

or even entirely, by nonbrain signals. Clearly, effective BCI research and development are not possible in such circumstances. (Indeed, even in the scientific literature there are examples of putative BCI studies in which EMG signals masquerade as EEG signals, so that the results reflect cranial-muscle control rather than brain-signal control.) Commercial devices (e.g., for gaming) that are currently marketed as BCIs often do not differentiate EEG from EMG or other nonbrain signals. Only if it is certain that the control signals arise from brain activity and not from other activity can the results of BCI studies be useful to people whose severe disabilities have eliminated their control of nonbrain signals.

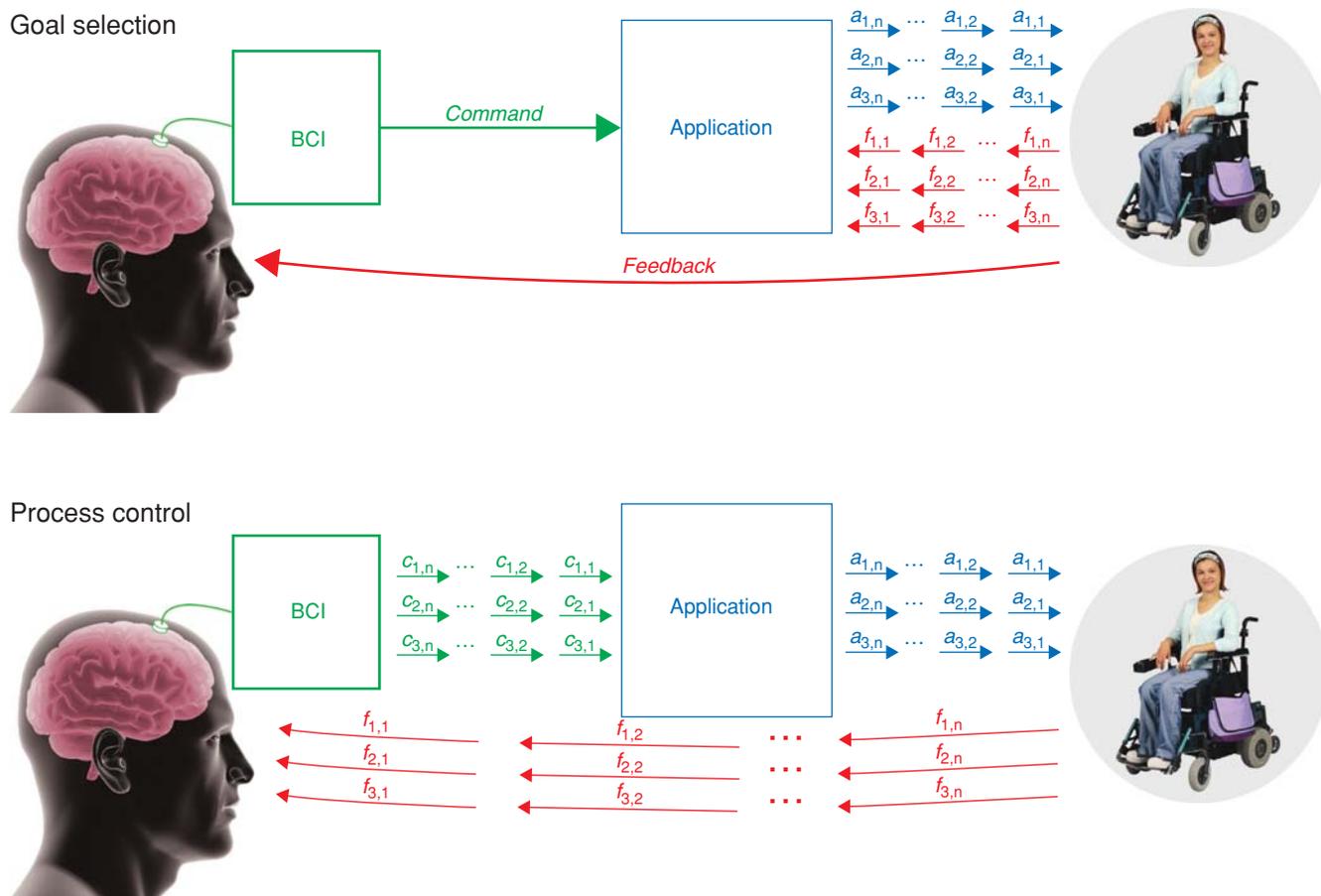
To avoid the danger of contamination by nonbrain signals, EEG-based BCI studies need to incorporate topographical and frequency analyses that are sufficiently comprehensive to distinguish between brain and nonbrain signals. Noninvasive metabolic BCI studies may need to incorporate analogous precautions. EEG studies that simply record from a single site, or that focus on a single narrow frequency band, cannot reliably

