CHAPTER

53

Spatial Cognition

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As we move through the world, new visual, auditory, vestibular, and somatosensory inputs are continuously presented to the brain. Given such constantly changing input, it is remarkable how easily we are able to keep track of where things are. We can reach for an object, or look at it, or even kick it without making a conscious effort to assess its location in space. But how do we construct a representation of space that allows us to act so effortlessly? This chapter will outline the contributions of several brain areas in the parietal, frontal, and hippocampal cortices to spatial representation, spatial memory, and the generation of actions in space.

THE NEUROANATOMY OF SPATIAL COGNITION

Dorsal Stream Areas Process Visuospatial Information

Within the cerebral hemisphere, visual information is processed serially by a succession of areas progressively more distant from the primary visual cortex of the occipital lobe. Within this hierarchical system, there are two parallel chains, or streams, of areas: the ventral stream, leading downward into the temporal lobe (area TE; see Chapter 52), and the dorsal stream, leading forward into the parietal lobe (area PG; see Chapter 52).[1] Although the two streams are interconnected to some degree, it is a fair first approximation to describe them as separate parallel systems.[2] Areas of the ventral stream play a critical role in the recognition of visual patterns, including faces, whereas areas of the dorsal stream contribute selectively to conscious spatial awareness and to the spatial guidance of actions, like reaching and grasping.[3–6] Dorsal stream areas have at least two distinctive functional traits: first, they contain a comparatively extensive representation of the peripheral visual field; second, they appear to be specialized for the detection and analysis of moving visual images. Both traits would be expected in any system processing visual information for use in spatial awareness and in the visual guidance of behavior.

Although visual input is important for spatial operations, awareness of space is more than just a visual function. We are able to apprehend the shape of an object, and we can tell where it is, regardless of whether we see it or sense it through touch. Accordingly, spatial awareness, considered as a general phenomenon, depends not on visual areas of the dorsal stream but rather on supravisual areas to which they send their output. The transition from areas serving merely visual functions to those mediating generalized spatial awareness is probably gradual, but certainly has been accomplished by the time the dorsal stream reaches its termination in the association cortex of the posterior parietal lobe.

Association Areas Responsible for Spatial Cognition Form a Tightly Interconnected System

The posterior parietal cortex appears to be preeminent among cortical areas responsible for spatial awareness, because lesions of the posterior parietal cortex lead to the most devastating and specific impairments of spatial cognition. However, numerous other

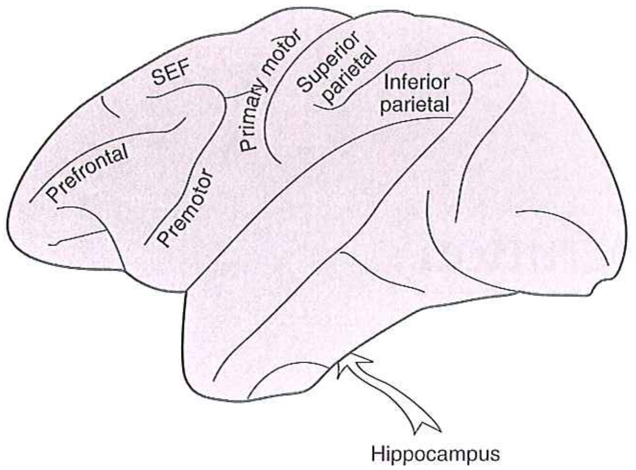

FIGURE 53.1 Lateral view of the left cerebral hemisphere of a rhesus monkey. Areas in the parietal and frontal cortex responsible for motor and cognitive processes of a spatial nature. SEF, supplementary eye field. Brain drawing, courtesy of Laboratory of Neuropsychology, NIMH.

areas in the cerebral hemisphere mediate cognitive functions that depend in some way on the use of spatial information. These **association** areas occupy a continuous swath of the cerebral hemisphere encompassing large parts of the frontal, cingulate, temporal, parahippocampal, and insular cortices. They are anatomically connected to each other and to the parietal cortex by a parallel distributed pathway through which signals are thought to shuttle back and forth in a complex recurrent pattern.[7-9] The functions of some parts of this system are especially well understood. For example, the frontal cortex is involved in the generation of voluntary behavior, and the medial temporal lobe, including the hippocampus, is important for memory. In the following sections, we first consider the spatial functions of the parietal cortex; we then consider how frontal areas program voluntary movements in spatial terms; and finally, we consider how the hippocampus and parahippocampal areas mediate the formation of memories with a spatial component.

In the human brain, the association areas of the nondominant (generally right) hemisphere are particularly important for spatial cognition. The issue of lateralization of function in the human brain is taken up in another chapter (see Chapter 58). We will not be emphasizing it here because the focus of this chapter is on parallels between humans and nonhuman species, and in nonhuman species lateralization is not pronounced. In general, spatial functions are represented in the same cortical areas in humans, monkeys, and rats, but the representation is symmetrically bilateral in lower species, whereas it is biased toward the right hemisphere in humans.

Summary

Spatial functions depend on the parietal cortex and a widely distributed network of areas to which it is linked.

THE PARIETAL CORTEX

The Parietal Cortex Contains Several Divisions

The parietal lobe is divided into the superior and inferior parietal lobules. Within each lobule, several subdivisions are distinguished by anatomical and functional properties.[10–13] In humans, various cytoarchitectural divisions, notably areas 5, 7, 39, and 40, have long been recognized. The functional significance of these divisions and their relation to cytoarchitectural areas recognized in the monkey are not yet well understood. The safest generalization applicable to both humans and monkeys is that the cortex at a more anterior location, corresponding roughly to the superior parietal lobule, serves functions related primarily to **somesthesis,** or tactile cognition, whereas the cortex at a more posterior location, corresponding roughly to the inferior parietal lobule (Fig. 53.1), serves functions related primarily to visuospatial cognition. We will focus our discussion on this more posterior division of the parietal cortex. In the monkey, this posterior division can be further subdivided into functionally distinct regions, including areas LIP (lateral intraparietal) and VIP (ventral intraparietal). Whether there are corresponding subdivisions in the human brain is not known.

Injury to the Human Posterior Parietal Cortex Causes Impairments of Spatial Function

A group of behavioral impairments specifically associated with damage to the parietal lobes was first described by Balint in 1909.[14-16] Balint syndrome includes difficulty in executing eye movements to engage visual targets, inaccuracy in reaching for visual targets, and a tendency not to see things in the peripheral visual field. This collection of symptoms reflects an impairment in the visual guidance of movement and, more generally, in spatial cognition.[17,18] In the following sections, we describe some of the specific impairments of spatial behavior that are known to arise from injury to the parietal lobe.

Simultanagnosia: An Inability to See Multiple Objects Simultaneously

Following injury to the posterior parietal cortex, some patients experience difficulty in the visual perception of spatial relations. They can see objects, but have difficulty making judgments whether two objects are the same size or which of two objects is closer to them. When asked to copy simple line drawings, they may omit or transpose parts, as if unable to judge accurately the spatial arrangement of the object's components. In some patients, failure on visuospatial tests arises from an inability to see more than one object at a time.[19,20] This condition, simultanagnosia, is commonly observed after bilateral damage to the parietal cortex. When looking at the flame of a match, a patient with simultanagnosia may be unable to see the hand holding it. When tested in controlled situations, simultanagnosic patients demonstrate a profound failure of simultaneous vision; for instance, they underestimate the number of dots in a multidot display.[21] See Box 53.1.[22]

Figure 53.2 illustrates the results of a particularly illuminating test carried out on simultanagnosic patients.[23] Presented with a field of randomly intermingled red and green circles (*random* condition in Fig. 53.2), the patients were unable to say whether the circles were of different colors, presumably because they could see only one circle at a time. In contrast, when pairs of circles of different colors were joined by line segments, unifying them into a single object, the patients were able to report that the colors were different (*mixed* condition in Fig. 53.2). This improvement was specific to the condition in which circles of different colors were joined, as shown by the fact that joining circles of the same color produced no improvement (*single* condition in Fig. 53.2). It is important to note that the average distance between circles of different colors was the same in all three conditions. This indicates that the inability of patients to see and compare pairs of circles in the *random* and *single* conditions was the result of the circles' belonging to separate objects and not simply of their being separated by a certain distance.

Simultanagnosia, by preventing simultaneous vision of two objects, gives rise to poor performance on tests requiring a comparison between objects. However, when tests are confined to a single object, it appears to leave spatial perception intact. Simultanagnosic patients are able to make accurate judgments of spatial relations so long as the judgments pertain to a single object; for example, they are able to determine whether a given rectangle is more elongated horizontally or vertically.

Optic Ataxia: An Impairment of Visually Guided Reaching

After damage to the parietal cortex, some patients experience difficulty in making visually guided arm movements. This condition is referred to as **misreach-**

BOX 53.1

SIMULTANAGNOSIA

Disorders of spatial awareness arising from parietal lobe injury are not merely a laboratory phenomenon but can have a profound impact on the patient's daily life, as described in the following case study of simultanagnosia (from Coslett and Saffran, 1991)[22]:

When first examined by the authors 4 months after the right hemisphere infarction, the patient's major complaint was that her environment appeared fragmented; although she saw individual items clearly, they appeared to be isolated and she could not discern any meaningful relationship among them. She stated, for example, that she could find her way in her home (in which she had lived for 25 years) with her eyes closed, but she became confused with her eyes open. On one occasion, for example, she attempted to find her way to her bedroom by using a large lamp as a landmark; while walking toward the lamp, she fell over her dining room table. Although she enjoyed listening to the radio, television programs bewildered her because she could only "see" one person or object at a time and therefore could not determine who was speaking or being spoken to; she reported watching a movie in which, after hearing a heated argument, she noted to her surprise and consternation that the character she had been watching was suddenly sent reeling across the room, apparently as a consequence of a punch thrown by a character she had never seen. Although she was able to read single words effortlessly, she stopped reading because the "competing words" confused her. She was unable to write, as she claimed to be able to see only a single letter; thus when creating a letter, she saw only the tip of the pencil and the letter under construction and "lost" the previously constructed letters.

