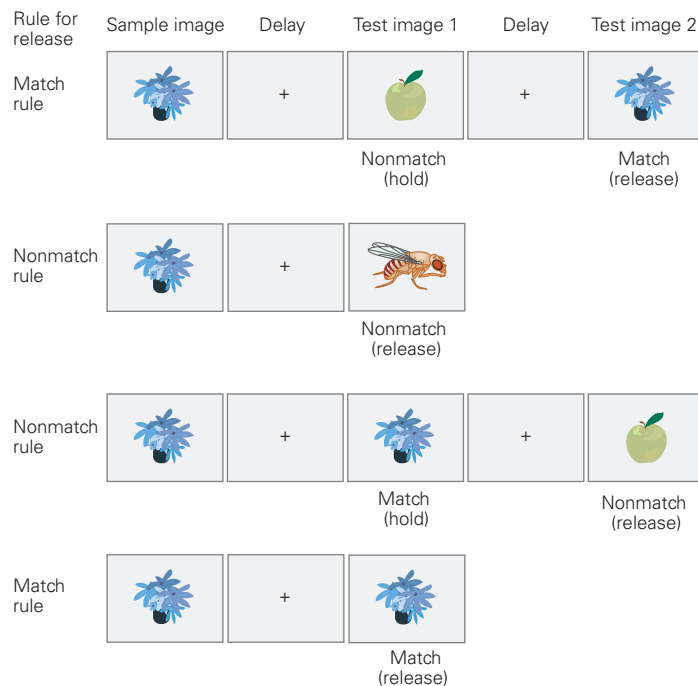
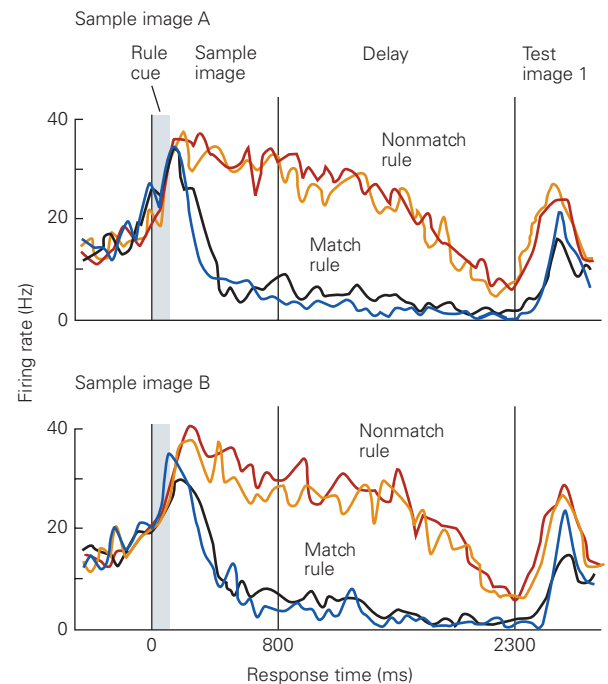


**A** Delayed match-to-sample task**B** Premotor neurons show rule-dependent activity

**Figure 34–11** Premotor cortex neurons in the monkey choose particular voluntary behaviors based on decisional rules. (Reproduced, with permission, from Wallis and Miller 2003.)

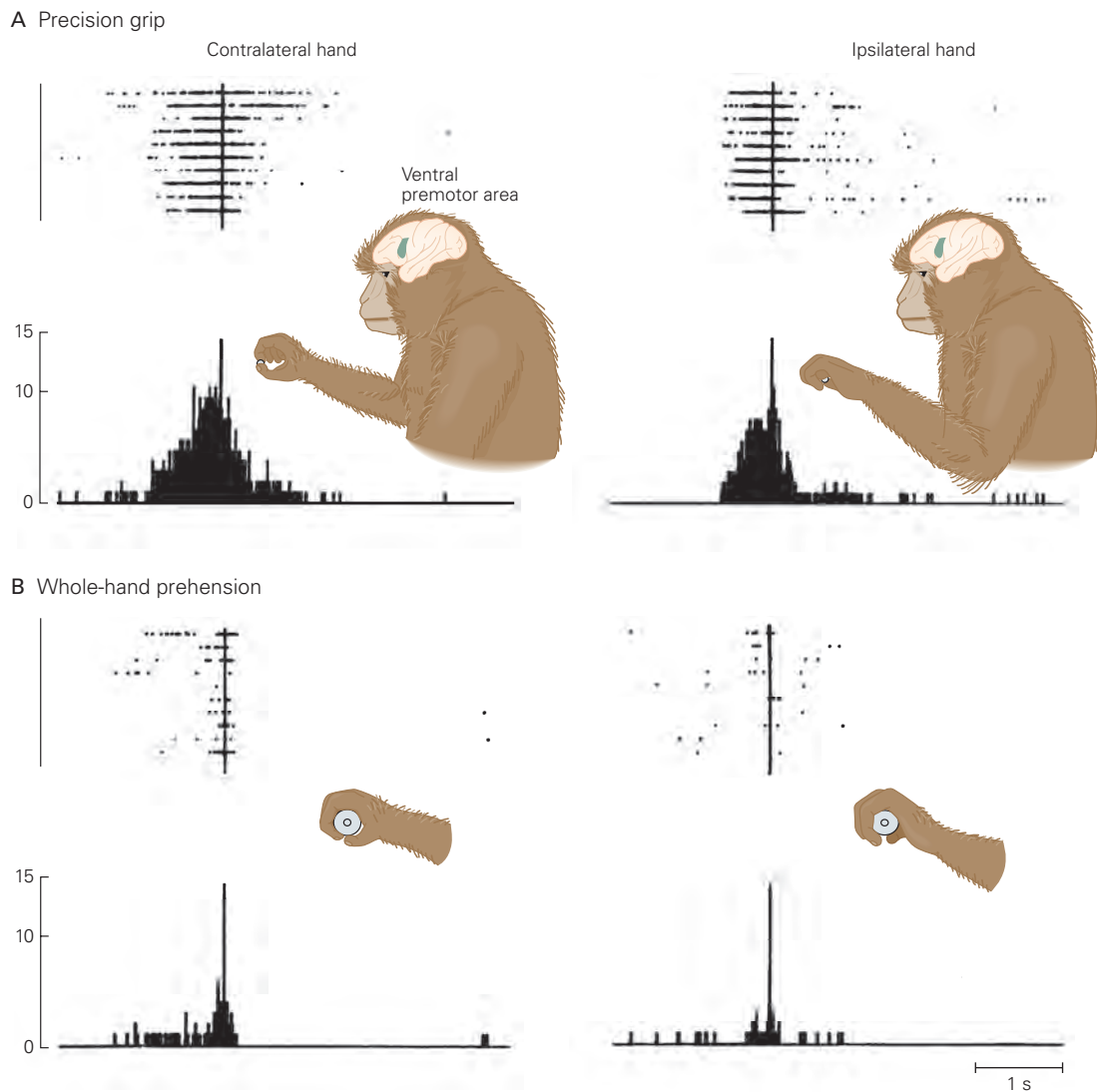
**A.** A monkey must make a decision about whether to release a lever or keep holding it based on two prior decisions: a perceptual choice, whether a test image is the same as or different from a sample image presented earlier, and a behavioral choice, whether the current rule is to release the lever when the test image is the same as the sample (match rule) or when it is different (nonmatch rule). The monkey is informed of the behavioral rule that applies in each trial by a rule cue, such as an auditory tone or juice drops, which is presented for 100 ms at the same time as the onset of the sample image at the start of the trial.