discriminate between EEG and EMG, and thus, their results may be misleading. These issues are addressed in greater detail in chapters 6 and 7.

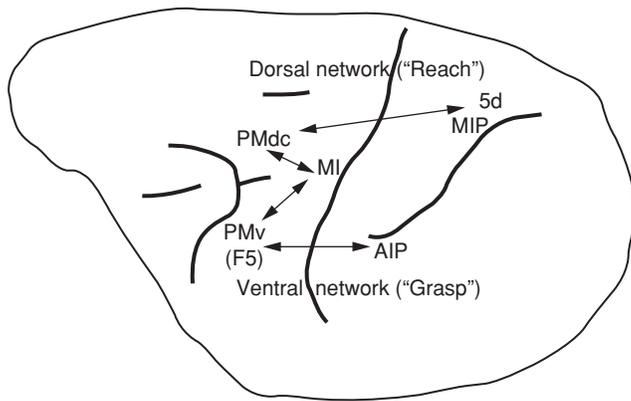
### BCI OUTPUT COMMANDS: GOAL SELECTION OR PROCESS CONTROL

A BCI can produce two kinds of output commands: a command that *selects a goal* or a command that *controls a process*. Figure 1.6 illustrates these two options applied to the movement of a motorized wheelchair.

In the *goal-selection* protocol shown at the top, the user and the BCI simply communicate the goal (i.e., the user's intent) to software in the application, and it is the application that then manages the process that accomplishes that intent. For example, the BCI might communicate the goal of moving to a location facing the television. The application device (i.e., the wheelchair) then produces the several concurrent sequences of actions (e.g., movements in  $x$  and  $y$  directions, turning,



**Figure 1.6** BCI outputs: goal selection versus process control. BCI output commands can either select goals or control processes. In goal selection the BCI command specifies only the user's intent; the process that achieves this intent is accomplished by the application (i.e., the motorized wheelchair), which produces several concurrent sequences of actions (e.g.,  $a_{1,1}, a_{1,2}, \dots, a_{1,n}; a_{2,1}, a_{2,2}, \dots, a_{2,n};$  etc.) that control its movement and also manage the ongoing interactions between these actions and the resulting sequences of feedback (e.g.,  $f_{1,1}, f_{1,2}, \dots, f_{1,n}; f_{2,1}, f_{2,2}, \dots, f_{2,n};$  etc.). The feedback to the user is mainly the end result. In process control the brain and the BCI provide several concurrent sequences of commands (e.g.,  $c_{1,1}, c_{1,2}, \dots, c_{1,n}; c_{2,1}, c_{2,2}, \dots, c_{2,n};$  etc.) that correspond to the sequences of actions that the application produces; and the brain and the BCI continue to manage the ongoing interactions between these actions and the resulting feedback. The most successful BCIs are likely to combine goal selection and process control appropriately for each purpose and to thereby emulate the distributed control characteristic of natural muscle-based CNS outputs. (Modified from Wolpaw, 2007.)