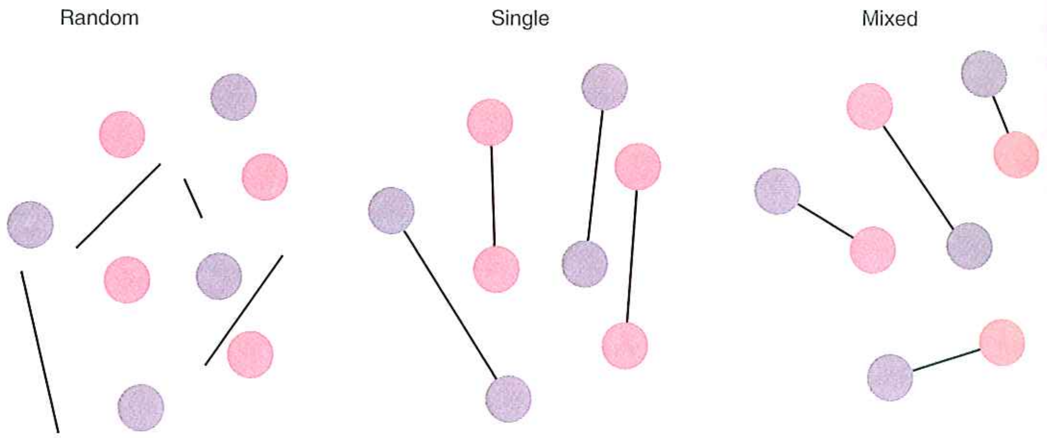

FIGURE 53.2 Three stimuli used for assessing simultanagnosia in human patients. Patients were consistently able to report that circles of different colors were present only in the mixed condition, in which red and green circles were unified into a single object by connecting line segments. From Humphreys and Riddoch.[23]

ing or **optic ataxia.**[24–26] Patients with optic ataxia experience difficulty in real-life situations requiring them to reach accurately under visual guidance. For example, a patient cutting food with a knife and fork may miss the plate altogether and hit the table when attempting to move the knife toward the food.

By testing patients with optic ataxia in controlled situations, neuropsychologists have been able to characterize their reaching deficits in considerable detail. Figure 53.3 illustrates results obtained when patients were required, while looking straight ahead, to reach out and insert one hand into a slot in the center of a disk held by the experimenter. The disk could be held in either the right or the left visual hemifield, and the patient could be asked to reach with either the right or the left hand. To perform the task required both

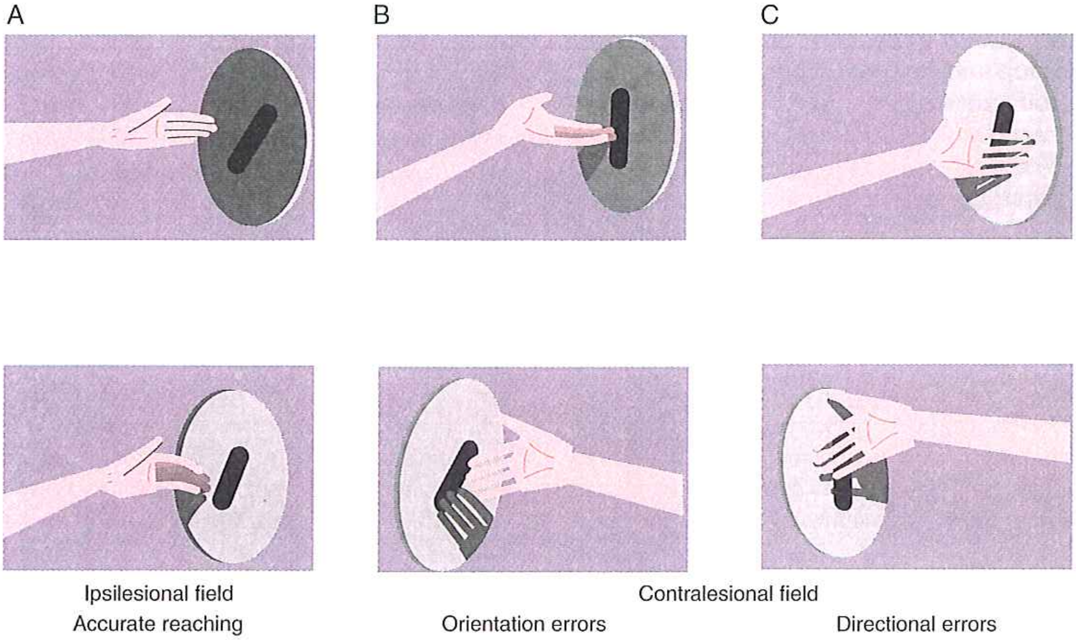

FIGURE 53.3 A test for optic ataxia. Under some conditions, especially when using the ipsilesional hand in the ipsilesional visual field, patients may reach accurately (A). However, under other conditions, especially when reaching into the contralesional visual field, they make errors of hand orientation (B) and of direction (C). The top and bottom rows show the performance of two different patients. From Perenin and Vighetto.[25]

directing the hand toward the center of the slot and orienting the hand so that it would pass into the slot Pictures in the top row of Fig. 53.3 show one patient reaching with the left hand following damage to the right parietal lobe. With the disk positioned in the right—**ipsilesional**—visual field, the patient was able to reach accurately for the slot (Fig. 53.3A). However, with the disk in the left—**contralesional**—visual field, the patient committed errors of hand orientation (Fig. 53.3B) and of reaching direction (Fig. 53.C). The lower row of Fig. 53.3 shows reaching by a patient with damage to the left parietal lobe. When using the left (ipsilesional) hand in the left (ipsilesional) visual field, the patient was able to reach accurately (lower left panel). However, when using the right (contralesional) hand in the right (contralesional) visual field, the patient committed errors of hand orientation (lower middle panel) and of reaching direction (lower right panel).

These results demonstrate that optic ataxia may be lateralized, occurring only when the patient is required to point to targets in one visual hemifield or only when one hand is used for pointing. Generally, in cases where the deficit is restricted to a single hemifield or a single arm, the affected hemifield or arm is opposite the injured parietal lobe. This situation is what would be expected if the parietal lobe of each hemisphere mediates communication between more posterior visual areas (which represent the contralateral half of visual space) and more anterior motor areas (which represent the contralateral arm). However, there are also cases in which the problem is bilateral or occurs for specific combinations of arm and hemifield. Optic ataxia is not simply a problem with visuospatial perception, as indicated by the fact that performance with one arm may be perfectly normal, nor is it simply a motor problem, as indicated by the fact that patients unable to reach accurately for visual targets can commonly touch points on their own bodies accurately under proprioceptive guidance. Optic ataxia is best characterized as a failure in the use of visuospatial information to guide arm movements.

Hemispatial Neglect: Unawareness of the Contralesional Half of Space

Hemispatial neglect is a classic symptom of injury to posterior parietal cortex.[27] It is a condition in which a lateralized failure of spatial awareness is present. Patients fail to notice things in the contralesional half of space (the half of space opposite the injured hemisphere). The most common form of neglect arises from damage to the right parietal lobe and is manifested as a failure to detect things in the left half of space. Patients with neglect experience problems in daily life, such as colliding with obstacles on the contralesional side of the body or mistakenly identifying letters on the contralesional side of a written word. When asked to copy pictures or to draw simple objects from memory, they leave out details on the affected side. When asked to say whether two objects are the same or different, they tend to indicate that two nonidentical objects are the same if the differentiating details are on the contralesional side. Whether the problem underlying neglect is a failure of attention to one half of space or a failure of the ability to form a mental representation of that half of space is not clear.

Neglect certainly is more than just a defect of attention to contralesional sensory events. For example, patients fail to report detail on the left half of an object even when they must form a mental representation of the object by viewing it one part at a time as it passes slowly behind a vertical slit.[28,29] Moreover, when asked to imagine themselves in a familiar public setting and then to report what they see around them, patients fail to report buildings on the contralesional side, regardless of which way they imagine themselves to be facing.[30] Buildings reported accurately when the patient imagines facing east will be neglected when the patient imagines facing west.

Given that neglect affects the half of space opposite an injured parietal lobe, each parietal lobe must represent the opposite half of space. On the face of it, this proposition does not sound particularly surprising. Most visual areas in each hemisphere represent the opposite half of the visual field, most somatosensory areas represent the opposite half of the skin surface, and most motor areas represent muscles on the opposite half of the body. Injury to these areas leads to a sensory loss or motor impairment that affects the opposite half of a functional space defined with respect to some anatomical reference frame (the retina, or the skin surface, or the muscles). In striking contrast, injury to the posterior parietal cortex gives rise to a neglect that is defined in part with respect to external space.

