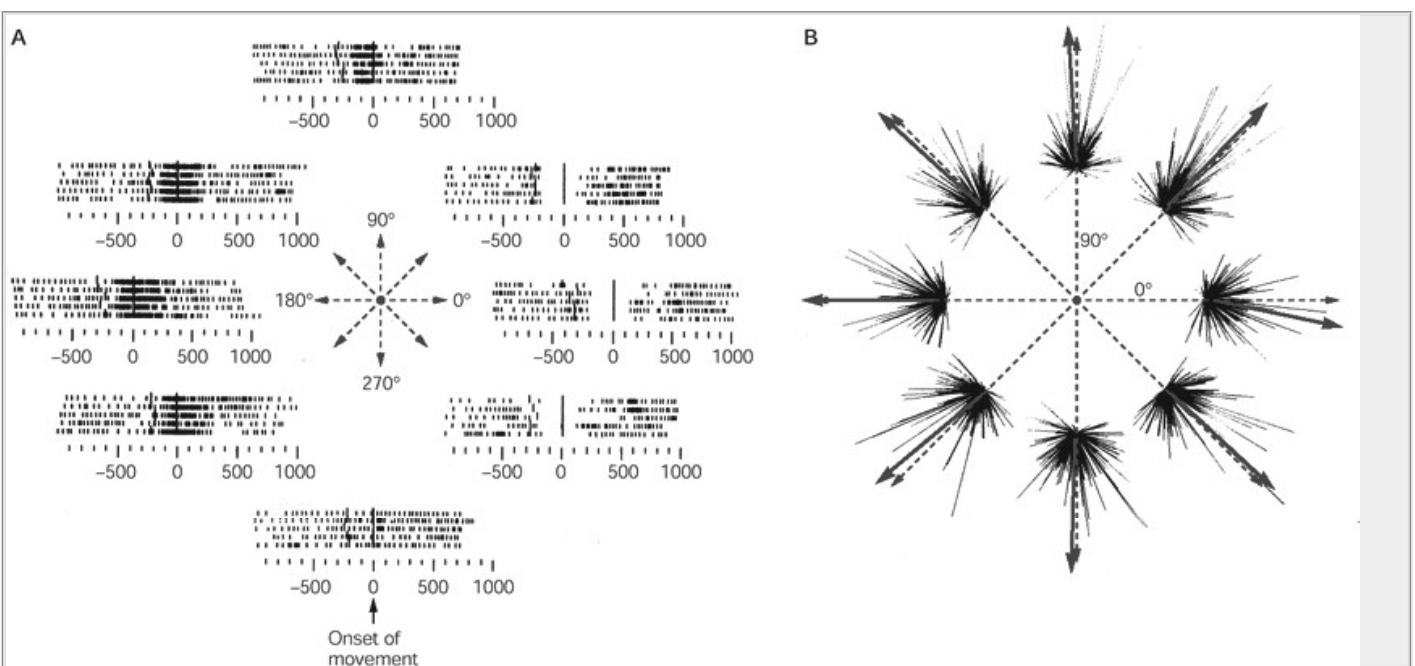


Figure 38-13 Direction of movement is encoded in the motor cortex by the pattern of activity in an entire population of cells. (From Georgopoulos et al. 1982.)

A. Motor cortical neurons are broadly tuned to the direction of movement, but individual cells fire preferentially in connection with movement in certain directions. Raster plots of the firing pattern of a single neuron during movement in eight directions show the cell firing at relatively higher rates during movements in the range from 90 degrees to 225 degrees. Different cells have different preferred movement directions. For these recordings a monkey was trained to move a handle to eight locations arranged radially in one plane around a central starting position. Each row of ticks in each raster plot represents activity in a single trial; the rows are aligned at zero time (the onset of movement).

B. Cortical neurons with different preferred directions are all active during movement in a particular direction. The entirety of this activity results in a population vector that closely matches that of the direction of movement. The eight clusters shown here represent the activity of the same population of neurons during reaching movements in eight different directions. **Solid arrows** are the population vectors; **dashed arrows** are the direction of movement of the target limb.

Roger Lemon and R. B. Muir demonstrated the importance of the task in determining which neurons in the primary motor cortex will be used to control a particular muscle. They examined the activity of individual CM cells in monkeys during two different finger tasks, a power grip and a precision grip, both of which involve contraction of the intrinsic hand muscles controlled by the identified CM cells. Cells that are active during the precision grip remain silent during the power grip, even though the contraction of the target muscle is stronger for the power grip than for the precision grip (Figure 38-16).

The observation that activity in a CM cell is not invariably coupled with activation of its target muscle fundamentally distinguishes CM cells from spinal motor neurons. The finding that a distinct population of cells in the primary motor cortex is active only during the precision grip is further evidence of the special role of the primary motor cortex in controlling individuated movements of the fingers. The power grip, which does not require individual finger movements, can be controlled by descending pathways, arising either within or outside of the primary motor cortex, that diverge extensively in the spinal cord and therefore can recruit a large number of muscles in a less differentiated synergy.