**Figure 2.13** Two proposed neural networks in the macaque monkey cortex involved in control of proximal reaching movements and distal grasping movements, respectively. A dorsal reach network consists of the superior parietal cortex (area 5d and MIP), caudal dorsal premotor cortex (PMdc) and primary motor cortex (M1). A ventral grasp network includes the anterior intraparietal area (AIP), rostral ventral premotor cortex (PMv; F5), and M1.

*mirror neurons*) discharges even when a monkey watches another individual (either monkey or human) make a particular grasping movement (di Pellegrino et al. 1992; Gallese et al. 1996). Thus, AIP appears to represent more abstract information (i.e., higher in the motor hierarchy) than does PMv, which itself is clearly at a higher level in the hierarchy than M1.

#### PRIMARY MOTOR CORTEX

The primary motor cortex (M1) is clearly involved in the control of distal as well as proximal components of arm movements. We have already described evidence that M1 neurons encode a variety of proximal reach movement parameters. Electrophysiological recordings in behaving monkeys have also shown that single neurons in M1 modulate their activity with many different aspects of distal limb function, including torque about the wrist (Evarts 1966; Murphy et al. 1979; Cheney and Fetz 1980; Kurata 1993; Kakei et al. 1999) and grip force (Hepp-Reymond et al. 1978; Muir and Lemon 1983; Wannier et al. 1991; Maier et al. 1993).

Lesions of M1 or the pyramidal tract in monkeys cause transient paresis or paralysis of the proximal limb and persistent loss of finely controlled wrist and finger movements (in particular, the loss of the ability to fractionate the movements of individual digits) (Denny-Brown 1950; Lawrence and Kuypers 1968a; Passingham et al. 1978). Intracortical microelectrode stimulation of M1 using short stimulation trains and low-current amplitudes can elicit muscle contractions and movements about the shoulder, elbow, wrist, and finger joints (Asanuma et al. 1976; Huntley and Jones 1991; Donoghue et al. 1992). Longer stimulation trains (lasting several hundred milliseconds) can elicit complex, apparently goal-directed movements involving proximal and distal joints that appear similar to natural reaching and grasping (Graziano et al. 2002, 2004). Consistent with these observations, a number of imaging and stimulation studies indicate that proximal and distal representations are intermingled and distributed throughout the arm area of M1 (Huntley and Jones 1991; Donoghue et al. 1992; Schieber and Hibbard 1993; Sanes et al. 1995).

Thus, despite extensive study, the existence of a strictly topographic organization within the arm area of M1 is still somewhat controversial. Modern stimulation studies argue for the existence of a *concentric* or *horse-shoe* organization, with distal representations mainly in the caudal portion of M1 (including the anterior bank of the central sulcus) that are surrounded by a zone of proximal-arm representations (see fig. 2.6) (Kwan et al. 1978a, 1978b; Park et al. 2001; Park et al. 2004). In between these two zones is a third zone in which low-current stimuli elicit activity in combinations of proximal and distal muscles (Park et al. 2001). There are two possible functional interpretations of this intermediate zone: that single neurons encoding either distal or proximal components are intermingled in close proximity to each other and can be excited concurrently with electrical stimulation; or, alternatively, that single neurons encode both proximal and distal components. Based on strong congruence between stimulus-triggered and spike-triggered averaging of EMG signals, Park et al. (2001, 2004) argue in favor of the second interpretation. As for the inner distal and outer proximal zones, coordination of reach and grasp might appear in the form of spatiotemporal patterning of the firing of these two populations of neurons.