Neglect can be expressed relative to any of several spatial reference frames. These include allocentric frames, in which locations are represented in coordinates extrinsic to the observer; and egocentric reference frames, in which locations are represented relative to the observer. Patients with neglect often show deficits with respect to more than one reference frame. Furthermore, they may show neglect for stimuli presented at particular distances. The following sections describe evidence for impairments of multiple spatial reference frames in neglect.

A patient with left hemispatial neglect, looking straight ahead at the center of some object, will tend not to see detail on its left side. This pattern is open to several interpretations. The simplest interpretation is that stimuli presented in the left visual field tend not to be registered. However, the fundamental problem might actually be with registering stimuli that are to the left of the head, or of the torso, or of the object itself. These possibilities cannot be disentangled without unyoking the various reference frames. Experiments aimed at identifying the reference frame with respect to which neglect is defined have indicated that the patient's failure to detect a stimulus is affected not only by its location relative to the retina but also by its location relative to the object or array within which it is contained, relative to the body, and even relative to a gravitationally defined reference frame.

In many patients, a component of neglect is object-centered. If these patients are presented with an image anywhere in the visual field, they tend to ignore its left side. In one experiment, patients with left hemispatial neglect were required to maintain foveal fixation on a small spot while chimeric faces (images formed by joining at the midline half-images representing the faces of two people) were presented at various visual field locations.[31] Their reports of what they saw were based predominantly on the right halves of the chimeric images. This was true even when the entire composite face was presented within the right visual hemifield. In another experiment, patients with left hemifield neglect were required to maintain foveal fixation on a small spot while four stimuli in a horizontal row were presented.[32] One of the stimuli, was a letter which was to be named. When the letter was in the leftmost location, they were slower to name it, even when the entire array was in the right visual field. Futher demonstrations of object-centered neglect have come from experiments in which, instead of displacing the object away from the visual field midline, one rotates it so that its vertical axis is no longer parallel to the retinal midline.[33] These experiments have demonstrated a form of neglect in which patients ignore detail occupying the left side of the object as defined with respect to the object's (*tilted*) midline rather than with respect to the vertical retinal meridian passing through the center of the object.

A particularly dramatic way of demonstrating the object-centered nature of neglect is to ask patients to make copies of simple line drawings.[34] Results obtained by this procedure are presented in Fig. 53.4, which shows two pictures (left column) and two copies of those pictures (right column) produced by a patient

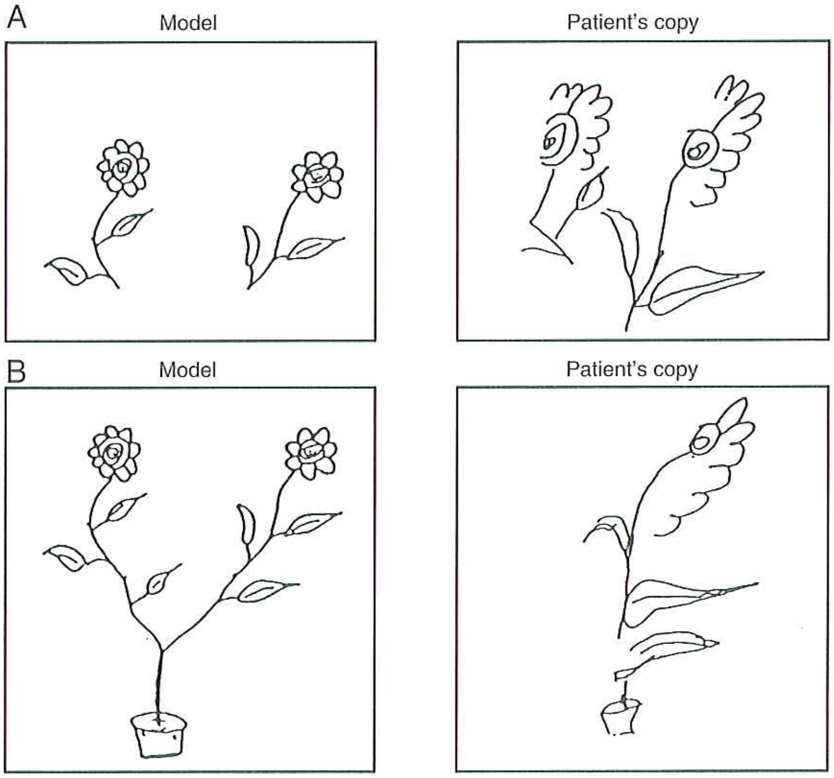

FIGURE 53.4 A test for object-centered neglect. When asked to copy the two drawings on the left, a patient made the two copies on the right. Detail is omitted from the left half of each object rather than from the left half of the drawing as a whole. From Marshall and Halligan.[34]

with right parietal lobe injury. In copying a picture of two flowers (top row, left), the patient saw and copied each flower but omitted the petals on the left half of each, thus showing evidence of left object-centered neglect. When the same two flowers were joined by a common stem (lower row, left), the patient saw and copied the plant, but omitted details on its left side, including all of the leftmost flower, thus showing neglect for the left half of the larger composite object.

Evidence that neglect is defined in part with respect to the midline of the body has come from a reaction-time study in which patients were required to make eye movements in response to suddenly appearing visual targets.[35] When seated with the torso, head, and eyes pointing straight toward the display screen, patients were slower to initiate eye movements into the left visual field than into the right visual field. This difference could be markedly reduced by rotating the patient's chair and torso to the left, while the head and eyes remained stationary and continued to point straight toward the display screen. The effect of this maneuver was to ensure that even stimuli in the left visual field now fell to the right of the midline of the trunk. The simplest interpretation of this result is that neglect in these patients was defined in part with respect to the midline of the trunk.

The role of the gravitational reference frame in neglect has emerged from studies in which patients face a display screen while sitting upright or lying on their side.[36,37] When the patient sits upright while facing the screen, the right and left halves of the screen coincide with the right and left retinal visual fields. However, when the patient lies on one side while facing the screen, the situation is changed. For example, reclining with the right side down, the patient sees the right and left halves of the screen as being in the upper and lower visual fields, respectively. Applying this procedure to patients with left hemispatial neglect enables the investigator to pose the question: Is the neglect specific for the left retinal visual field or is it specific for the left half of the screen? Neglect has turned out to depend in part on each of these factors.

Further evidence that the parietal cortex represents the locations of objects relative to an external, rather than anatomical, framework has come from the observation that neglect, in a few patients, is restricted to stimuli within a certain range of distances from the body.[38,39] The form of neglect termed **peripersonal** or **proximal** is specific for stimuli in the immediate vicinity of the body. Another form of neglect, termed **extrapersonal,** is specific for more distant stimuli. The implication of these findings is that there is a localization of function within the parietal cortex and that neurons in discrete areas process sensory input from objects at different distances. Discrete areas of the parietal cortex may also be specialized for relaying sensory information to different motor systems. Sensory input from peripersonal space is uniquely significant for guiding reaching movements. In contrast, sensory input from greater distances (extrapersonal space) is primarily linked to control of eye movements.

Lesions of the Parietal Cortex in Monkeys Produce Spatial and Attentional Problems

The original distinction between the dorsal and the ventral processing streams in the primate visual system was based in part on differences in the effects of lesions of the posterior parietal cortex and the inferior temporal cortex.[1] Monkeys with posterior parietal lesions are selectively impaired in visuospatial performance, such as judging which of two identical objects is located closer to a visual landmark. In contrast, inferior temporal cortex lesions produce deficits in visual discrimination (for example, shape or pattern recognition; see Chapter 52).

In addition to spatial perceptual deficits, parietal lesions also produce spatial motor deficits. After parietal lesions, monkeys have difficulty directing eye movements toward targets in the hemispace opposite the side of the lesion.[40] Further, when two targets are presented simultaneously in the ipsilesional and contralesional fields, lesioned monkeys tend to ignore the contralesional stimulus, an effect termed **visual extinction**. Parietal lesions also have profound effects on the monkeys' ability to reach toward an object. Lesions confined to inferior parietal cortex impair reaching with the contralesional limb toward a target in contralesional space. Lesions extending across the intraparietal sulcus to include superior parietal cortex produce impairments in reaching with the contralateral arm into either half of space. The deficits observed following parietal lesions indicate that animals are unable either to assess spatial relations between objects or to judge locations of objects relative to themselves.

Parietal Neurons Have Response Properties Related to Spatial Information Processing

To understand more precisely how the parietal cortex contributes to spatial cognition, several groups of investigators have measured the electrical activity of single neurons during the performance of spatial tasks. These studies were done in alert monkeys trained to make eye movements to visual targets. Because brain tissue itself has no sensory receptors, microelectrodes can be introduced into the brain without disturbing the animal's performance on a task. By recording single neuron activity during specially designed tasks, neural activity can be related directly to the sensory, cognitive, and motor processes that underlie spatial behavior.[41,42] The following three sections describe how neurons in different areas within the parietal cortex are selectively activated during spatial tasks and how they contribute to spatial representation.

Area LIP

Neurons in area LIP exhibit many different kinds of task-related activities.[43] First, LIP neurons, like neurons elsewhere in striate and extrastriate visual cortex (Chapter 28), respond to the onset of a visual stimulus in their receptive field, the part of the retina to which they are sensitive.[44]

Second, these visual responses can be enhanced by requiring the monkey to attend to the stimulus in order to detect a faint dimming;[45] that is, the amplitude of the visual response is increased when the stimulus or stimulus location becomes the focus of attention. This enhancement occurs regardless of how the monkey will respond to the stimulus. Whether the task requires a hand movement or an eye movement or requires that the monkey refrain from moving toward the stimulus, the visual response of an LIP neuron becomes larger when the stimulus becomes behaviorally relevant. This means that the same physical stimulus arriving at the retina can evoke very different responses centrally as a result of spatial attention.