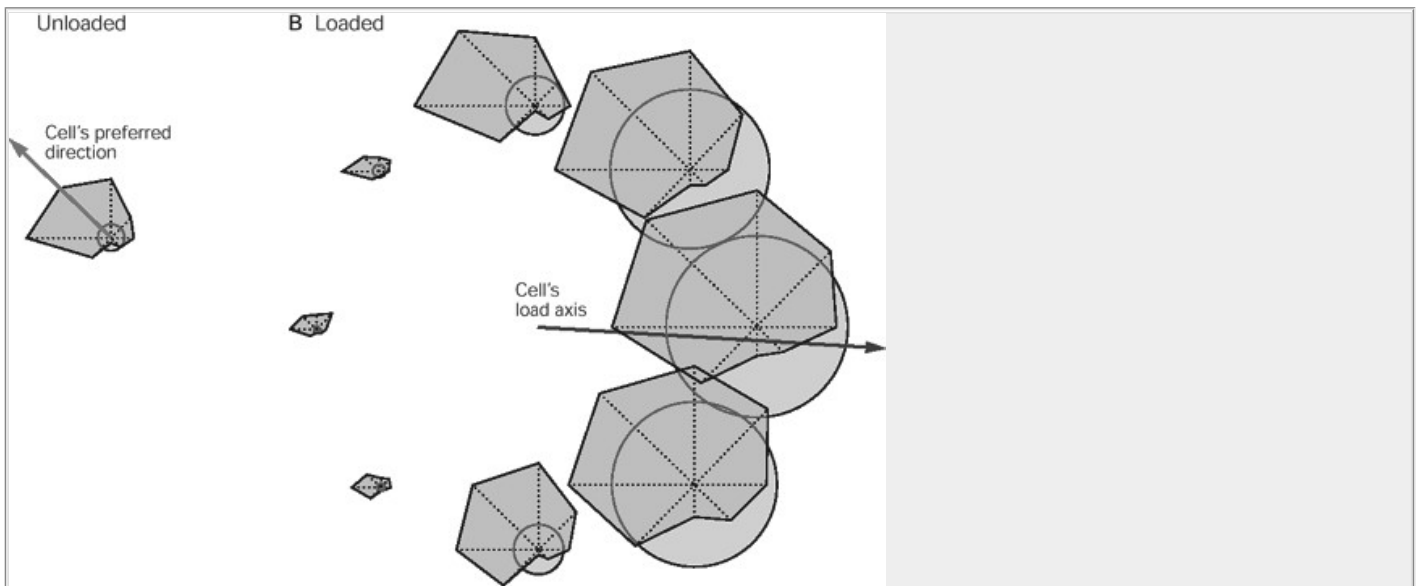


Figure 38-14 Motor cortical cells can code for the force required to maintain a trajectory. A monkey was trained to reach in eight directions while external loads pulled the arm in one of these directions. Polar plots represent the activity of a single cell in the primary motor cortex while the arm moved with external loads. The magnitude of the cell's discharge is plotted as the length of a vector extending in the direction of the executed movement (**dotted line**). The tips of all vectors are joined by a **solid line**. The radius of the circle indicates the magnitude of cell activity while holding the arm at the central starting position before movement.

A. Plot showing the preference of the cell for movement to the upper left during movements in eight directions without an external load applied to the arm.

B. Polar plots for the same cell when loads are applied in eight directions. The position of each polar plot corresponds to the direction in which the load pulled the arm. The cell's firing rate increases in all directions when the arm is pulled right. This rightward direction is the load axis of the cell, which is approximately opposite to its preferred movement direction. Thus the cell's firing rate is related to the amount of force required to maintain an arm trajectory in a given direction, not just to the direction itself. (From Kalaska et al. 1989.)

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Certain motor cortical cells fire less and less often as muscle force increases. That is, their activity is correlated negatively with force. However, like neurons with positive correlations (see Figure 38-12), these cells also facilitate their target muscles. They discharge only during tasks that require precise control of force and smooth changes in force. Thus their function may be to provide more precise derecruiting of motor units than would be afforded simply by inhibiting the so-called positive cortical neurons. This would be helpful, for example, in releasing delicate objects carefully.

In conclusion, the primary cortex has two levels of functional organization. First, a low-level control system, the CM cells, controls groups of muscles that can be brought together into task-specific combinations. Second, a higher-level control system encodes more global features of the movement. Practice and learning adjust the relation between these two levels of organization.

Each Premotor Area Contributes to Different Aspects of Motor Planning

Although the outputs of the premotor areas and the primary motor cortex overlap in the spinal cord, the inputs to the premotor areas are quite different from those to the primary motor cortex (see Figure 38-4). Moreover, damage to premotor areas causes more complex motor impairments than does damage to primary motor cortex. When a monkey with a large lesion of the premotor area is presented with food behind a transparent shield it will reach directly for the food and bump into the shield. Unlike a normal animal it is unable to incorporate visuospatial information about the shield into the kinematic plan for moving its hand.

The idea that premotor areas are involved in planning movement has received crucial support during the past 20 years from physiological and imaging studies of

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humans and monkeys performing a variety of special tasks. In monkeys distinct populations of cells are active in connection with ipsilateral movements, bilateral movements, or specific combinations of movements. Set-related and preparatory activity predominates, and cell activity is often associated primarily with specific tasks as we will see below.

Studies of the premotor areas have identified several basic features of the neural organization of motor preparation. First, movements that are initiated internally by the subject—such as the sequencing of finger movements when manipulating an object—involve primarily the supplementary motor area. Second, movements triggered by external sensory events involve primarily the lateral premotor areas. More specifically, separate populations of lateral premotor neurons map the often arbitrary relationship between stimulus and response. The lateral dorsal premotor area is also concerned with delayed action (executed later on cue), whereas the lateral ventral premotor area is concerned with conforming the hand to the shape of objects.

Third, mental rehearsal of a movement—that is, the use of visual imagery to plan a movement—invokes the same patterns of activity in the premotor and posterior parietal cortical areas as those that occur during performance of the movement. Psychophysical studies have shown that mental rehearsal of movement has a similar time course and closely simulates task performance. This observation helps explain the importance of mental rehearsal to athletes and skilled performers. Fourth, the premotor areas activated during a particular task are not the same over time but change progressively as performance becomes automatic.

The Supplementary and Presupplementary Motor Areas Play an Important Role in Learning Sequences of Discrete Movements

Motor actions are often self-initiated without an environmental cue. Nearly a full second before a self-initiated voluntary movement begins, a characteristic negative shift in cortical potentials is seen in the electroencephalogram (EEG) record of medial premotor regions, where the supplementary motor area is situated. This negative potential, referred to as the *preparatory potential* or *Bereitschaft potential*, signals the planning that occurs before movement is executed.

The region responsible for this negative potential was localized more precisely in a study comparing increases in regional cerebral blood flow (a measure of increases in neuronal activity) during simple, complex,

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and imagined sequences of finger movements. Complex movement sequences require more planning than do simple repetitive movements. Imagining complex movements might require the same amount of planning as real movements. As expected, during forceful repetitive finger flexions against a spring-loaded movable cylinder, increases in regional cerebral blood flow were largely confined to the contralateral primary sensorimotor hand-control region. A complex sequence of finger movements was accompanied by regional cerebral blood flow increases within the supplementary motor area. Remarkably, when the complex sequence of finger movements was simply imagined, regional cerebral blood flow increased in an area anterior to the supplementary motor area on both sides (Figure 38-17). This area,

the presupplementary motor area, provides the main input to the supplementary motor area and is discussed in detail below.