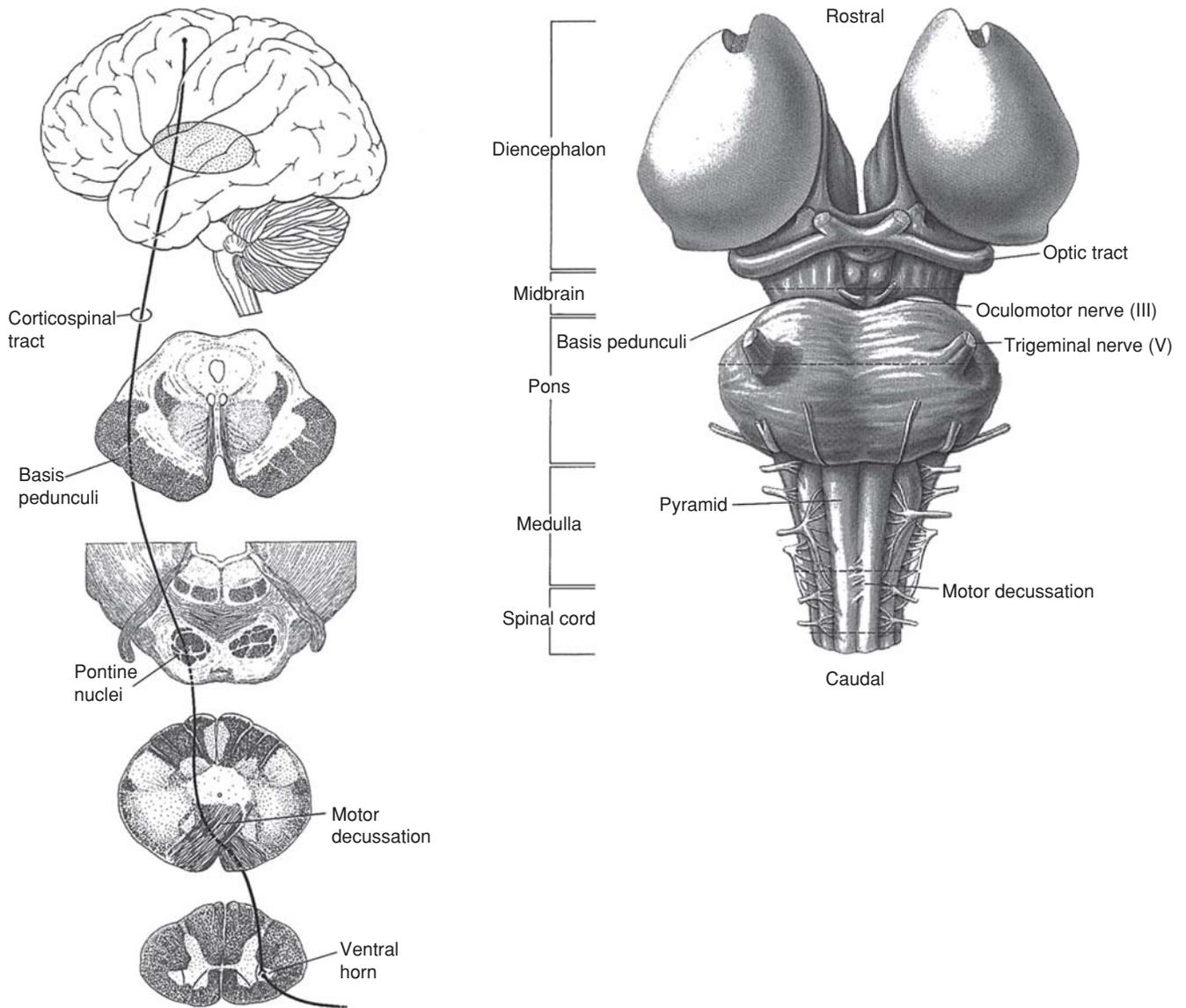
Recent anatomical studies using retrograde transneuronal rabies-virus transport from individual muscles have demonstrated that direct projections from cortex to spinal motoneurons arise almost exclusively from the caudal portion of M1 in the anterior bank of the central sulcus (Rathelot and Strick 2006). Moreover, these studies demonstrate that motor neurons innervating proximal as well as distal muscles receive these monosynaptic projections and form a medial-to-lateral topography within caudal M1 such that proximal cells reside more medially and distal cells more laterally. Therefore, caudal M1 may be a particularly important area for producing coordinated reach-to-grasp behaviors.