A third interesting feature of LIP neuron activity is the prolonged, or tonic, responses observed when the monkey must remember the location at which the stimulus appeared.[46] In this task, a stimulus is flashed only briefly in the *receptive field* but the neuron continues to fire for several seconds after the stimulus is gone, as though the neuron were holding an image of the target location. A particularly interesting question in understanding spatial representation concerns the fate of memory-related activity in area LIP following an eye movement, as will be described later. A fourth kind of activation commonly observed in LIP neurons is specifically related to performance of a **saccade**—a rapid eye movement—toward the receptive field. LIP neurons fire just before the monkey initiates a saccade that would move the fovea onto the target in the receptive field.[47,48] LIP neurons have overlapping sensory and motor fields, just like neurons in the superior colliculus (see Chapter 36). Finally, LIP neuron activity can be modulated by the position of the eye in the orbit.[49] For instance, the visual response of a given cell may become larger when the monkey is looking toward the left part of the screen than when it is looking toward the right. This property is interesting because it suggests that neurons in area LIP may contribute to spatial representations that go beyond simple retinotopy.[50] This idea is discussed in more detail in the next section.

In sum, individual LIP neurons have receptive fields at particular retinal locations and carry visual, memory, and saccade-related signals that can be modulated by attention and by orbital position. Activity in area LIP cannot be characterized as a simple visual or motor signal. Rather, the level of activation in a given LIP neuron reflects the degree to which attention has been allocated to a location within the receptive field.

Spatial Representation in Area LIP

Every time we move our eyes, each object in our surroundings activates a new set of retinal neurons. Despite this constantly changing input, we experience a stable visual world. How is this possible? More than a century ago, Helmholtz[51] proposed that the reason the world appears to stay still when we move our eyes is that the effort of will involved in making a saccade simultaneously adjusts our perception to take that specific eye movement into account. He suggested that when a motor command to shift the eyes in a given direction is issued, a copy of that command, or corollary discharge, is sent to brain areas responsible for generating our internal image of the world. This image is then updated so as to be aligned with the new visual information that will arrive in cortex after the eye movement. A simple experiment convinces most people that Helmholtz's account must be essentially true. When the retina is displaced by pressing on the eye, the world does seem to move, presumably because there is no corollary discharge.

Recent experiments indicate that neurons in area LIP contribute to this updating of the internal image.[52,53] The experiment illustrated in Fig. 53.5 shows that the memory trace of a previous stimulus event is shifted following an eye movement to match the new eye position. The activity of a single LIP neuron was recorded under three different conditions. Under the first set of conditions, shown in Fig. 53.5A, the monkey looked steadily at a fixed point on the screen while a stimulus spot was flashed in the receptive field. In the cartoon at the top, the dot is the fixation point, the dashed circle shows the location of the receptive field when the monkey was looking at the fixation point, and the asterisk represents the visual stimulus. The time lines just below the cartoon show that the vertical and horizontal components of eye position remained steady throughout the trial. The stimulus time line shows that the stimulus started 400 ms after the beginning of the trial and continued for the entire trial. The long vertical line running through the whole panel shows when the stimulus started. The raster display shows the electrical activity of a single LIP neuron in 16 successive trials. In these rasters, each dot indicates

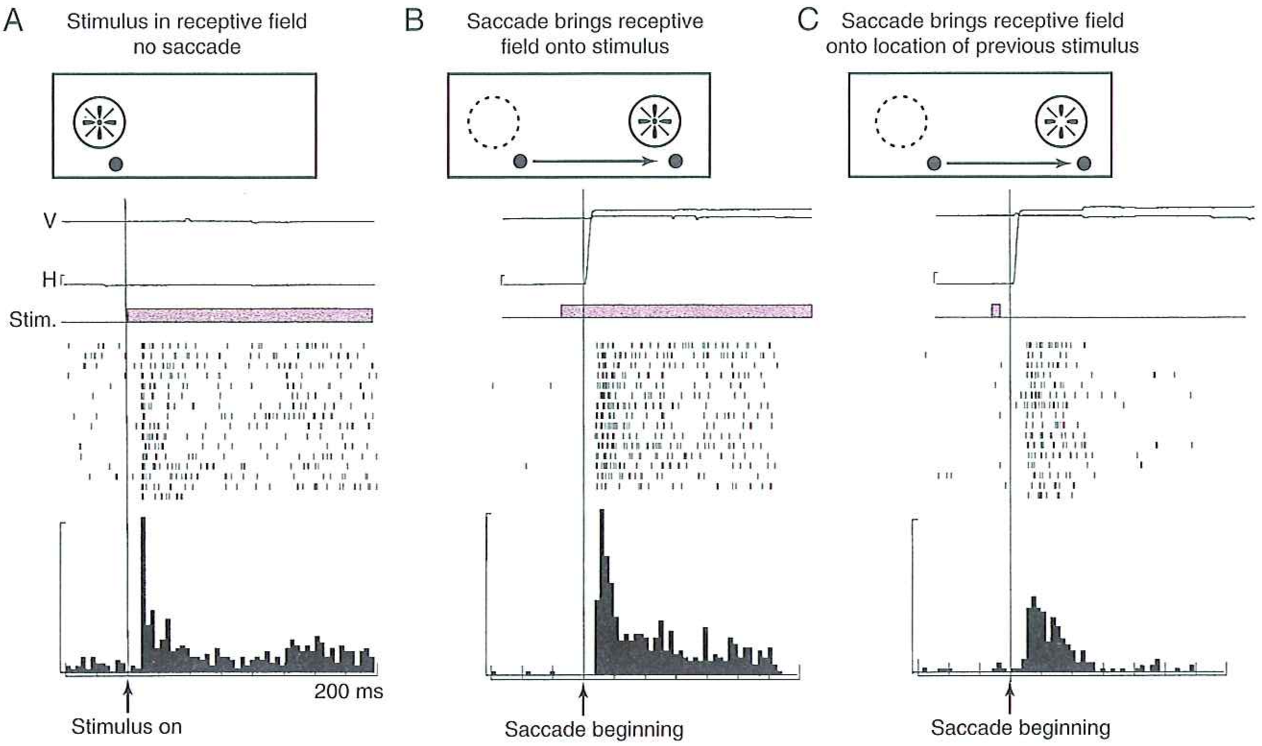

FIGURE 53.5 The remapping of visual memory trace activity in area LIP (see text for a detailed description of the experiment). The activity of a single neuron was recorded under three different conditions. (A) Simple visual response to a constant stimulus in the receptive field, presented while the monkey is fixating. The rasters and histogram are aligned on the time of stimulus onset. (B) Response following a saccade that brings the receptive field onto the location of a constant visual stimulus. (C) Response following a saccade that brings the receptive field onto the location where a stimulus was previously presented. The stimulus is extinguished before the saccade begins, so it is never physically present in the receptive field. The neuron responds to the memory trace of the stimulus. From Duhamel *et al.*[52] V, vertical eye position; H, horizontal eye position.

the time at which an action potential occurred, and each horizontal line of dots represents activity in a single trial. In each trial, there was a brief initial burst of action potentials shortly after the stimulus appeared, followed by continuing neural activity at a lower level. The histogram at the bottom of the panel shows the average firing rate as a function of time. The visual response shown in this left panel is typical of that observed in neurons in many visual areas. Basically, the neuron fired when a stimulus appeared in the particular region of visual space to which that neuron was most sensitive.

In the second set of trials (Fig. 53.5B), the visual response occurred when the stimulus was brought into the receptive field as the result of a saccade. At the beginning of the trial, the monkey was looking at the fixation point on the left, and the rest of the screen was blank. Simultaneously, a new fixation point appeared on the right and a visual stimulus appeared above it. The monkey made a saccade from the old fixation point to the new one, indicated by the arrow in the cartoon. The eye movement was straight to the right, so only the horizontal eye position trace shows a change. At the end of this saccade, the receptive field had been moved to the screen location containing the visual stimulus. The rasters and histogram in this panel are aligned on the time that the saccade began. In each trial, the neuron began to respond after the receptive field had landed on the stimulus. This result is just what would be expected for neurons in any visual area with retinotopic receptive fields.

The surprising finding is shown in Fig. 53.5C. In this set of trials, the monkey made a saccade that would bring a stimulus into the receptive field, just as in the previous experiment (Fig. 53.5B). The only difference was the duration of the stimulus, which lasted for only 50 ms instead of staying on for the entire trial. As can be seen on the stimulus time line, the stimulus actually disappeared before the saccade began. This means that the stimulus was never physically present in the receptive field. Nevertheless, the neuron fired as though there were a stimulus on the screen. This result shows that LIP neurons respond to the memory trace of a previous stimulus and that the representation of the memory trace is updated at the time of a saccade. The general idea of how a memory trace can be updated is as follows: At the beginning of the trial, while the monkey is looking at the initial fixation point, the onset of the stimulus activates those neurons whose receptive fields encompass the stimulated location. Some of these neurons continue to respond after stimulus offset, encoding the location at which the stimulus occurred. When the monkey moves its eyes toward the new fixation point, a copy of the eye movement command is sent to parietal cortex. This corollary discharge causes the active LIP neurons to transmit their activity to another set of neurons whose receptive fields will encompass the stimulated screen location after the saccade. By this means, LIP neurons encode the spatially updated memory trace of a previous stimulus.