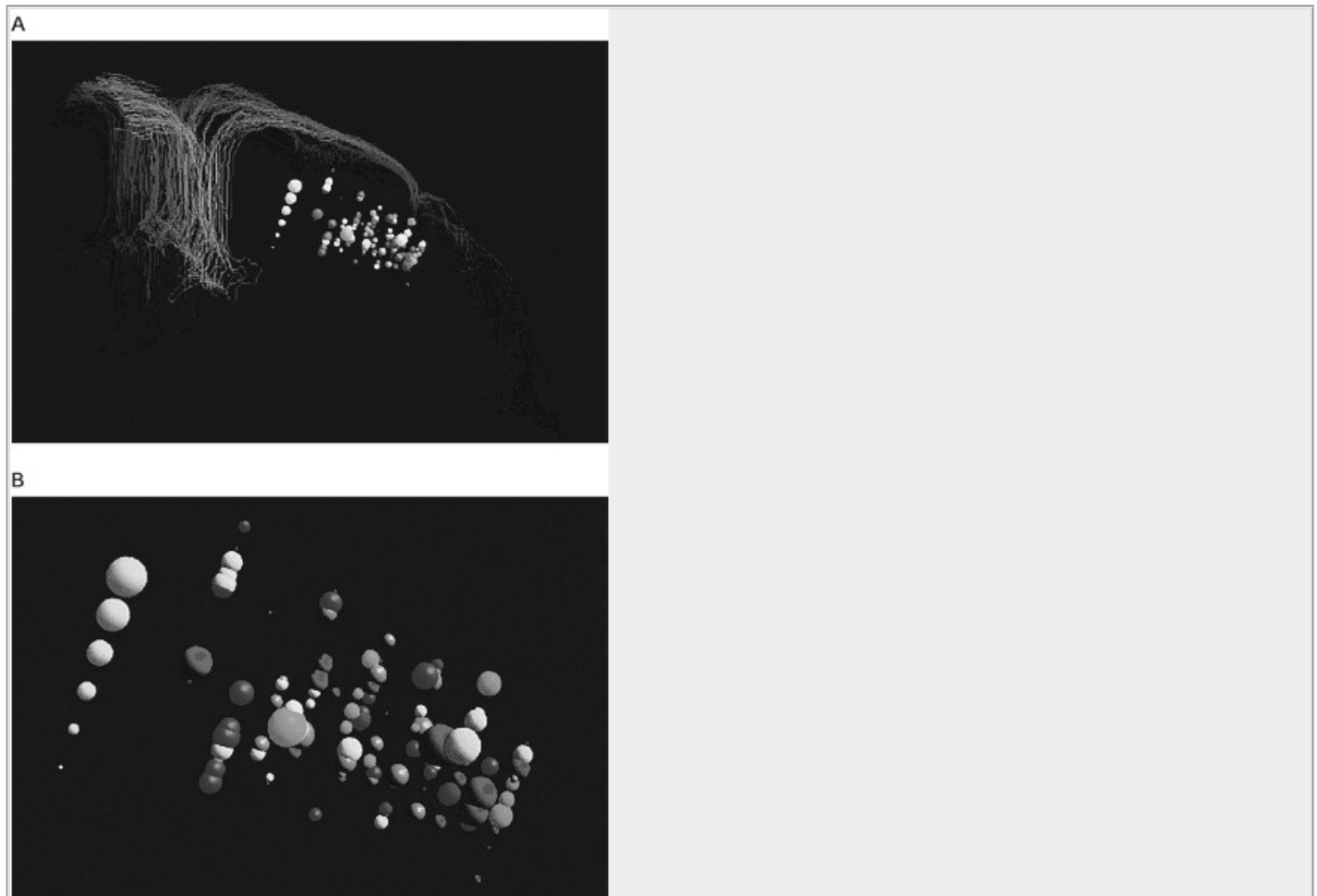


Figure 38-15 Cortical neurons that govern finger movements are distributed throughout the hand-control area of the primary motor cortex. (From Schieber and Hibbard 1993.)

A. View of the frontal pole of the monkey cortex, showing the interhemispheric fissure and the lateral convexity. The **colored dots** and **spheres** represent sites of single neurons in the hand-control region of the primary motor cortex from which recordings were made.

B. A plot of each neuron's maximal activity shows that neurons that are maximally active for a particular digit or for the wrist are not grouped together but instead are distributed throughout the hand-control area of the primary motor cortex. Each digit and the wrist are represented by a different color. The diameter of the sphere is proportional to the neuron's activity (the radii of the white spheres represent changes in firing frequency of 0, 40, 80, 120, 160, and 200 spikes per second.)

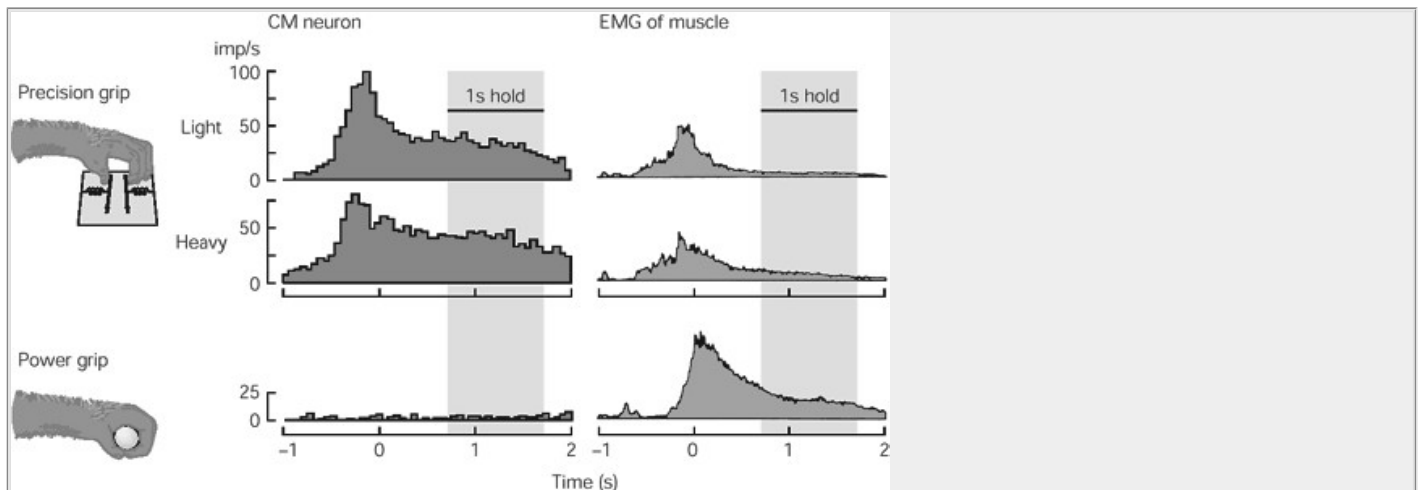


Figure 38-16 Whether an individual corticomotoneuronal (CM) cell is active depends on the motor task. The activity of a CM cell and the activity in its target muscle are not directly related. Cumulative histograms show the activity of a single neuron during a precision grip and a power grip. During the precision grip the neuron's activity is the same whether overall force is light or heavy and the level of electromyographic (EMG) activity in the target muscle is similar for both forces. During the power grip there is almost no activity in the neuron despite a greater amount of EMG activity in the muscle. Thus, even if a given motor neuron is monosynaptically connected to a given CM cell, their firing patterns do not have to parallel each other because the multiplicity of connections to motor neurons allows task flexibility. (**imp/s** = impulses per second.) (Maier et al 1993.)