**B.** A neuron in the dorsal premotor cortex has a higher discharge rate whenever the nonmatch rule is in effect during the delay between the presentation of the first and second images. The responses to two different sample images (upper and lower plots) were recorded from the same cell, indicating that the rule-dependent activity is not altered by changing the images. Nor, as shown by the pairs of curves associated with each rule, does activity depend on the type of rule cue (auditory tone or juice drops). (Tone cue trials: orange and blue curves; juice cue trials: red and black curves). Other dorsal premotor cortex cells (not shown) respond preferentially to the match rule over the nonmatch rule. The differential activity of the neuron up to presentation of the test image reflects the rule that will guide the animal's motor response to the test image, not the physical properties of the visual stimuli or the motor response.

presented; (4) compare  $f_2$  to the memory trace of  $f_1$ ; (5) decide whether the frequency of  $f_2$  is higher or lower than that of  $f_1$ ; and finally, (6) use that decision to choose the appropriate movement of the other hand. Everything prior to the last step would appear to fall entirely within the domain of sensory discriminative processing.

While the monkeys performed the task, neurons in the primary (S-I) and secondary (S-II) somatosensory cortices encoded the frequencies of the stimuli while they were presented. During the interval between  $f_1$  and  $f_2$ , there was no sustained activity in S-I representing the memorized  $f_1$  and only a transient representation in S-II, which vanished before  $f_2$  was presented.

Strikingly, however, the activity of many neurons in the prefrontal cortex, SMC, and PMv scaled with the frequencies of  $f_1$  and  $f_2$  while they were being delivered. Furthermore, some prefrontal and premotor neurons showed sustained activity proportional to the frequency of  $f_1$  during the delay period between  $f_1$  and  $f_2$ . Most remarkably, many neurons in those areas, especially in PMv, encoded the *difference* in frequency between  $f_2$  and  $f_1$  independently of their actual frequencies when  $f_2$  was delivered (Figure 34–13). This centrally generated signal is appropriate to mediate the perceptual discrimination that determines which button to push. Neurons that encoded the  $f_2$ – $f_1$  difference were absent in S-I and were far more common in SMC and PMv than in S-II.



**Figure 34-12** Some neurons in the ventral premotor cortex of a monkey discharge selectively during one type of grasping. This neuron discharges vigorously during a precision grip with the thumb and index finger of either the right or the left hand but very weakly during whole-hand prehension with either hand.

Raster plots and histograms are aligned (vertical line) with the moment the monkey touches the food (A) or grasps the handle (B). (Reproduced, with permission, from Rizzolatti et al. 1988. Copyright © Springer-Verlag 1988.)

### Several Cortical Motor Areas Are Active When the Motor Actions of Others Are Being Observed

Some premotor and parietal areas can be activated when no overt action is intended, such as when an individual is asked to imagine performing a certain motor act. This phenomenon, termed *motor imagery*, has been demonstrated in humans using functional brain imaging. The neural activity evoked by motor imagery presumably reflects brain mechanisms associated with motor planning and preparation that have been disassociated from its overt execution.