The significance of this result lies in what it tells us about spatial representation in area LIP. It suggests that the internal image is dynamic rather than static. Tonic, memory-related activity in area LIP not only allows neurons to encode a salient spatial location after the stimulus is gone but also allows for dynamic remapping of visual information in conjunction with eye movements. This updating of the internal visual image has specific consequences for spatial representation in the parietal cortex. Instead of being encoded in purely retinotopic coordinates, tied to the specific neurons initially activated by the stimulus, the information is encoded in eye-centered coordinates. This is a subtle distinction but a very important one in generating accurate spatial behavior. Maintaining visual information in eye-centered coordinates tells the monkey not just where the stimulus was on the retina when it first appeared, but where it would be now on the retina following an intervening eye movement. The result is that the monkey always has accurate information with which to program an eye movement toward a real or a remembered target. Further results from this series of experiments indicate that humans also depend on this kind of remapping for accurate spatial representation.[54,55]

Area VIP

In contrast to the eye-centered spatial representation found in area LIP, some neurons in the adjacent area VIP encode locations with respect to a head-centered reference frame. These neurons have several interesting properties. They respond strongly to moving stimuli and are selective for both the speed and the direction of the stimulus.[56] In this respect, VIP neurons are similar to those in other dorsal stream visual areas that process stimulus motion, especially areas MT and MST (see Chapter 28). A surprising finding in area VIP is that most of these visually responsive neurons also respond to somatosensory stimuli, such as a light touch.[57] Most of these bimodal neurons have somatosensory receptive fields on the head and face. These neurons are truly bimodal, in the sense that they can be driven equally well by either a visual or a somatosensory stimulus. Further, these neurons have corresponding visual and somatosensory receptive fields. This correspondence is illustrated in Fig. 53.6, which shows visual and somatosensory receptive fields for 14 VIP neurons.

Three kinds of correspondence are shown. First, receptive fields in each modality match in location for a given neuron. For example, a neuron that responds to a visual stimulus in the upper left visual field also responds when the left brow is touched (Fig. 53.6, top right inset). Second, receptive fields match in size. A neuron with a restricted visual receptive field also has a small somatosensory receptive field. Third, preferred directions of movement in the two modalities are matched. For instance, a neuron responsive to a visual stimulus moving toward the right also responds when a small probe is brushed lightly to the right across the monkey's face (Fig. 53.6, lower left inset). In sum, visual and somatosensory receptive fields for individual VIP neurons match in location, size, and directional preference.

This observation of correspondence in receptive field location immediately raises a question: What happens to the relative locations of the visual and somatosensory receptive fields when the eyes move? If the visual receptive field were simply retinotopic, it would move when the eyes do; and if the somatosensory receptive field were purely somatotopic, it would be unchanged by eye movements. There could not be a consistent correspondence in location if visual receptive fields were defined with respect to the retina while somatosensory receptive fields were defined with respect to the skin surface.

The answer is that visual receptive fields shift their location on the retina when the eyes move. A neuron that responds best to a visual stimulus approaching the mouth and has a somatosensory receptive field around the mouth will continue to respond best to a

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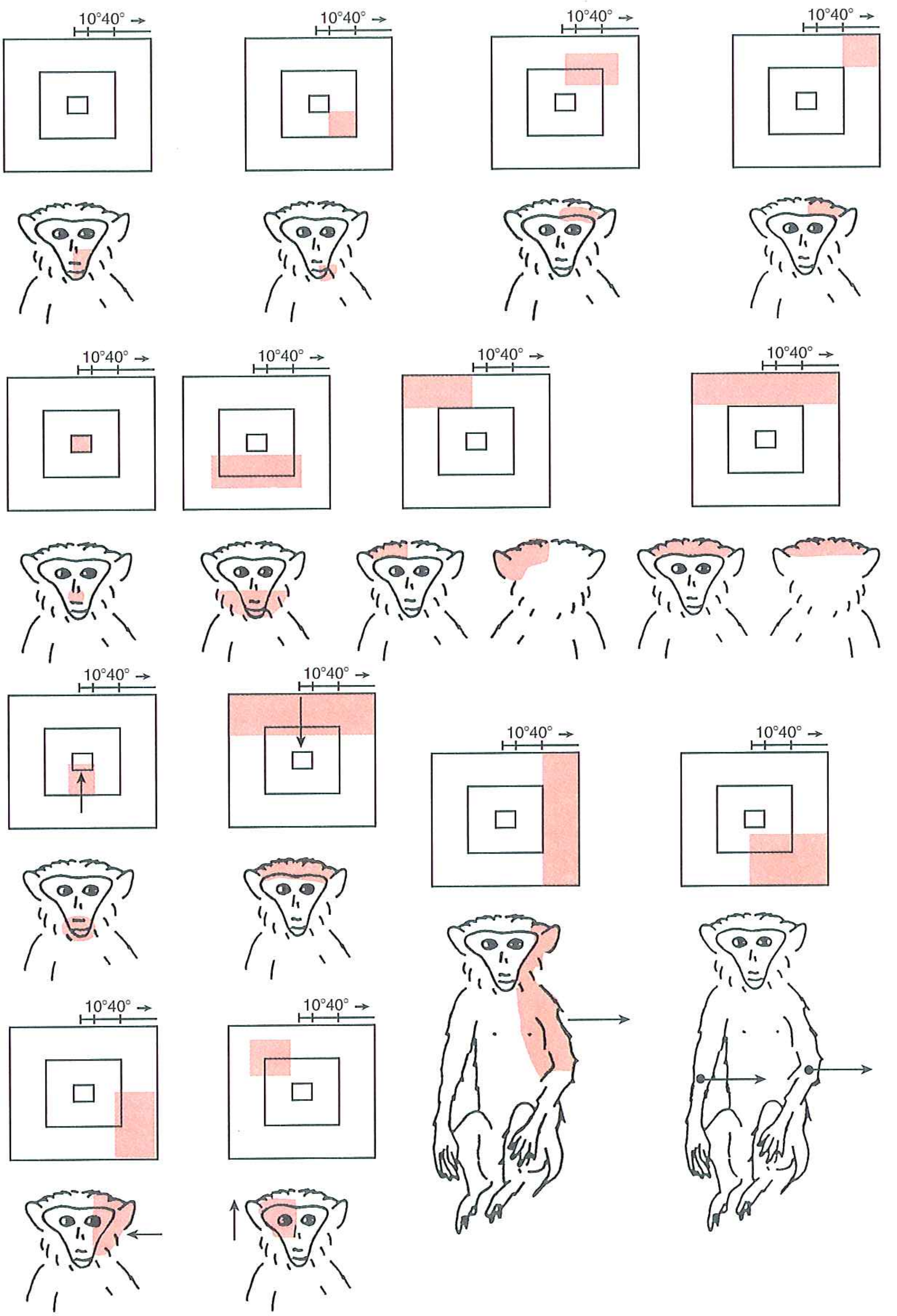
FIGURE 53.6 Matching of the visual and somatosensory receptive fields of 14 neurons from area VIP. On each outline of the monkey's head, the patch of color corresponds to one neuron's somatosensory receptive field. On the square above the head, the patch of texture corresponds to the same neuron's visual receptive field. The square can be thought of as a screen placed in front of the monkey so that its center is directly ahead of the monkey's eyes. From Duhamel *et al.*[57] by permission of Oxford University Press.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visual stimulus moving toward the mouth regardless of where the monkey is fixating. Thus, both the visual and the somatosensory receptive fields are defined with respect to the skin surface. In this sense, the receptive fields are head-centered: a given VIP neuron responds to stimulation of a certain portion of the skin surface and to the visual stimulus aligned with it, no matter which part of the retina is activated.

In sum, neurons in area VIP encode bimodal sensory information in a head-centered representation of space. This kind of representation would be most useful for guiding head movements. Anatomical studies indicate that area VIP sends information to the specific region of the premotor cortex that is involved in generating head movements. In contrast, neurons in area LIP encode sensory information in an eye-centered representation of space, in a form most useful for guiding eye movements. Area LIP sends projections to both the superior colliculus and the frontal eye fields, regions that are involved in generating eye movements. The parietal cortex contains a number of other areas, especially within the intraparietal sulcus, each of which may be specialized for particular types of stimuli and particular regions of space.[58] The general point is that the problem of spatial representation may be solved in several ways, and each solution may contribute to the generation of a different kind of action.

Summary

The posterior parietal cortex plays a critical role in spatial awareness. Injury to parietal cortex in humans and monkeys leads to deficits in spatial perception and action. Physiological studies in monkeys have shown that parietal neurons construct a representation of space by combining signals from multiple sensory modalities with motor signals. An intriguing physiological finding is that parietal neurons represent spatial locations relative to multiple reference frames, including ones centered on the eye and the head. In accord with the physiology, human neuropsychological studies have shown that neglect resulting from parietal lobe injury can be expressed with respect to several different reference frames.