The specific role of the supplementary motor area in the internal representation of sequences of movements was examined in another experiment, in which recordings were made from neurons in the primary motor cortex, supplementary motor area, and lateral premotor areas of monkeys while the animals performed two variations of an *instructed-delay task*. In this type of task subjects are taught which movements to make and later given a cue telling them when to make the movements. The monkeys in this experiment were instructed to touch three panels in a specific sequence. In one variation the instruction was visual: Three panels were lit up in a sequence that the monkeys had to follow. In the other variation the monkeys were instructed to perform a previously memorized sequence. As expected, neurons in the primary motor cortex generally discharged before and during movements to the same degree for visually guided and memorized sequences. In contrast, many

supplementary motor area neurons fired only before and during performance of a memorized sequence. The reverse was true for the lateral premotor neurons (Figure 38-18). In addition, the movement-related discharge of some supplementary motor area neurons is specific to a particular sequence of movements such as pushing followed by turning a handle. The cells do not fire in connection with other combinations of the same movements. Thus the supplementary motor area seems to be involved in preparing movement sequences from memory in the absence of visual cues.

The main cortical input to the supplementary motor area arises from the presupplementary motor area (see Figure 38-4). This region projects only to the supplementary motor area and has no clear somatotopy. Whereas the supplementary motor area is involved in setting the motor programs for learned sequences, the presupplementary motor area is thought to be involved in learning these sequences. For example, in one study the presupplementary motor area was preferentially activated while subjects learned a new sequence of button presses; the supplementary motor area became active only during the performance of the movements once they were learned. This motor learning likely involves a continuous interchange of information with the prefrontal cortex (area 46) and other areas of cortex.

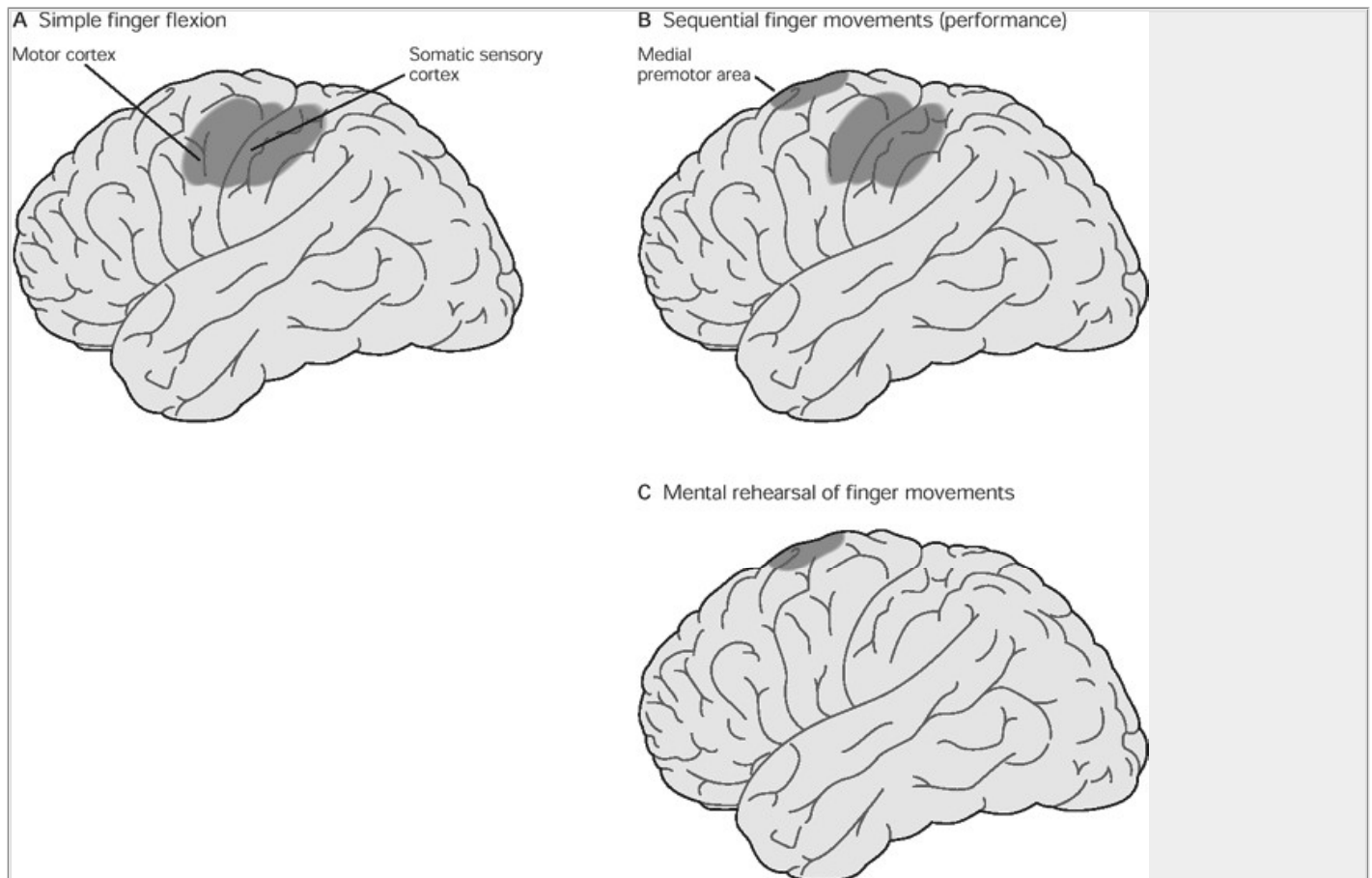


Figure 38-17 Different areas of cortex are activated during simple, complex, and imagined sequences of finger movements. Local increases in cerebral blood flow during a behavior indicate which areas of motor cortex are involved in the behavior. In the experiment illustrated here blood flow was measured by intravenously injecting radioactive xenon dissolved in a saline solution and measuring the radioactivity over different parts of cortex using arrays of detectors placed over the scalp. Because local tissue perfusion varies with neural activity, the measured radioactivity provides a good index of regional activity in the surface of the brain. (Adapted from Roland et al. 1980.)