A second condition in which cortical motor circuits are activated without intending overt action is when an individual observes another individual performing motor acts that are part of her own motor repertoire. The control of behavior and social interaction depends greatly on the ability to recognize and understand what others are doing and why they are doing it. Such understanding could result from a high-order visual perceptual analysis of the nature of the observed behavior and by drawing inferences about the motivation and purpose of the behavior based on

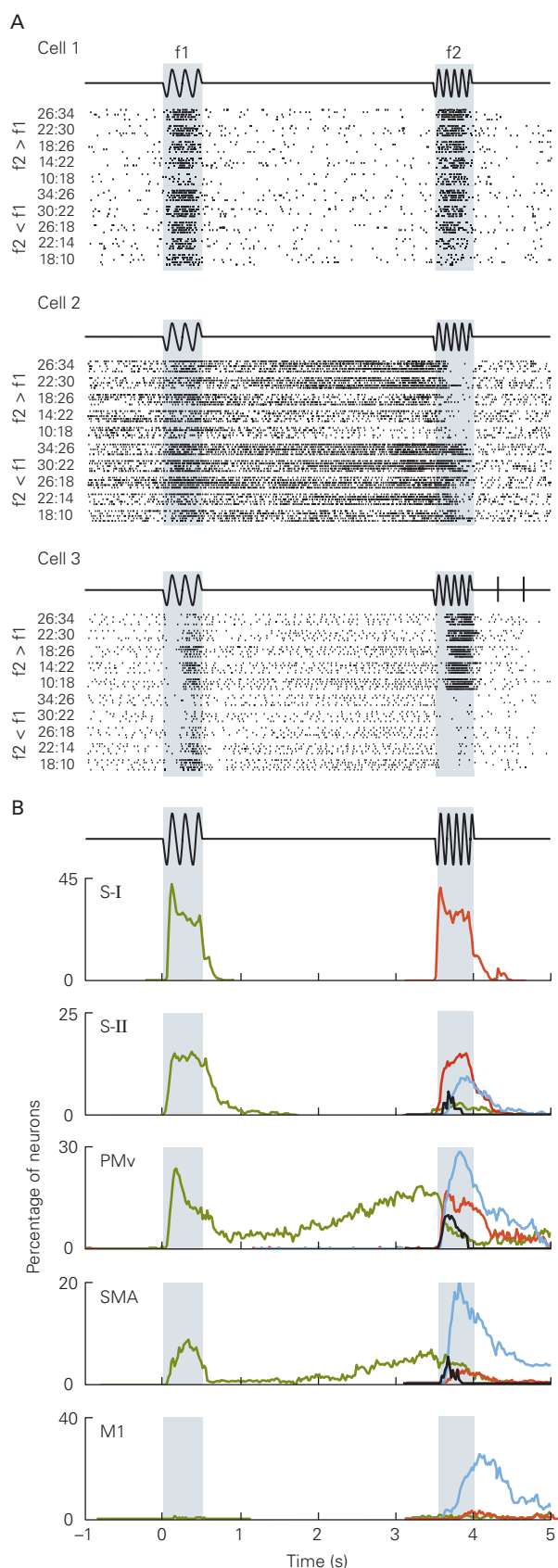
one's own experience. An alternative explanation is the *direct-matching hypothesis*, the idea that observation of the actions of others activates motor circuits in the observer that control similar motor actions. According to this hypothesis, empathetic activation of motor circuits could provide a link between the observed actions and the observer's stored knowledge of the nature, motives, and consequences of similar actions that they had performed in the past.

Striking evidence in support of the direct-matching hypothesis was provided by the discovery of a remarkable population of neurons called mirror neurons, first in PMv and later in the parietal AIP of monkeys. Mirror neurons discharge both when the monkey actively grasps and manipulates objects and when it observes similar actions performed by another monkey or the experimenter (Figure 34–14). Mirror neurons typically do not respond when a monkey simply observes a potential target object or when it observes mimed arm and hand actions without a target object. Some parietal mirror neurons can even differentiate the ultimate goal of similar observed actions, such as grasping and picking up food to eat it versus putting it into a cup.

**Figure 34–13** (Right) Neural activity in ventral premotor cortex in monkeys expresses the operations required to choose a motor response based on sensory information. (Adapted, with permission, from Romo, Hernández, and Zainos 2004. Copyright © 2004 Cell Press.)

**A.** These records of three neurons in the ventral premotor cortex of a monkey were made while the animal performed a task in which it had to decide whether the second of two vibration stimuli (**f1** and **f2**, applied to the index finger of one hand) was of higher or lower frequency than the first. The choice was signaled by pushing one of two buttons with the nonstimulated hand. The frequencies of **f1** and **f2** are indicated by the numbers on the left of each set of raster plots. Cell 1 encoded the frequencies of both **f1** and **f2** while the stimuli were being presented but was not active at any other time. This response profile resembles that of many neurons in the primary somatosensory cortex. Cell 2 encoded the frequency of **f1** and sustained its response during the delay period. During the presentation of **f2**, the neuron's response was enhanced when **f1** was higher than **f2** and suppressed when it was lower. Cell 3 responded to **f1** during stimulation and was weakly active during the delay period. However, during exposure to **f2**, the cell's activity robustly signaled the difference **f2**–**f1** independently of the specific frequencies **f1** and **f2**.

**B.** Histograms show the percentage of neurons in different cortical areas whose activity correlated at each instant with different parameters during the tactile discrimination task. **Green** shows the correlation with **f1**, **red** the correlation with **f2**, **black** the interaction between **f1** and **f2**, and **blue** the correlation with the difference between **f2**–**f1**. (**Abbreviations:** **M1**, primary motor cortex; **PMv**, ventral premotor cortex; **S-I**, primary somatosensory cortex; **S-II**, secondary somatosensory cortex; **SMA**, supplementary motor area.)