THE FRONTAL CORTEX

The Frontal Cortex Contributes to Voluntary Movement and the Regulation of Behavior

The cortex at the front of the cerebral hemisphere is involved in spatial functions as a natural result of its being involved in behavioral regulation. The three main divisions of the frontal lobe are the **primary motor cortex** on the precentral gyrus, the **premotor cortex** located in front of the primary motor cortex, and the **prefrontal cortex,** which has the most anterior location (see Fig. 53.1). The motor, premotor, and prefrontal areas all contribute to behavioral regulation, but they differ from each other with respect to the quality of their contribution. This difference is seen in the effects of brain injury. Injury to the primary motor cortex leads to weakness and paralysis of the contralateral muscles.[59] In contrast, injury to the premotor cortex leads to difficulty in producing movements in certain circumstances, for example, when the patient is asked to mime the use of a tool or to learn arbitrary associations between stimuli and responses.[60] Finally, injury to the prefrontal cortex results in a classic syndrome characterized by lack of drive and poor ability to carry through on plans.[61] These effects indicate that progressively more anterior parts of frontal cortex contribute to progressively more abstract aspects of behavioral regulation. Each of these three districts participates in spatial processes insofar as the kind of behavioral regulation to which it is dedicated has a spatial component.

Neurons in the Primary Motor Cortex May Represent Movement Direction Relative to a Spatial Frame

The primary motor cortex contains a map of the muscles of the body in which the leg is represented medially, the head laterally, and other body parts at intermediate locations. Within the map are patches of neurons that represent different muscles. The neurons within a given patch receive proprioceptive input from a muscle or small group of synergistic muscles and send their output back to that muscle or group of synergists by way of a **multisynaptic pathway** traversing the brainstem and spinal cord. There have been many studies in which the electrical activity of neurons in the primary motor cortex is monitored while animals move. The general thrust of these studies is that neurons in the primary motor cortex are active when the corresponding muscles are undergoing active contraction.

Neurons in the primary motor cortex probably do more than simply encode the levels of activation of individual muscles or groups of muscles. One proposal is that they encode movement trajectories. Every voluntary movement can be described in two quite different, but perfectly complementary, ways: in terms of the lengths of the muscles and in terms of the position of the part of the body being moved. For example, during an arm movement, conjoint changes both in the lengths of muscles acting on the arm and in the position of the hand take place. Could it be that neurons in the primary motor cortex encode a spatial variable, such as the direction of movement of the hand, rather than a muscle variable?

Evidence supporting the idea that neurons of the primary motor cortex encode movement direction has come from studies in which monkeys make reaching movements from a central starting point to targets displaced from it in various directions. Individual neurons are selective for movement direction under these conditions; a given neuron may fire most strongly during movements up and to the right and progressively less strongly during movements that deviate by progressively greater angles from the preferred direction.[62,63] The patterns of selectivity are well defined and the preferred directions of different neurons cover the range of possible movements fairly evenly, so that by monitoring the activity of the entire population of neurons one could, in principle, quite accurately describe the movement. However, there are some impediments to concluding that these neurons encode movement trajectories. Over a small range of movements, muscle activation is almost linearly related to movement direction, so that determining whether neuronal activity reflects muscle activation or movement direction is difficult. Moreover, if the two factors are dissociated by inducing a monkey to move its hand along the same trajectory, but with the arm in different postures so that different patterns of muscle activation are required, then the relation between neuronal activity and the direction of movement of the hand seems to break down.[64]

Neurons in the Premotor Cortex Have Head-Centered and Hand-Centered Visual Receptive Fields

One of the functions of premotor cortical areas is to act as a conduit through which sensory signals are relayed to the motor system. The sensory information that reaches these areas has been highly processed already in the posterior cerebral hemisphere and thus it is not surprising, although it is still striking, that the sensory receptive fields of some neurons in premotor cortex are defined with respect to an external spatial framework, in a form suitable for motor use.

Two different forms of spatially organized visual responsiveness have been described in premotor cortex. First, in subdivisions of the premotor cortex representing orofacial movements, neurons respond to visual stimuli at a certain location relative to the head.[65,66] These neurons have been characterized by monitoring their electrical activity while objects approach the monkey's head along various trajectories. A typical experiment is illustrated in Fig. 53.7. In the first phase of the experiment, as shown in Fig. 53.7A, the monkey looked straight ahead at a small fixation target (F) while an object approached the face and receded, following a trajectory that brought it either to the right side of the head (trajectory 1) or to the left side of the head (trajectory 2). Records of neuronal activity (panel C) showed that the neuron fired when the object approached along trajectory 1 (panel A) but not when it approached along trajectory 2 (panel A). We conclude that the neuron had a receptive field located to the right of the monkey's head or at least to the right in his retinal visual field (shaded area in Fig. 53.7A). To determine whether the receptive field was head-centered or retina-centered required a further phase of testing. In this phase, as shown in Fig. 53.7B, the monkey looked far to the left at a small fixation target (F). While he maintained a leftward gaze, objects again approached the face, following trajectories 1 and 2. If the receptive field of the neuron were head-centered, one would predict that it should continue to respond as the object approached along trajectory 1. However, if the receptive field were fixed to the retina, then one would predict that the neuron should respond as the object approached along trajectory 2. Records of the neuron's electrical activity, monitored while the object moved along trajectory 1 (panel B) and trajectory 2 (panel B), clearly indicate that the neuron had a head-centered visual receptive field; it was selective for stimuli presented to the right of the head's midline, not to the right of the retina's midline. The head-centered spatial selectivity of neurons in the premotor cortex is reminiscent of the properties of some neurons in the parietal cortex, as described previously in connection with area VIP. That neurons in the two areas should exhibit similar patterns of spatial selectivity is not surprising because the parietal and premotor cortices are strongly interconnected.

A second pattern has been observed in subdivisions of the premotor cortex representing arm movements. Here, neurons respond to visual stimuli if those stimuli are presented in the vicinity of the hand.[67] When the hand moves to a new location, the visual receptive field moves with it. The visual receptive field remains fixed to the hand regardless of where the monkey is looking and, thus, regardless of the part of the retina on which the image is cast. These two forms of body-centered visual responsiveness presumably reflect the involvement of premotor neurons in visual guidance of orofacial and arm movements.

Neurons in the Supplementary Eye Field Encode the Object-Centered Direction of Eye Movements

The supplementary eye field (SEF; see Fig. 53.1) is a division of the premotor cortex with attentional and

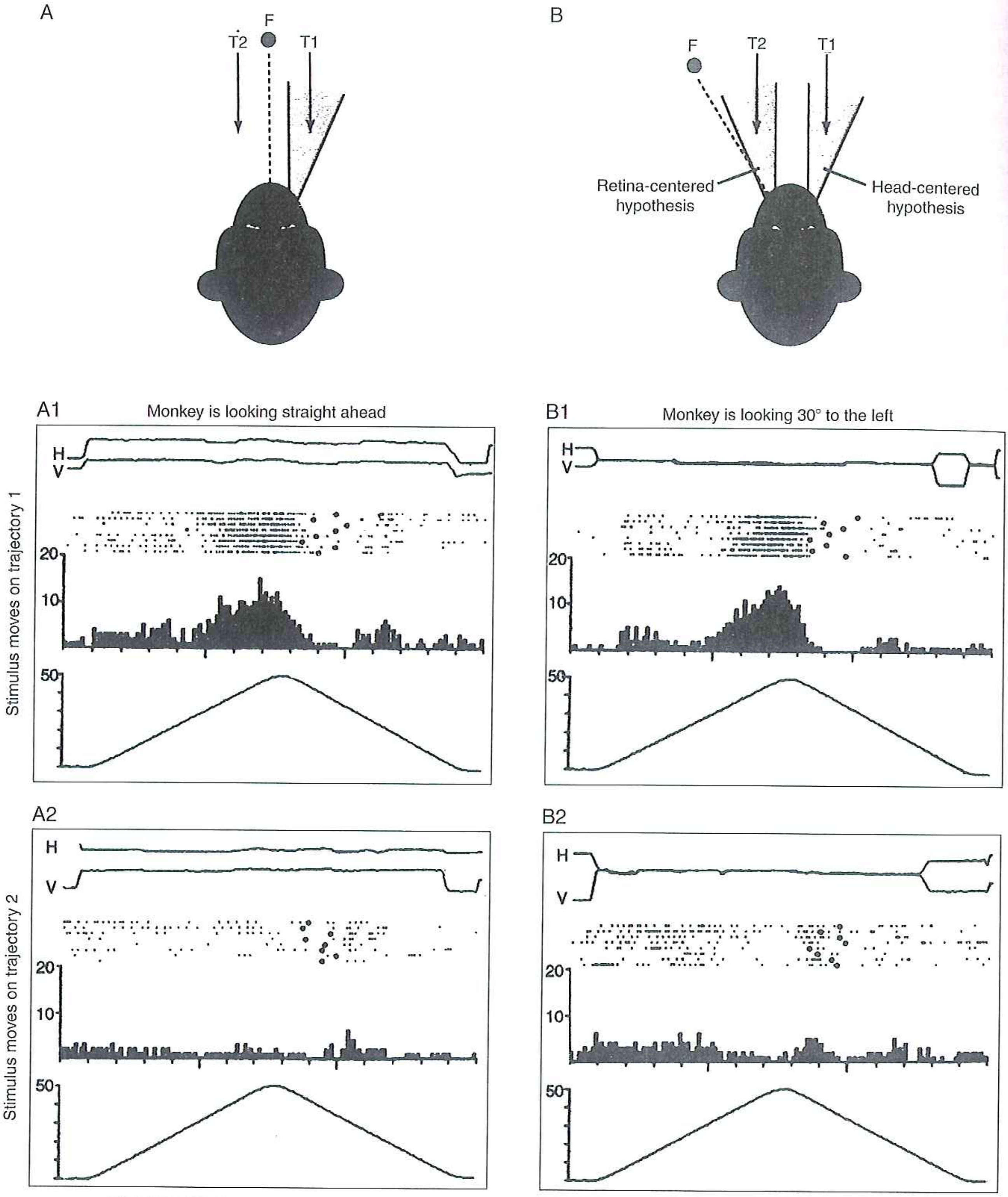

FIGURE 53.7 Data from a neuron in the premotor cortex with a head-centered visual receptive field. While the monkey was looking at a fixation point (F) directly in front of the head (A) or to the left of the head (B), a visible object approached the head and receded, traveling either along trajectory 1 (to the right of the head) or along trajectory 2 (to the left of the head). The neuron fired strongly when the object approached along trajectory 1, regardless of whether the monkey was looking straight ahead (A) or to the left (B). The neuron did not fire strongly when the object approached along trajectory 2, regardless of whether the monkey was looking straight ahead (A) or to the left (B). From Fogassi *et al.*[66]