A. When a finger is pressed repeatedly against a spring, increased blood flow is detected in the hand-control areas of the primary motor and sensory cortices. The increase in the motor area is related to the execution of the response, whereas the increase in the sensory area reflects the activation of peripheral receptors.

B. During a complex sequence of finger movements the increase in blood flow extends to the medial premotor area, which includes the supplementary motor area (SMA) and presupplementary motor area (preSMA).

C. During mental rehearsal of the same sequence illustrated in part B, blood flow increases only in the medial motor area.

When proficiency and skill are gained, the neural control of task performance can also shift from the supplementary motor area to the primary motor cortex. In one recent study with monkeys, premovement activity in the supplementary motor area during the performance of a key-pressing task disappeared after 12 months of overtraining. Subsequently, an experimental lesion in the right primary motor cortex of these overtrained monkeys caused weakness in the left digits, thereby greatly compromising the monkeys' ability to perform the task. After 21 days the monkeys had recovered sufficiently to press the keys with the same skill as before they received the lesion. Twenty-two days after the monkeys received the lesion recordings from the supplementary motor area showed that neurons were again very active before movement.

Much as extended practice influences the extent of

motor representation in the primary motor cortex, a shift in representation occurs in the supplementary motor cortex as a task goes from being novel to automatic. Conversely, recovery of function following damage to the primary motor cortex represents a new learning challenge in which the supplementary and perhaps presupplementary motor areas participate anew.

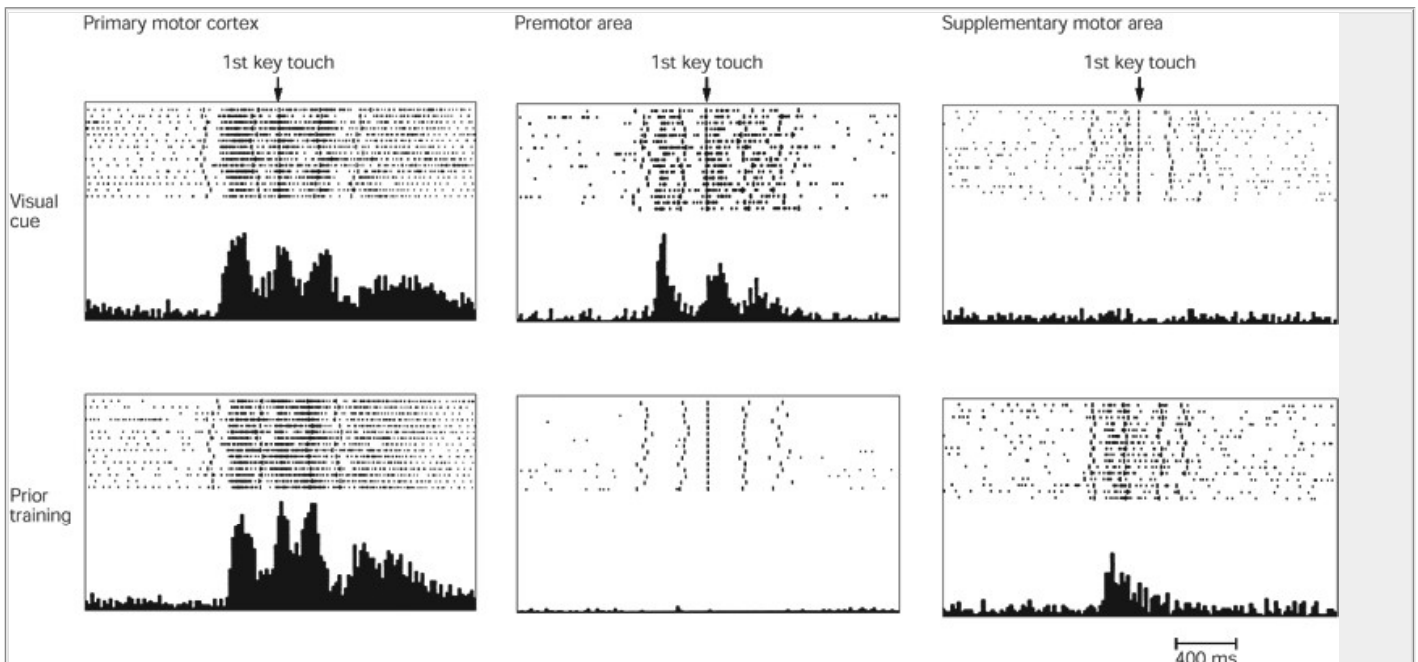


Figure 38-18 Cell activity in the motor cortex depends on whether a sequence of movements is guided by visual cues or by prior training. Monkeys were required to press three buttons either in a sequence presented by lighting three panels in turn or in a sequence they had learned previously. After being instructed to perform the observed sequence or the trained sequence, there was a delay before the animal was given a signal to initiate the movement. Raster plots represent cell discharge before and during movement on 16 trials, and the histogram shows the summed activity over all trials. Data are aligned to the onset of the first key touch. The cell in the primary cortex fired whether the sequence performed was the one learned in prior training or the one cued by lighted panels. The cell in the lateral premotor area fired only when the visually cued sequence was used, whereas the cell in the supplementary motor area fired only when the trained sequence was used. (From Mushiaké 1991.)

The Lateral Premotor Areas Contribute to the Selection of Action and to Sensorimotor Transformations

Selection of appropriate action can be the result of internal reflection, which may involve evocation of mental imagery. More often, however, actions are responses to visual or auditory cues. Such cues may signify that a particular action is required immediately (eg, a red light telling us to stop) or that some type of situation is imminent in which action will be required (eg, a yellow light signaling an imminent change to red). The ability to learn new, adaptive responses to particular environmental stimuli is crucial to effective and accurate movement.

We have seen that set-related activity occurs in the primary motor cortex and supplementary motor area before movement is executed. In the primary motor cortex this activity represents specific parameters of a particular movement; in the supplementary motor area it represents a specific order of responses. In the lateral premotor areas it represents how visual or other sensory stimuli are to be used to direct the movement. Characteristically, set-related activity in the premotor area persists during the entire interval between an anticipatory cue and the signal to move (Figure 38-19).