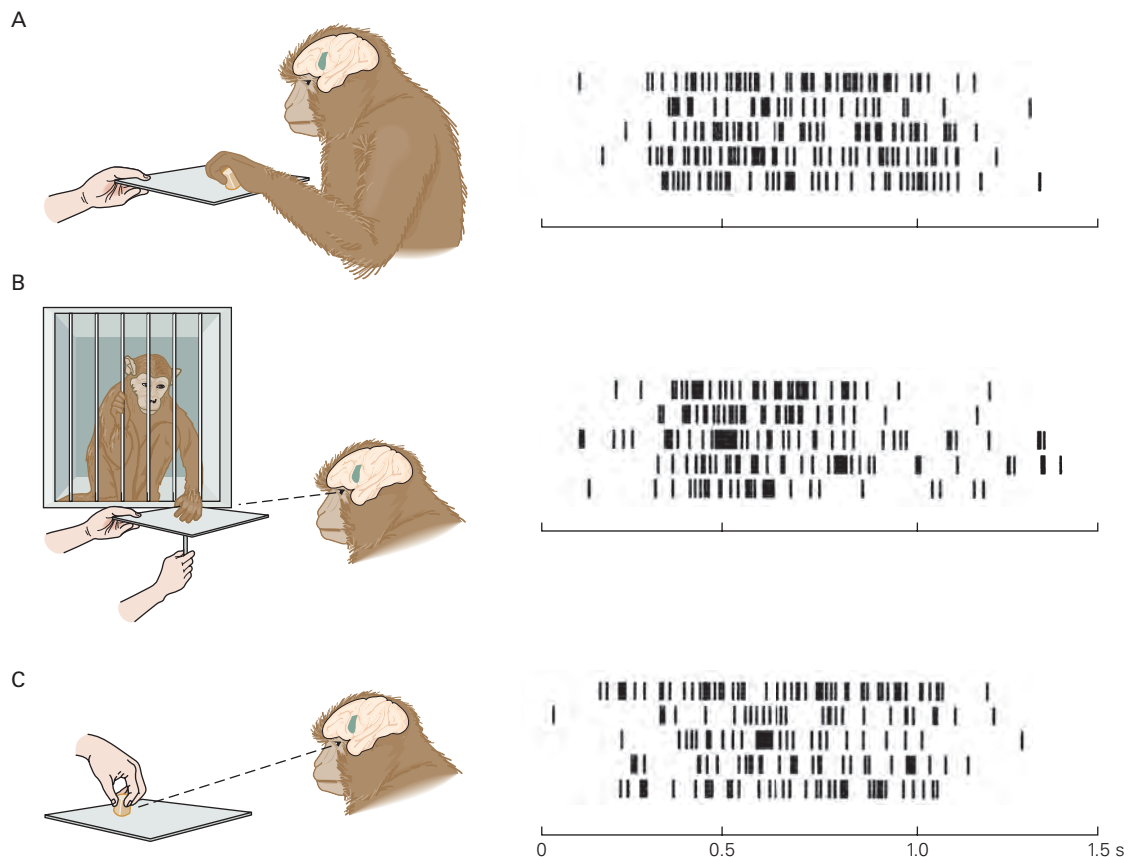
Neural-recording and brain-imaging studies show that humans are also endowed with a mirror-like mechanism to match observed actions with actions encoded in their motor system. This activity arises in various areas of cortex, including the rostral inferior parietal lobule, IPS, PMv, and posterior sector of the inferior frontal gyrus.

Cortical motor circuits appear to be involved in understanding and predicting the outcomes of observed events. In one experiment, PMd neurons implicated in the selection of reaching targets using visual cues (Figure 34–8) also discharged when monkeys simply watched the same cues and cursor motions on the monitor while an unseen party performed the task. The monkeys received a free juice reward when the cursor moved to the correct target but not if it moved to the wrong target. The monkeys began to lick the juice tube shortly after the cursor started to move to the correct target well before the juice was actually delivered, but

quickly removed their mouth from the tube when the cursor moved toward the wrong target. This behavior showed that the monkeys correctly interpreted what they saw and accurately predicted its consequences.

Remarkably, the activity of most of the task-related PMd neurons was strikingly similar whether the monkeys used visual cues to plan and make arm movements or simply observed the visual events and predicted their outcome. Those neurons stopped responding during observation if no reward was delivered after correct trials or if the animal was sated and not interested in drinking juice. This showed that the neurons were not simply responding to the sensory inputs, but instead were processing the observed sensory events to predict their ultimate outcome for the monkey, namely the likelihood of a free juice reward.

This activation in connection with passive observation supports the idea that activation of premotor



**Figure 34–14** A mirror neuron in the ventral premotor cortex (area F5) of a monkey. (Reproduced, with permission, from Rizzolatti et al. 1996. Copyright © 1996 Elsevier Science B.V.)

- A. The neuron is active when the monkey grasps an object.
- B. The same neuron is also excited when the monkey observes another monkey grasping the object.

C. The neuron is similarly activated when the monkey observes the human experimenter grasping the object.

Time zero in the cell activity rasters corresponds approximately to the time of presentation of the object to grasp (panel A) or the onset of the observed grasping actions (panels B and C).