oculomotor functions. Neurons here fire before and during the execution of saccadic eye movements, the rapid eye movements by which the eye darts from point to point between periods of fixation. In standard tests of oculomotor function, which involve monitoring neuronal activity while monkeys make eye movements between spots of light projected on a screen, neurons of the SEF exhibit directional selectivity. Each neuron has a preferred direction. It fires strongly before and during eye movements in this direction and at a progressively lower rate during eye movements that deviate by a progressively greater angle from this direction. A few traits of the SEF set it apart from brainstem oculomotor centers and suggest that its contribution to eye movement control occurs at a comparatively abstract level. For example, neurons here fire during a period when the monkey is waiting to make an eye movement in the preferred direction, as well as during overt execution of the eye movement. Moveover, some SEF neurons become especially active during a period when the monkey is learning to associate arbitrary visual cues with particular directions of eye movements.[68]

In monkeys trained to make eye movements to particular locations on an object, SEF neurons exhibit a unique form of spatial selectivity: they encode the direction of the impending eye movement as defined relative to an object-centered reference frame.[69,70] An experiment demonstrating this point is presented in Fig. 53.8. This figure shows data collected from a single SEF neuron while the monkey performed a so-called bar task. At the beginning of each 1- to 2-s trial, the monkey fixated a dot at the center of a video screen. While the monkey fixated the central dot, a sample-cue display was presented in the right visual field. The display consisted of a cue spot flashed on either the right or the left end of a short horizontal sample bar. Following extinction of the sample-cue display, the monkey maintained fixation of the central spot for around a second. Then, simultaneously, the central spot was extinguished and a target bar appeared at an unpredictable location in the monkey's upper visual

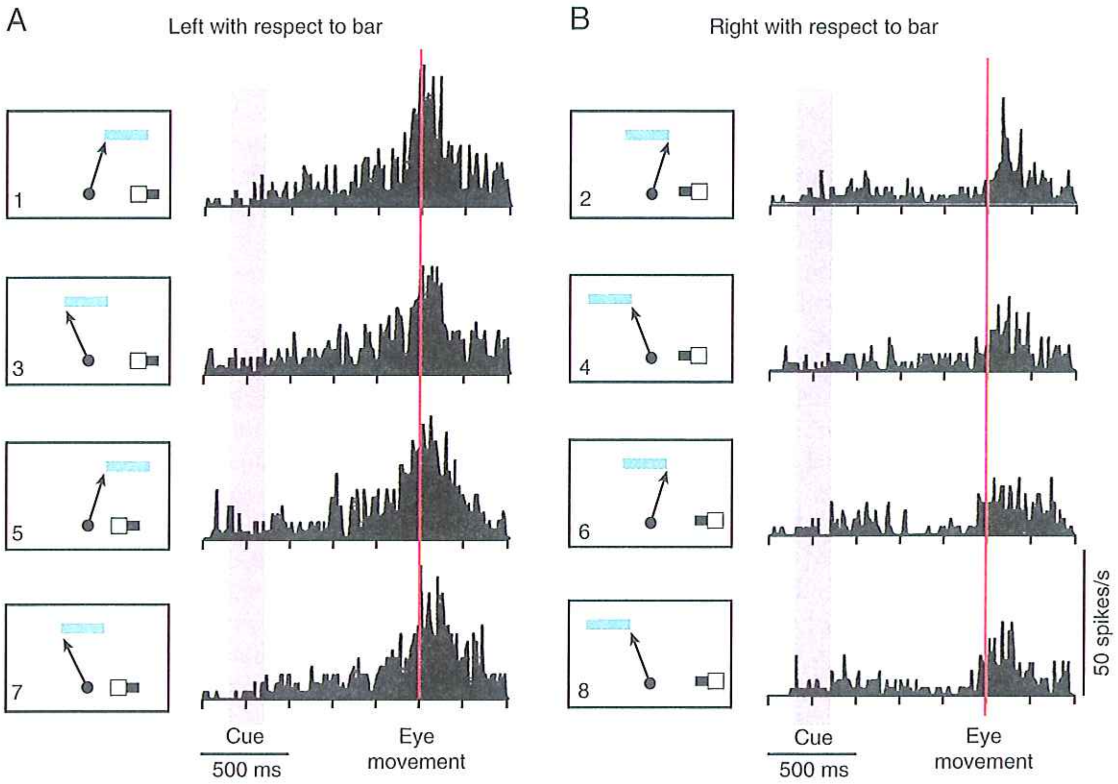

FIGURE 53.8 Data from a neuron in the SEF selective for the object-centered direction of eye movements. The monkey was trained to make eye movements to the right or left end of a horizontal bar that could be presented at several locations. The arrow in the panel next to each histogram indicates the direction of the eye movement. The neuron fired strongly when the eye movement was directed to the left end of the target bar (conditions 1, 3, 5, and 7) regardless of whether the eye's physical movement was up and to the right (conditions 1 and 5) or up and to the left (conditions 3 and 7). From Olson and Gettner.[69]

field. The monkey then had to make an eye movement to the end of the target bar corresponding to the cued end of the sample bar. In a series of trials, the sample bar, cue spot, and target bar were presented at various locations. The eight different conditions are shown in panels 1 through 8 of Fig. 53.8. The dot at the center of each panel represents the central fixation point, the elements at the right of the panel are the sample bar and cue spot, the element at the top of the panel is the target bar, and the arrow indicates the direction of the monkey's eye movement. The physical direction of the eye movement could be either up and to the right (panels 1, 2, 5, and 6) or up and to the left (panels 3, 4, 7, and 8). The object-centered direction of the eye movement could be either to the left end of the target bar (panels 1, 3, 5, and 7) or to the right end of the target bar (panels 2, 4, 6, and 8). Across this set of conditions, the object-centered direction of the eye movement was completely independent of its physical direction.

This situation made it possible to ask whether the electrical activity of the neuron was related to the movement's object-centered direction or to its physical direction. To the right of each panel in Fig. 53.8 is shown the average neuronal firing rate as a function of time during the trial. Regardless of the direction of the eye's physical movement, firing was clearly stronger on trials in which the monkey made an eye movement to the left end of the target bar than on trials in which the target was the bar's right end. For example, in conditions 1 and 2, the physical direction of the eye movement was exactly the same, and yet firing was much stronger when the bar's left end was the target (condition 1) than when the bar's right end was the target (condition 2). This neuron exhibited object-centered direction selectivity in the sense that it fired most strongly before and during movements to a certain location on a reference object. About half of the neurons in the SEF exhibit object-centered direction selectivity, each neuron favoring a particular location on the object, for example, the top, bottom, right end, left end, or center.

Object-centered direction selectivity, although it may at first seem to be an esoteric phenomenon, probably serves an important function in natural settings. In scanning the environment, we sometimes look toward locations where things are expected to appear, but which, at the time, contain no detail—for example, the center of a blank screen or the center of an empty doorway. Our eyes are guided to these featureless locations by surrounding features that define them indirectly. It is specifically in these cases that the SEF may contribute to the selection of the target for an eye movement. If so, then lesions of the SEF should selectively impair eye movements to targets defined indirectly by their spatial relation to visible features. This prediction can be given an even more specific form because the SEF areas of the right and left hemispheres are functionally specialized. In each SEF, neurons selective for eye movements to the contralateral ends of objects are preponderant (e.g., in the right hemisphere for eye movements to the left end of an object). Therefore, injury to one SEF should produce an impairment of eye movements to the contralateral ends of bars or other reference objects, a condition analogous to the objected-centered neglect that arises from unilateral parietal injury.