## SOMATOSENSORY FEEDBACK IN CONTROL OF MOVEMENT

### PROPRIOCEPTION

At present, the user of a BCI that controls movement of a cursor or robotic limb must rely on relatively slow visual feedback to guide the movement and to correct errors. In contrast, in normal movements these functions are accomplished in large part by the proprioceptive system. People suffering loss of proprioceptive feedback can rely on watching their limbs, but their movements are typically slower and less coordinated than normal and require great concentration (Ghez et al. 1995; Sainburg et al. 1995). Thus, sensorimotor feedback in the form of proprioception is an important modulator of movement control.

Proprioceptive sense comes from a variety of muscle and joint sensory organs (e.g., muscle spindles, Golgi tendon organs, joint receptors, etc.). Their inputs converge onto cortical areas 3a and 2 of the primary somatosensory cortex (S1). Additional complexity arises because the position and velocity sensitivities of muscle spindles can be modulated by descending input from the brain (Burke et al. 1978; Loeb and Duysens 1979;



**Figure 2.3** (Left) The corticospinal tract as it descends from the cerebrum through the brainstem to the spinal cord. (Right) Ventral view of the midbrain, pons, medulla, and spinal cord; the cerebellum (not shown) is behind (i.e., dorsal to) the pons and medulla. Adapted from Kandel et al. (1991).

along the sides of the brain. They are critical for auditory signal processing, higher-level visual processing, and memory.

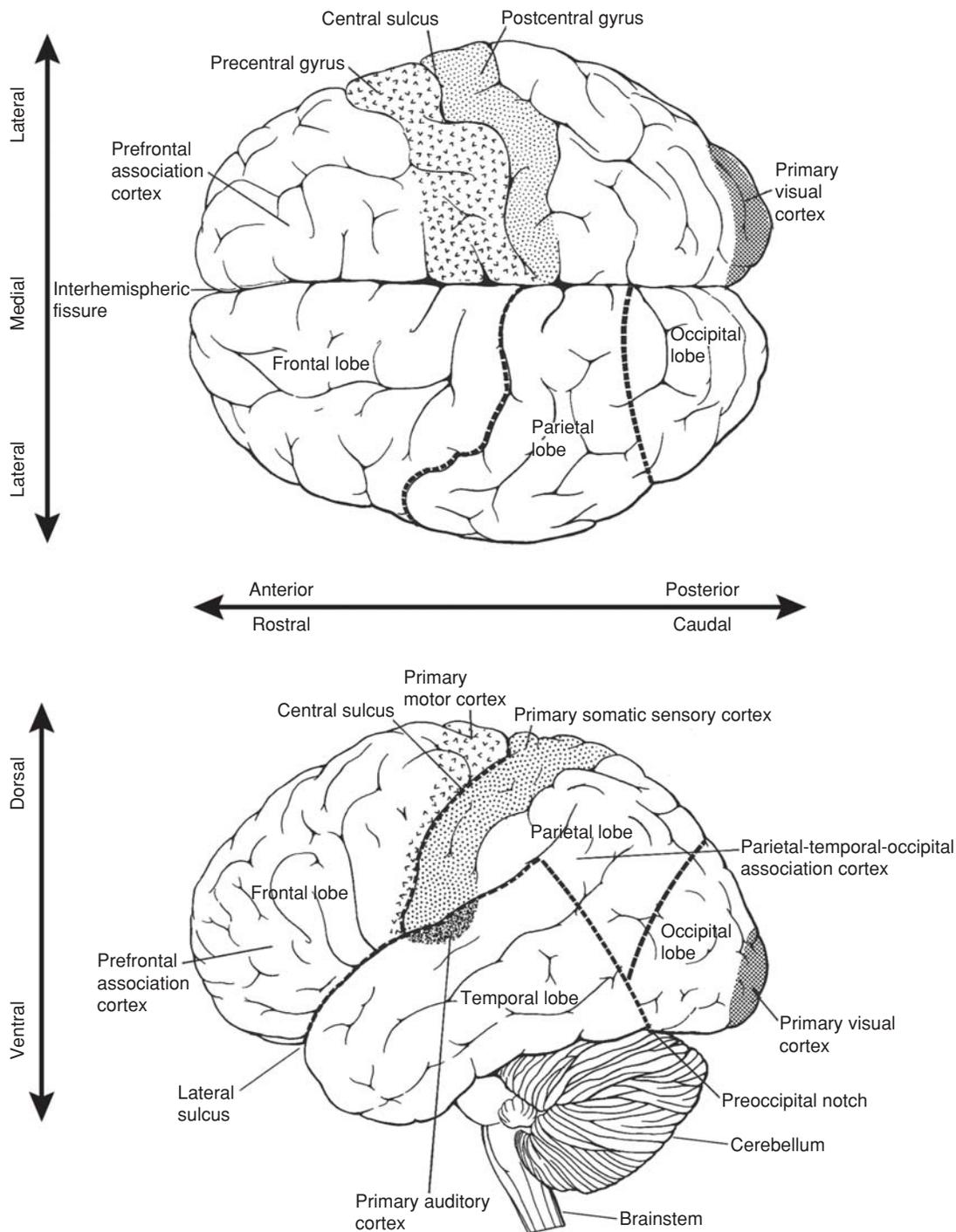
The cerebral cortex has three histologically distinguishable parts: the neocortex; the paleocortex; and the archicortex. The *neocortex* comprises most of the cortex in mammals and is discussed in detail in this chapter. The paleocortex and archicortex are evolutionarily older forms of cortex. The paleocortex comprises a region at the bottom (i.e., the ventral side) of the cerebrum that includes, but is not limited to, the olfactory cortex. The archicortex (largely synonymous with the *hippocampus*) is a structure located deep within the temporal lobes that plays a critical role in the formation of new memories and in spatial navigation.