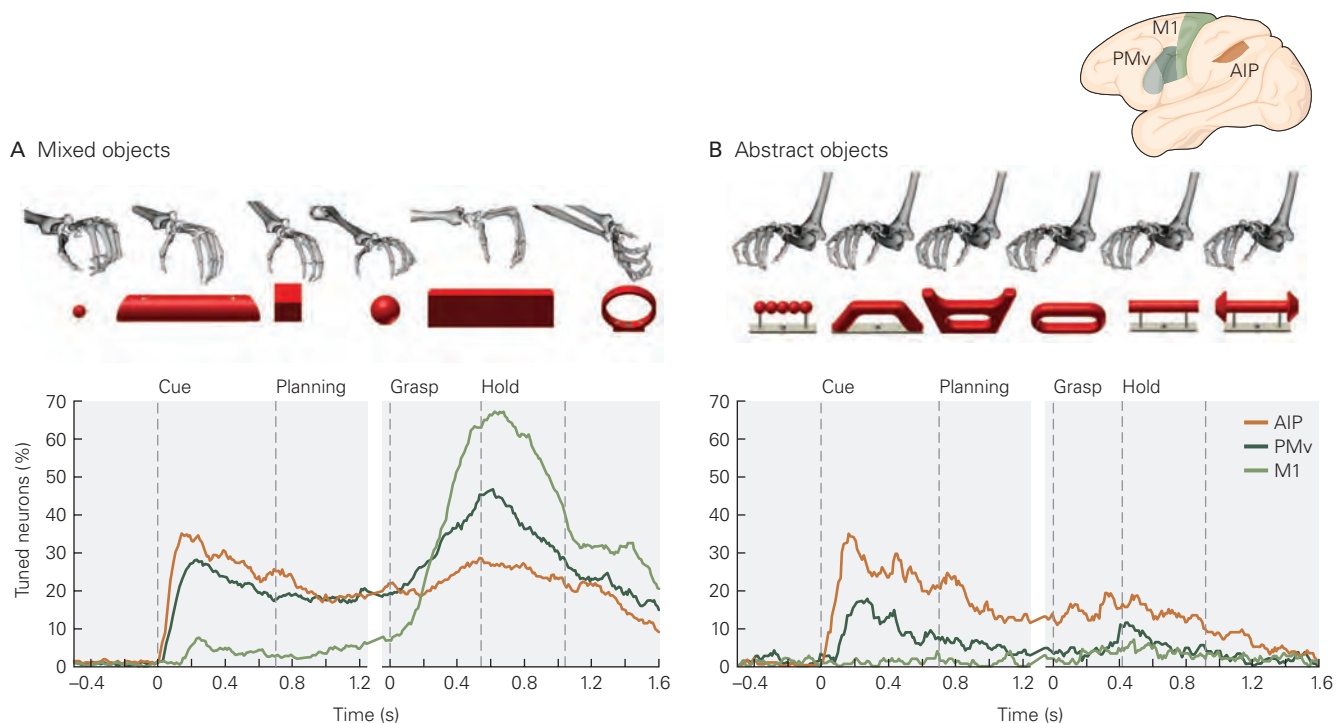
circuits in nonmotor contexts may contribute to understanding the nature and consequences of observed events in the environment. It has also been implicated in the ability of human subjects to learn new motor skills simply by observing a skilled person perform the same actions. Moreover, dysfunction of the mirror-neuron system in young children may contribute to some of the symptoms of autism.

### Many Aspects of Voluntary Control Are Distributed Across Parietal and Premotor Cortex

While we have described the roles of premotor areas in parietal and precentral cortex separately, it must be

emphasized that major sensorimotor control processes are shared across multiple cortical regions via their reciprocal interconnections.

For instance, the neural processes that link the physical affordances of target objects to appropriate hand actions are distributed across parietal area AIP, premotor area PMv, and M1, with visuospatial aspects of the process more prominent in AIP and motor components more prevalent in precentral cortex (Figure 34–15). Likewise, as already noted, neural correlates of reach target selection in PRR (Figure 34–8B) strikingly resemble those reported in PMd (Figure 34–8A).



**Figure 34–15** Visuomotor processing of object shape is distributed across several cortical areas in the monkey. (Reproduced, with permission, from Schaffelhofer and Scherberger 2016.)

**A.** A set of “mixed” objects elicit different visual responses and require different motor responses to grasp them. The plots show the percentages of neurons in the anterior intraparietal areas (AIP; orange), ventral premotor cortex (PMv; F5; dark green), and primary motor cortex (M1; light green) that significantly modulated their response as a function of object identity across time. Monkeys were first shown the object to grasp (cue and planning periods) and then allowed to reach to, grasp, and hold the object (grasp and hold periods). The proportion of neurons that varied their activity across object types (tuned neurons) during the cue and planning periods was greatest in

AIP and least in M1, indicating that sensitivity to object visual shape was most prominent in AIP. During motor action (grasp and hold periods), the reverse pattern was observed, with many neurons in PMv and especially M1 displaying a strong dependence on the different grasping actions required to hold onto the different objects.

**B.** A set of “abstract” objects elicit different visual responses but require similar motor responses to grasp them. As with the “mixed” object set, many AIP neurons varied their activity as a function of object shape during the cue and planning periods, but fewer PMv and almost no M1 neurons showed sensitivity to observed object shape. During motor action (grasp and hold periods), very few PMv and M1 neurons showed any difference in activity as a function of the shape of the different objects, all of which required the same grasping action.



## The Primary Motor Cortex Plays an Important Role in Motor Execution

Once an individual has decided on a behavioral goal, motor commands must then be communicated to muscles to move the body. The complexity of this problem cannot be underestimated as it requires precise control of the spatiotemporal patterns of activity of large numbers of muscles acting across many joints to achieve the behavioral goal, while also accounting for the complex, nonlinear mechanical properties of the musculoskeletal system and forces and loads imposed by the environment. These detailed patterns of muscle activity are coordinated by spinal motor neurons and interneuronal circuits (Chapter 32). However, the primary motor cortex (M1) plays an important role in generating the motor commands that control that spinal activity, including essential information necessary to select and control the timing and magnitude of muscle activity.

### The Primary Motor Cortex Includes a Detailed Map of the Motor Periphery

The idea that a local region of the cerebral cortex contains a motor map of the body dedicated to voluntary motor control dates back to the work of the English neurologist John Hughlings Jackson in the middle of the 19th century. He reached this conclusion while treating patients with epileptic seizures that were characterized by recurring spasmodic involuntary movements that sometimes resembled fragments of purposive voluntary actions and that progressed systematically to include different parts of the body during each seizure episode (Chapter 58). Later in the 19th century, improved anesthesia and aseptic surgical techniques allowed direct experimental study of the cerebral cortex in experimental animals. Using those new methods, Gustav Fritsch and Eduard Hitzig in Berlin and David Ferrier in England showed that electrical stimulation of the surface of a limited area of cortex in different anesthetized mammalian species evoked movements of parts of the contralateral body. In monkeys, the electric currents needed to evoke movements were lowest in a narrow strip along the rostral bank of the central sulcus, the same region now called primary motor cortex.