Set-related activity in the lateral dorsal premotor area is related predominantly to sensory stimuli that do not convey spatial cues to direct movement. For example, the stimulus could be a light in a location that is not

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related to the direction in which the movement is to be executed. Thus the lateral dorsal premotor area is involved in learning to associate a particular sensory event with a specific movement (associative learning). Consistent with this, monkeys with lesions in the lateral dorsal premotor area have difficulty with associative learning. In one study monkeys were taught to associate pulling or pushing a joystick with a particular background light (red or blue). The lateral premotor cortex was then removed from both hemispheres and the animals were retrained two weeks after surgery. Although the monkeys were able to execute the required movements without impairment, none was able to relearn the association between the background color and whether to push or pull.

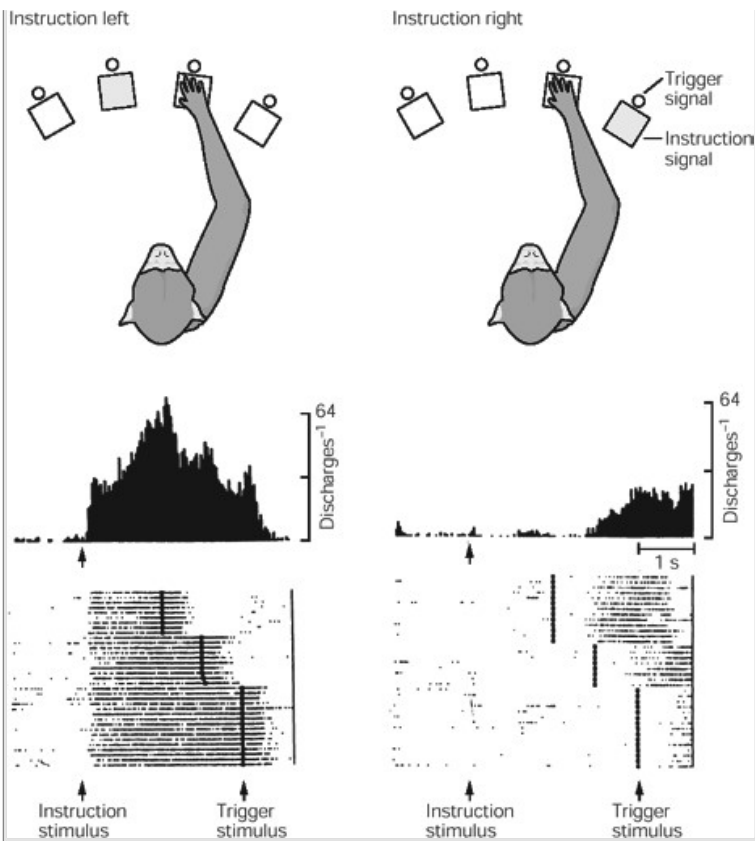


Figure 38-19 A set-related neuron in the dorsal premotor area becomes active while the monkey prepares to make a movement to the left. An instruction signal (illumination of one of four panels) tells the monkey which panel it will have to depress when a trigger signal (illumination of a nearby light-emitting diode) is presented. In the raster plots each dot on each line represents a spike in the recorded neuron. Each line is one trial, and successive trials are aligned on the onset of the instruction signal. The delay between the instruction and trigger signals varied randomly among three values. In the raster plots and histograms the responses made with each delay time are grouped to show that the discharge of the neuron coincides with the instruction signal and lasts until the response is made after the trigger signal. (From Weinrich and Wise 1982.)

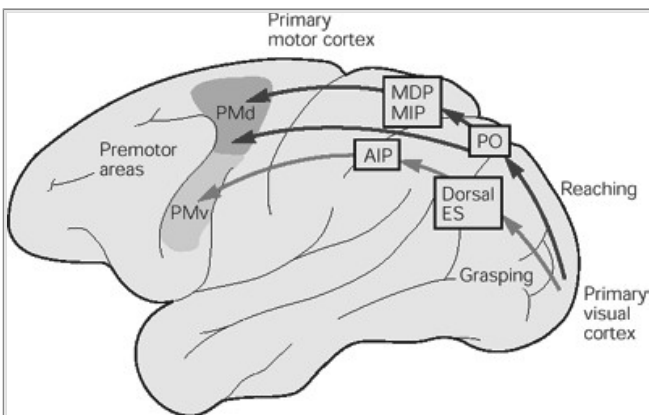


Figure 38-20 The visuomotor transformations required for reaching and grasping involve two different pathways from the primary visual cortex to the premotor areas.

Reaching. A path connects the parieto-occipital extrastriate area (**PO**) and the dorsal premotor area (**PMd**). Some of these connections reach PMd directly, and some relay via areas in the intraparietal sulcus: the medial dorsal parietal (**MDP**) and medial intraparietal (**MIP**) areas. This system is responsible for transforming visual information about the location of objects in extrapersonal space into the direction of a reaching movement.

Grasping. A path connects the dorsal extrastriate (**ES**) cortex and the ventral premotor area (**PMv**) via the anterior intraparietal area (**AIP**). This system is responsible for transforming visual information about the properties of objects, such as shape and size, into commands for effective grasping.