In the early 1900s, Korbinian Brodmann differentiated approximately 50 areas within the cerebral cortex, based largely on the distribution, density, and types of cells within each area (Brodmann 1909). His published cytoarchitectonic map provided the framework for many subsequent investigations

into the functional differentiation of the cerebral cortex. This map is shown in figure 2.4, and some of the important areas are noted in table 2.1. With the advent of modern anatomical and physiological techniques, many of the Brodmann areas have been further subdivided. The overlap between the anatomically defined maps and functional maps determined later by physiological methods is rather remarkable.

### THE SIX LAYERS OF NEOCORTEX

Neocortex is composed of six morphologically distinct layers (labeled I–VI), distinguishable mainly by the types of cells they contain. *Pyramidal cells* (named for their pyramidal shape) are projection neurons (i.e., their axons extend to other cortical regions and/or to subcortical regions as far away as the spinal cord). Of the nonpyramidal neurons, *stellate cells* (also called *granule cells*) are the most numerous; stellate cells have extensive



**Figure 2.2** Major divisions of the human cerebral cortex in dorsal (from above) and lateral views. The four major lobes (frontal, parietal, occipital, and temporal) are indicated, as well as several of the functionally defined cortical areas. Adapted from Kandel et al. (1991).

*postcentral gyrus*. Primary motor cortex (M1) lies along the anterior wall of CS and continues into the precentral gyrus. Primary somatosensory cortex (S1) lies along the posterior wall of the CS and continues into the postcentral gyrus.

The frontal lobe is dramatically expanded in humans, even compared to our closest primate relatives. Much of this expansion is within the most anterior, *prefrontal area* (fig. 2.2), which is involved in higher-order executive function, including complex cognitive behaviors, personality, and decision making.

Posterior (or caudal) to the CS are the *parietal lobe* and then the *occipital lobe*. Primary somatosensory cortex (S1) is within the most anterior part of the parietal lobe. Farther posterior, in what is referred to as the *posterior parietal cortex* (PPC), is a region of *multimodal association cortex*, that receives input from the somatosensory, visual, and auditory sensory areas that surround it.

The *occipital lobe*, at the posterior pole of the brain, consists primarily of visual areas. The *temporal lobes* are located ventrally