Their experiments demonstrated that within this strip of tissue stimulation of adjacent sites evoked movements in adjacent body parts, starting with the foot, leg, and tail medially, and proceeding to the trunk, arm, hand, face, mouth, and tongue more laterally. When they lesioned a cortical site at which stimulation had evoked movements of a part of the body,

movement of that body part was perturbed or lost after the animal recovered from surgery. These early experiments showed that the motor cortex contains an orderly motor map of major parts of the contralateral body and that the integrity of the motor map is necessary for voluntary control of the corresponding body parts. Studies in the first half of the 20th century on many species by Clinton Woolsey and on humans undergoing surgery by Wilder Penfield demonstrated that the general topographic organization of the rostral bank of the central sulcus is conserved across many species (Figure 34–16). One important observation was that the motor map is not an exact point-to-point reproduction of the body's anatomical form. Instead, the most finely controlled body parts, such as the fingers, face, and mouth, are represented by disproportionately large areas, reflecting the larger number of neurons needed for fine motor control.

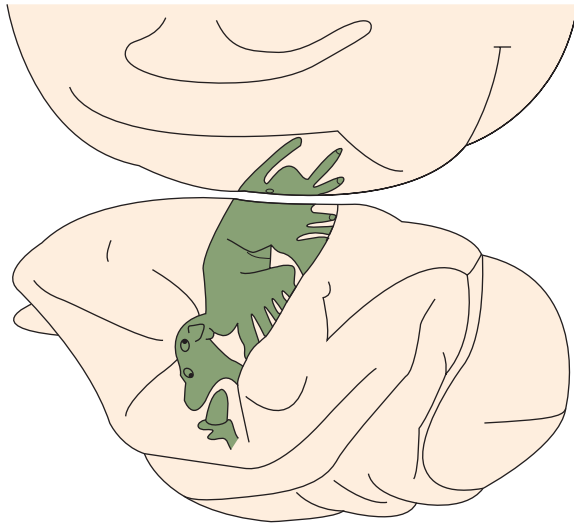
Today the best-studied regions of the map are those parts controlling the arm and hand and reveal far more complexity than conveyed in the classic diagrams shown in Figure 34–16A,B. First, neurons controlling the muscles of the digits, hand, and distal arm tend to be concentrated within a central zone, whereas those controlling more proximal arm muscles are located in a horseshoe-shaped ring around the central core (Figure 34–16C). Second, stimulation sites overlap extensively, allowing control of muscles acting across different joints; conversely, each muscle can be activated by stimulating many sites dispersed across the arm/hand motor map. Finally, local horizontal axonal connections link different sites across the motor map, likely allowing coordination of activity across the map during the formation of motor commands.

### Some Neurons in the Primary Motor Cortex Project Directly to Spinal Motor Neurons

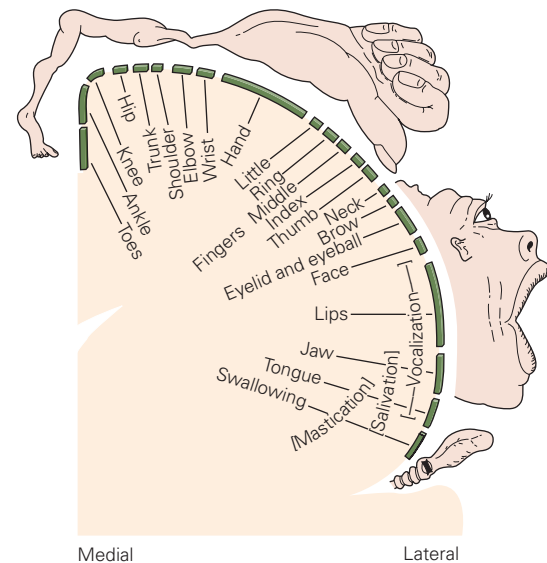
As already noted, while many corticospinal axons in primates terminate only on spinal interneurons, others also synapse directly onto spinal motor neurons. These corticomotoneuronal (CM) cells are found only in the most caudal part of M1 that lies within the anterior bank of the central sulcus. There is extensive overlap in the distribution of the CM cells that project to the spinal motor neuron pools innervating different muscles (Figure 34–17A).

CM cells are very rare or absent in nonprimate species and become a progressively larger component of the corticospinal tract in primate phylogeny from prosimians to monkeys, great apes, and humans. In monkeys, more CM cells project to the motor pools for muscles of the digits, hand, and wrist than to