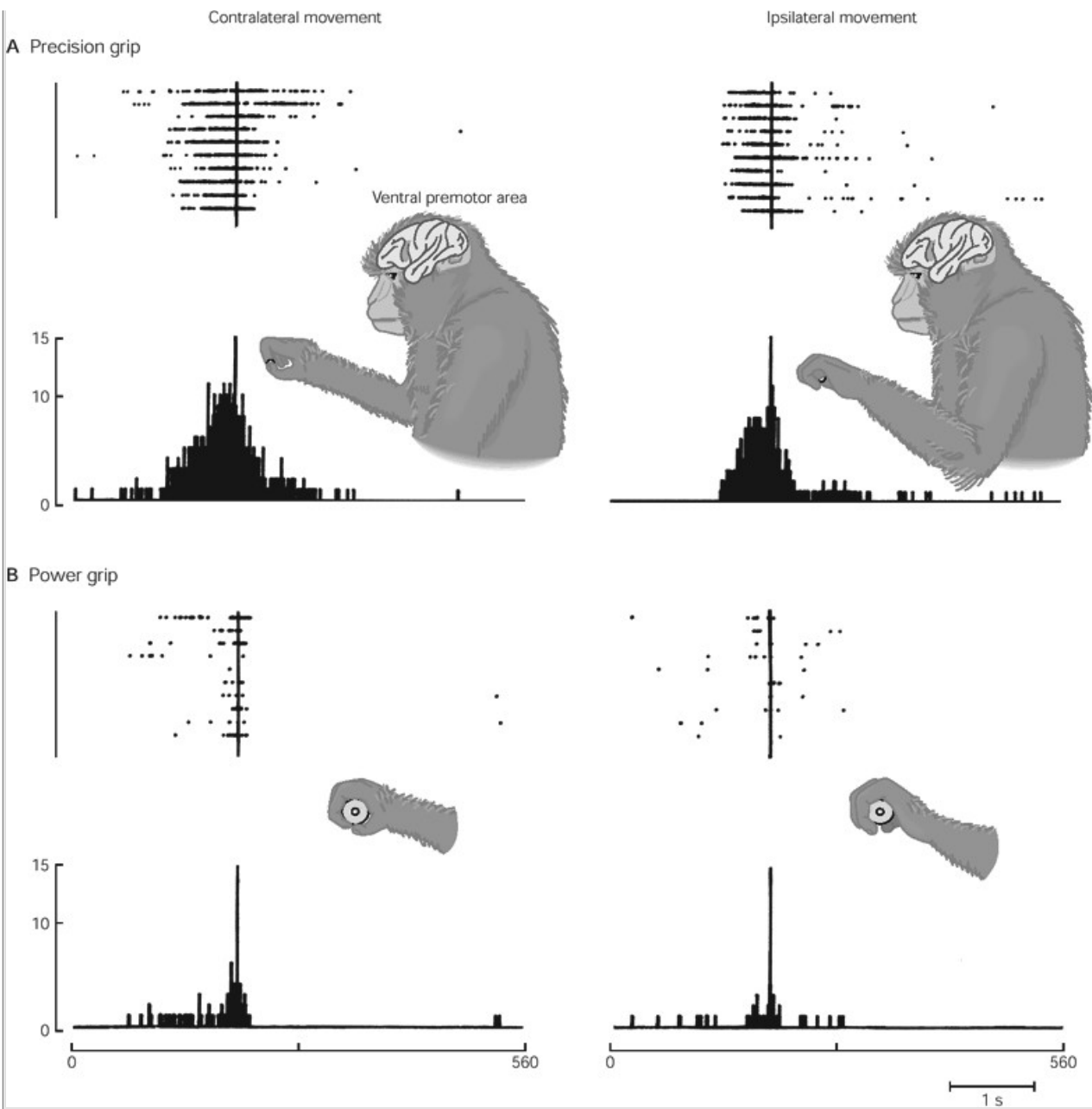


Figure 38-21 Individual neurons in the ventral premotor area fire during specific hand actions only. Raster plots and cumulative histograms show the discharge of a single neuron in the lateral ventral premotor area (F5) of a monkey during a precision grip and a power grip involving all the fingers. The cell is active during the precision grip by either arm but not during the power grip by either arm. Thus its activity is specific to the grip type employed by either hand. The fact that the neuron is active during movement of both arms excludes the possibility that this difference is due solely to the different patterns of corticospinal activation required by the two grips; if this were the case, only contralateral activation would occur. (From Rizzolatti et al. 1996.)

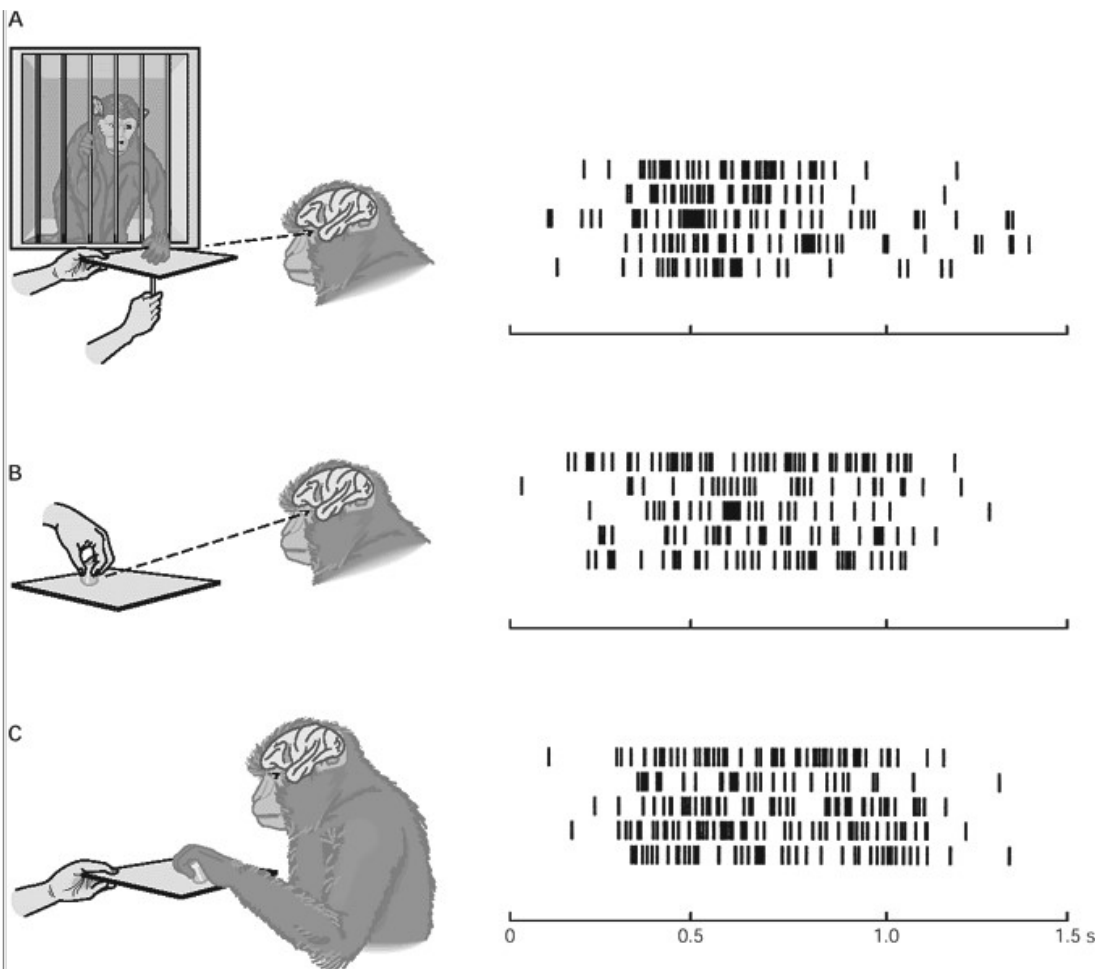


Figure 38-22 An individual cell in the ventral premotor area is active whether the monkey performs a task or observes someone else perform the task. The fact that the same cell is active during action or observation suggests that it is involved in the abstract representation of the motor task.