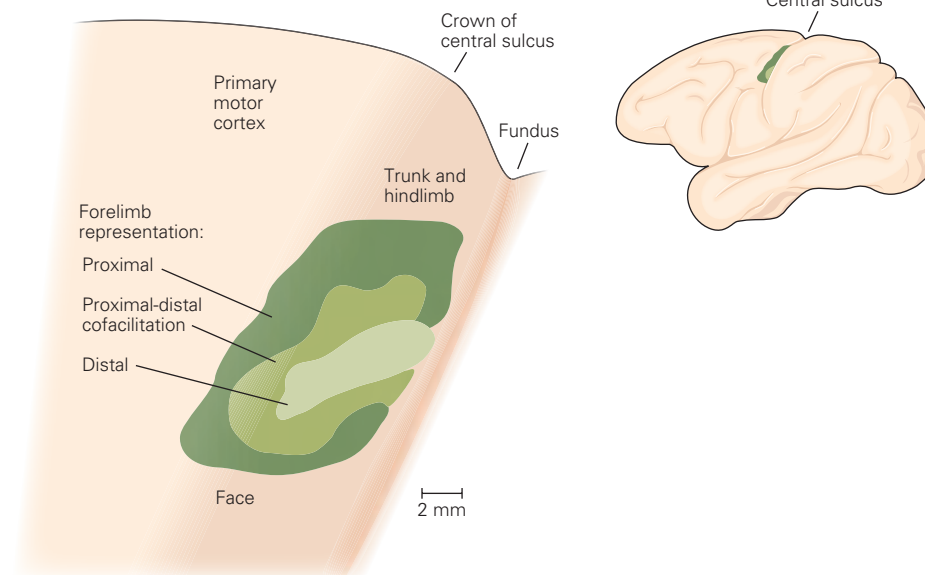
A Macaque monkey



B Human



C Forelimb representation



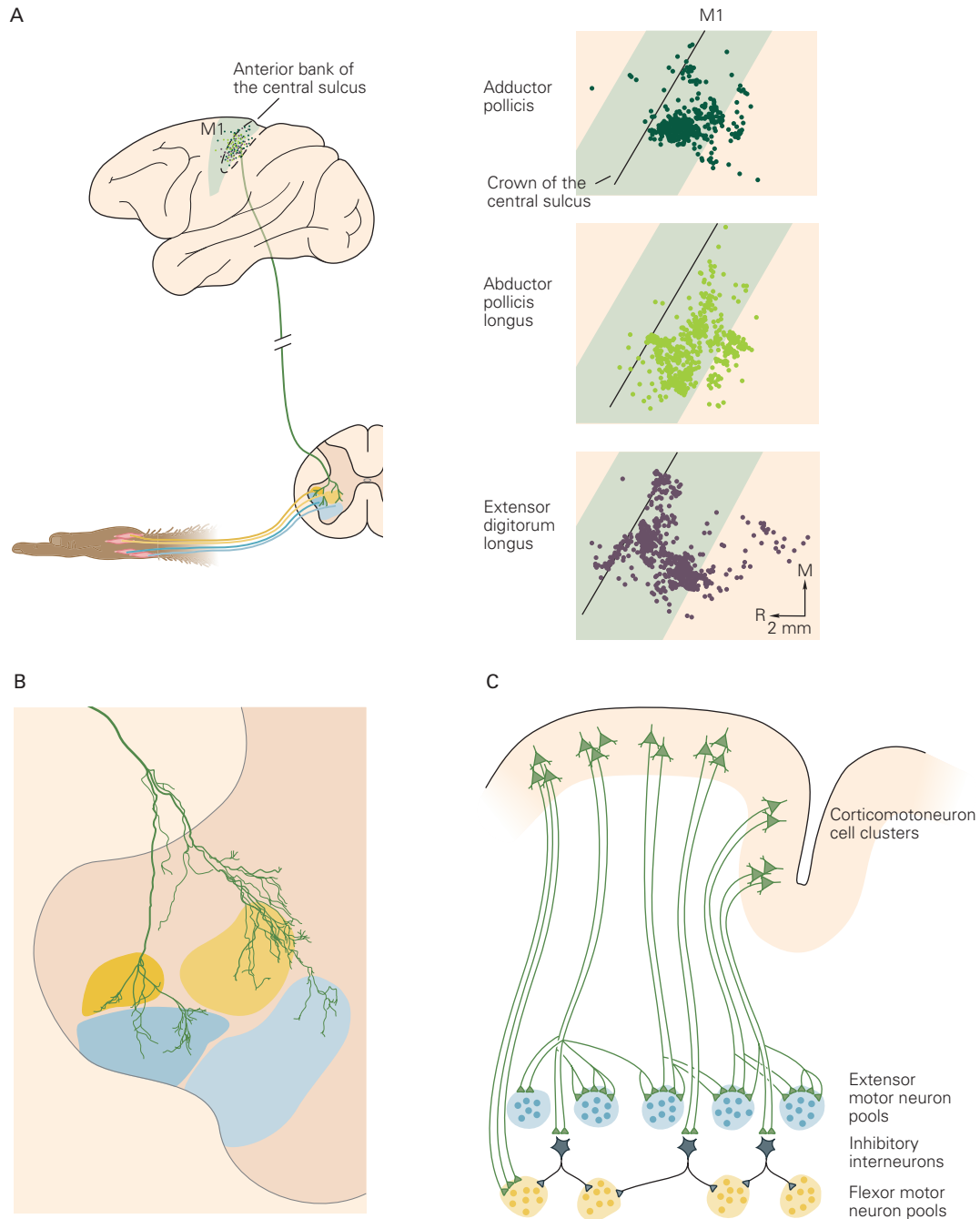
**Figure 34–16** The motor cortex contains a topographic map of motor output to different parts of the body.

**A.** Studies by Clinton Woolsey and colleagues confirmed that the representation of different body parts in the monkey follows an orderly plan. Motor output to the foot and leg is medial, whereas the arm, face, and mouth areas are more lateral. The areas of cortex controlling the foot, hand, and mouth are much larger than the regions controlling other parts of the body.

**B.** Wilder Penfield and colleagues showed that the human motor cortex motor map has the same general mediolateral organization as in the monkey. However, the areas controlling the hand and mouth are even larger than in monkeys, whereas the area controlling the foot is much smaller. Penfield

emphasized that this cartoon illustrated the relative size of the representation of each body part in the motor map; he did not claim that each body part was controlled by a single separate part of the motor map.

**C.** The arm motor map in monkeys has a concentric, horse-shoe-shaped organization. Neurons that control the distal arm (digits and wrist) are concentrated in a central core (**pale green**) surrounded by neurons that control the proximal arm (elbow and shoulder; **dark green**). The neuron populations that control the distal and proximal parts of the arm overlap extensively in a zone of proximal-distal co-facilitation (**intermediate green**). (Reproduced, with permission, from Park et al. 2001. Copyright © 2001 Society for Neuroscience.)



**Figure 34–17** Corticomotoneuronal cells activate complex muscle patterns through divergent connections with spinal motor neurons that innervate different arm muscles.

**A.** Corticomotoneuronal (CM) cells, which project monosynaptically to spinal motor neurons, are located almost exclusively within the anterior bank of the central sulcus in the caudal part of the primary motor cortex (M1). The CM cells that control a single hand muscle are widely distributed throughout the arm motor map, and there is extensive overlap of the distribution of neurons projecting to different hand muscles. The distributions of the cell bodies of CM cells that project to the spinal motor pools that innervate the adductor pollicis, abductor pollicis longus, and extensor digitorum communis (shown on the right) illustrate this pattern of wide distribution and extensive overlap of CM cells projecting to different muscles. (Abbreviations: **M**, medial; **R**, rostral.) (Reproduced, with permission, from Rathelot and Strick 2006.)

**B.** A single CM axon terminal is shown arborized in the ventral horn of one segment of the spinal cord. It forms synapses with the spinal motor neuron pools of four different intrinsic hand muscles (**yellow** and **blue** zones), as well as with surrounding interneuron networks. Each axon has several such terminal arborizations distributed along several spinal segments. (Reproduced, with permission, from Shinoda, Yokota, and Futami 1981.)

**C.** Different colonies of CM cells in the primary motor cortex terminate on different combinations of spinal interneuron networks and spinal motor pools, thus activating different combinations of agonist and antagonist muscles. Many other corticospinal axons terminate only on spinal interneurons (not shown). The figure shows CM projections largely onto extensor motor neuron pools. Flexor motor pools receive similar complex projections (not shown). (Adapted, with permission, from Cheney, Fetz, and Palmer 1985.)



those for more proximal parts of the arm. The terminal of a CM cell axon often branches and terminates on spinal motor neurons for several different agonist muscles and can also influence the contractile activity of still more muscles through synapses on spinal interneurons (Figure 34–17B,C). This termination pattern is organized to produce coordinated patterns of activity in a *muscle field* of agonist and antagonist muscles. Most frequently, a CM cell axon directly excites the spinal motor neurons for several agonist muscles and indirectly suppresses the activity of some antagonist muscles through spinal inhibitory interneurons (Figure 34–17C). The fact that CM cells are more prominent in humans than in other species may be one of the reasons why lesions of M1 in humans have a more profound effect on voluntary motor control compared to other mammals (Box 34–3).

The complexity of the motor map in M1—as revealed by short trains of electrical stimuli and anatomical and neurophysiological studies of direct and indirect M1 descending outputs targeting single muscles and small muscle groups—shows how motor commands from M1 to the spinal motor apparatus are

able to control movements of every part of the body, with special focus on the fingers, hand, arm, face, and mouth in primates.

### Activity in the Primary Motor Cortex Reflects Many Spatial and Temporal Features of Motor Output

As already noted, a given action such as reaching for an object can be described on many levels, ranging from the hand's spatial trajectory and velocity to its joint-centered causal forces and muscle activity (Figure 34–1A). Representational models assume that the motor system directly plans and controls specific parameters of movement. They predict that different neural populations encode the intended movement in a parameter space (ie, hand or joint motion or joint muscular torque) and perform the transformations between them. Dynamical models predict that neural circuits control movements through changes in their activation state from its current state to the desired final state. As their activity changes across time, correlates of various parameters and properties of the intended movement can be observed in the activity

#### Box 34–3 Lesions in Primary Motor Cortex Lead to Impairments in Motor Execution

The effects of primary motor cortex (M1) lesions differ across species. Large lesions in cats do not cause paralysis; the animals can move and walk on a flat open surface. However, they have severe difficulties using visual information to navigate within a complex environment, avoid obstacles, or climb the rungs of a ladder. In cats, the pyramidal tract neurons in M1 are much more strongly activated when an animal must modify its normal stepping motion to clear an obstacle under visual guidance than during normal unimpeded locomotion over a flat, featureless surface (Chapter 33).

Large M1 lesions in monkeys have more drastic consequences, including initial paralysis and usually the permanent loss of independent movements of the thumb and fingers. Monkeys nevertheless recover some ability to make clumsy movements of the hands and arms and to walk and climb.

More focal lesions of M1 typically result in muscle weakness, slowing and imprecision of movements, and discoordination of multi-joint motions, perhaps as a result of selective perturbations of the control circuitry for specific muscles or muscle groups. Lesions limited to part of the motor map, such as the contralateral arm,

leg, or face, lead to paralysis of that body part. There is diminished use of the affected body part, and movements of the distal extremities are much more affected than those of the proximal arm and trunk.

The severity of the deficits also depends on the level of required skill. Control of fine motor skills, such as independent movements of the fingers and hand and precision grip, is abolished. Any residual control of the fingers and the hand is usually reduced to clumsy, claw-like, synchronous flexion and extension motions of all fingers, not unlike the unskilled grasps of young infants. Remaining motor functions, such as postural activity, locomotion, reaching, and grasping objects with the whole hand, are often clumsy.

In humans, large motor cortex lesions are particularly devastating, resulting in severe motor deficits or complete paralysis of affected body parts, usually with limited potential for recovery. This presumably reflects the increased importance in humans of descending signals from M1 onto spinal interneuronal circuits and spinal motor neurons and a diminished capacity of other cortical and subcortical motor structures to compensate for the loss of those descending M1 signals.