- A.** Activity in the neuron as the monkey observes another monkey make a precision grip.
- B.** Activity in the same neuron as the monkey observes the human experimenter make the precision grip.
- C.** Activity in the same neuron as the monkey itself performs a precision grip. (From Rizzolatti et al 1996.)

Reaching and Grasping Are Mediated by Separate Parieto-Premotor Channels

Goal-directed movements require transformation of sensory representations of the environment into muscle-control

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signals, a process termed *sensorimotor transformation*. Reaching, a goal-directed movement, requires that visual information about target location and the position of the upper limb be used to specify critical features of the upcoming arm movement. In addition, reaching is commonly coupled with grasping an object.

The parameters for reaching movement, notably direction and extent, depend on the location of the target relative to the body, shoulder, or hand. Grasping, in contrast, is governed mainly by the shape and dimensions of the object. Grasping involves first a separation of the fingers sufficient to enclose the object and then closure as the object is gripped between the pads. Separation of the fingers occurs during transport of the hand toward the object. The kinematics of grasping thus depend on the object itself and not on its location. Thus reaching and grasping are interesting behaviors to study in order to better understand the process of visuomotor transformation.

Anatomical evidence and single-cell recordings have shown that separate but parallel parieto-premotor channels mediate visuomotor transformations required for reaching and grasping (Figure 38-20). During reaching, neurons in parietal area 5 code for direction of the movement but discharge later than dorsal premotor neurons to which they are connected. These neurons could monitor ongoing movements and improve the planning and execution of subsequent reaches by premotor areas.

During grasping, different neurons in the lateral ventral premotor area of monkeys fire in connection with different hand actions and object shapes. These neurons are active throughout reach, well before the fingers begin to grasp. Moreover, different cells fire during different patterns of hand shaping. Some neurons are active only when the action is a precision grip; others are active only when the action is a swiping movement to retrieve food; still others are active only if the action is a power grip (Figure 38-21A). The cells in the lateral ventral premotor area thus seem to direct motor acts that can be guided by visual information about object shape received from the posterior parietal cortex. Another set of neurons discharges whether an object is grasped or bitten.

A unique type of neuron has been discovered in the lateral ventral premotor area. Like others, these neurons discharge when the monkey performs a specific grasping movement, but they also discharge when the monkey observes the same movement being made by another monkey or even by the experimenter. These neurons have been called *mirror neurons* (Figure 38-22).

These different neurons all share the characteristic of encoding a vocabulary of goal-directed behaviors rather than how these behaviors will be carried out.

The ventral premotor area receives its main input from neurons with similar task related properties in the anterior intraparietal region, a region buried in the intraparietal sulcus. Recordings of these neurons were made while a monkey performed a series of tasks involving several different switches and knobs. Cells fired selectively when particular switches were grasped and also fired when the monkey visually fixated the same switch without grasping it. These cells may have a role in transforming the dimensions of an object in visual space into motor signals.

An Overall View

Our understanding of the functional organization of the motor areas of the cerebral cortex has undergone substantial change in recent years, as a new picture of the cortical control of movement has emerged. The primary motor cortex can no longer be seen as a simple motor map of the body, in which adjacent muscles or joints are represented in adjacent cortical sites. Instead, individual muscles and joints are represented repeatedly in a complex mosaic that makes it possible for the cortex to

organize combinations of movements suitable to specific tasks. Each muscle and joint is represented by columnar arrays of neurons whose axons branch and make connections with several functionally related motor nuclei. This branching is more modest for cells that control distal muscles, providing these muscles with more independent control.

In addition to terminating on spinal motor neurons, corticospinal neurons also terminate on interneurons in the spinal cord. These connections can gate reflex circuits, allowing voluntary movements to take advantage of spinal circuits, as these circuits can link local sensory input to output.

Distinct populations of motor cortical neurons appear to have specialized roles in determining specific features of motor performance. The characteristics of these different populations and their distribution within the motor areas of cortex point to a hierarchical organization of motor tasks. Thus most neurons in the primary motor cortex become active only shortly before and during movement. Neurons of the primary motor cortex differ from spinal motor neurons in that the former fire only in connection with certain tasks and spatial patterns of muscle activation (eg, precision grip versus

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power grip), they encode a more restricted range of contractile force than do spinal motor neurons, and some even encode decrements in force. The kinematic details of movement are determined by population codes, the summed activity of entire populations of neurons.

In contrast to neurons in the primary motor cortex, movement-related neurons in the premotor areas may fire during movements that are related to specific tasks and not others to encode a more global feature. Set-related neurons, which are relatively rare in the primary motor cortex, are more common in premotor areas. These cells are active in the absence of any overt behavior, such as during a delay between task instructions and execution of the task. Some encode a response to be made after a delay; others encode a global sensorimotor transformation (eg, "always move at 180 degrees from the visual stimulus"). Thus, just as there is a hierarchy of spinal and supraspinal motor control, there is a hierarchy of neuronal representations of task features within the different cortical areas.

The planning and execution of voluntary movement relies on sensorimotor transformations in which representations of the external environment are integrated into motor programs. This integration is the product of premotor and primary motor areas operating in conjunction with sensory and association areas. We have seen an example of this in the communication between parietal and motor areas during visually guided reaching.

In contrast to reflex movements, voluntary movements are highly adaptable—they improve in speed and accuracy with repeated trials of practice. This adaptability may reflect an optimization process in which the minimal circuits needed to accomplish a behavior are, with training, selected from redundant sensorimotor connections. Such an optimization process could be responsible for the observed shift in the encoding of particular parameters of movement from one group of cells to another, or from one area of cortex to another, as proficiency develops.

A novel behavior initially requires processing in multiple motor and parietal areas as it is continuously monitored for errors and subsequently modified. As the behavior becomes more accurate, the need for sampling of the sensory inflow and updating of the motor program decreases and the need for the computational power of large networks lessens. For example, the presupplementary motor area is active during the learning of a behavior but becomes less active as learning progresses. After long periods of practice, when the behavior becomes automatic, activity in the supplementary motor area ceases.

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