The Prefrontal Cortex Mediates Working Memory for Spatial Information

Working memory is required to hold a plan in mind and carry it out step by step (see Chapter 56). The fact that this ability is severely impaired in some patients suffering from prefrontal injury indicates that the prefrontal cortex, which forms the anterior pole of the cerebral hemisphere, plays a crucial role in working memory (see Chapter 59). Insofar as plans and working memory have a spatial component, operations carried out by the prefrontal cortex should also be spatial in nature. Single-neuron-recording experiments in monkeys performing delayed-response tasks have demonstrated the importance of the dorsolateral prefrontal cortex for both spatial and nonspatial forms of working memory.[71] A delayed-response task consists of several trials, each several seconds long. At the beginning of each trial, a cue is presented briefly, instructing the monkey which response to make, but the reponse must be withheld until the end of the trial. Delayed-response tasks can be designed so that both cues (for instance, spots flashed to the right or left of fixation) and responses (for instance, eye movements to the right or left) may be spatial. In the context of these spatial tasks, prefrontal neurons are active during the period between the cue and the signal to respond, when the monkey is holding spatial information in working memory. Just as for visual responses, some neurons are selective for the direction of the response. The simple interpretation of this pattern of activity is that it is a neural correlate of the monkey's actively remembering the cue and holding in mind the intended response. This interpretation is also supported by recent experiments based on imaging of brain activation in humans.[72]

The view that prefrontal cortex mediates spatial working memory has received further support from lesion experiments in monkeys. After injury to or inactivation of specific locations in the prefrontal cortex,

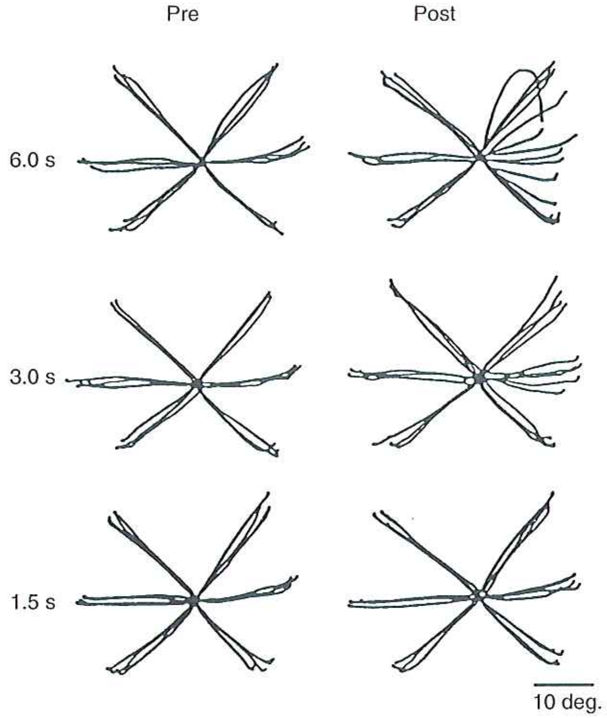

FIGURE 53.9 Inactivation of the left prefrontal cortex disrupts spatial working memory in the right half of space. A monkey was trained to fixate a central spot while a peripheral cue was presented briefly at one of six locations. After an interval of 1.5, 3, or 6 s, the fixation spot was extinguished and the monkey made an eye movement to the remembered location. Each inset of diverging rays shows the trajectories of eye movements executed under a certain set of conditions. Trajectories before and after prefrontal inactivation are shown on the left and right, respectively. Trajectories in the three rows are from trials with three different delay durations. When the cue was in the right hemifield and the monkey was required to remember it over long delays, the movements became highly inaccurate. From Sawaguchi and Goldman-Rakic.[74]

monkeys are poor at remembering locations in the opposite half of space, as indicated by the fact that their delayed responses are inaccurate and by the fact that the inaccuracy is exacerbated by longer delays, which tax active memory more heavily.[73,74] An experiment demonstrating the importance of the prefrontal cortex for spatial working memory is illustrated in Fig. 53.9, which shows behavioral data from a monkey trained to perform an oculomotor delayed-response task. At the outset of each trial, the monkey fixated a spot at the center of the screen. While the monkey maintained central fixation, a cue was flashed at one of six possible locations at positions 1, 3, 5, 7, 9, and 11 o'clock relative to the central spot. Following presentation of the cue, a delay of 1–6 s ensued before the monkey was permitted to make an eye movement to the cued location. Monkeys were able to perform this task with a high degree of accuracy.

Data from a normal monkey are shown in the left column of Fig. 53.9. In each inset, the six bundles of radiating rays represent the eye trajectories on trials when the cue was at the six different locations. The bottom, middle, and top insets represent eye movements on trials when the monkey had to remember the cue for 1.5, 3, and 6 s, respectively. Even when required to remember the cue for 6 s, the monkey made accurate eye movements to the cued location. Data in the right column are from the same monkey after a dopamine antagonist was injected into the left prefrontal cortex. The monkey's ability to remember the location of cue, as evidenced by execution of accurate eye movements to the cued location, remained intact when the cue was in the left (ipsilesional) visual field. However, performance deteriorated on trials when the cue was in the right (contralesional) visual field. Specifically, after long delays (middle and top insets), the direction of the eye movement began to deviate from the location of the cue, as if the monkey's working memory were fading. The fact that this deficit was specific to long delays is noteworthy because it rules out any simple explanation based on interference with visual or motor processes as opposed to working memory itself.

Summary

Neurons in frontal cortex represent spatial information as a natural consequence of their role in controlling behavior. Neurons in primary motor cortex encode the directions of movements. Neurons in premotor cortex encode the locations of objects relative to the body, even when these objects are not the immediate targets of actions. Finally, neurons in prefrontal cortex encode the locations of objects being held in short-term memory.

THE HIPPOCAMPUS AND ADJACENT CORTEX

The Hippocampal System Is Associated with Memory Formation

The hippocampus is an area of primitive cortex, or allocortex, hidden on the underside of the temporal lobe, where it occupies a medial location. The hippocampus is connected to a set of immediately adjacent cortical areas. These cortical areas, closely affiliated with the hippocampus in what might be termed a hippocampal system, include the perirhinal, entorhinal, and parahippocampal cortices.[75,76] The locations of the

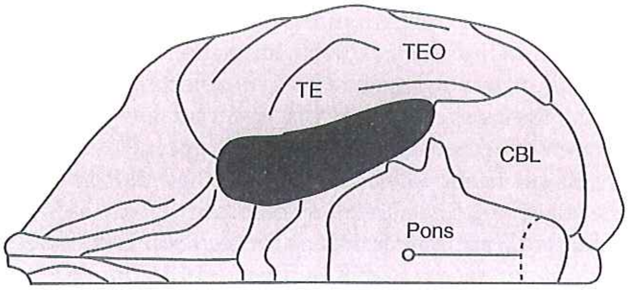

FIGURE 53.10 In this ventral view of the left cerebral hemisphere of a rhesus monkey, shading indicates the location of the hippocampus and the perirhinal and parahippocampal cortical areas. They occupy the ventral and medial aspects of the temporal lobe. This ventral view should be compared with Fig. 53.1, which shows a lateral view of the hemisphere. TE and TEO, visual cortical areas lateral to the parahippocampal cortex. CBL, cerebellum; Pons, pons: brainstem structures ventral and medial to the temporal lobe. Modified from Squire and Zola-Morgan.[77]

hippocampus and adjacent cortex are indicated in Fig. 53.10.[77]

Amnesia Resulting from Hippocampal Injury in Humans Includes a Spatial Component

Extensive evidence implicates the hippocampus and related medial temporal structures in the formation of episodic memories in humans. Memories dependent on the hippocampus include, although they are by no means restricted to, memories for spatial material.[78–80] In addition to other signs, the amnesia of the celebrated patient H.M., who sustained medial temporal lobe surgery, was manifested by his inability to learn to find his way through new neighborhoods. Patients with damage to the hippocampus and especially to the right hippocampus perform poorly on tests requiring them to inspect a scene with many objects and then to recall the locations of individual objects.

Neurons of the Hippocampal System Have Place Fields and Are Sensitive to Directional Orientation of the Head

Neuronal electrical activity has been monitored in the hippocampus of rats running eight-arm radial mazes and performing other tasks that require locomotion within a workspace. These experiments have revealed a remarkable degree of spatial selectivity. Many (perhaps a majority of) neurons throughout the hippocampus have place fields; that is, a given neuron will fire most strongly when the rat is within a certain sector of the workspace.[81–83] Different neurons have different place fields, so that, collectively, they cover the workspace.

Place fields are defined relative to prominent environmental landmarks; if a radially symmetric eight-arm maze is rotated relative to a surrounding room containing salient landmarks, then the place fields remain fixed with respect to the room. However, even in darkness, neurons continue to fire when the rat is in their place field. If the rat is placed in a new environment, hippocampal neurons rapidly manifest place fields relative to that environment. The location of a neuron's place field relative to the new environment is not predictable from its location relative to the old environment. This is true even in cases where the workspace is changed without any change in the surrounding room, for instance, through replacement of an eight-arm radial maze by a free field. Some hippocampal system neurons are sensitive not only to the rat's location but also to the direction in which the head is pointing.[82,84] Sensitivity to heading, although not the most distinctive feature of hippocampal neurons, is dominant in the postsubiculum, a cortical area adjacent to and closely linked to the hippocampus. Each postsubicular neuron fires most strongly when the rat's head is pointing in its preferred direction and fires progressively less strongly as the orientation of the rat's head deviates farther from that direction. In a room plunged into darkness, postsubicular neurons remain sensitive to the rat's heading so long as the rat retains a sense of spatial orientation, as reflected by error-free performance on spatial tests. When the rat's sense of spatial orientation drifts away from **veridicality** during prolonged darkness, as evidenced by the occurrence of systematic errors on spatial tests, then the preferred headings of postsubicular neurons exhibit a commensurate drift. These observations establish that neurons of the hippocampal system are sensitive to the rat's spatial orientation. How the hippocampus uses spatial information, along with nonspatial information, to form new memories is taken up in Chapter 56.

Summary

The hippocampal system mediates the formation of memories, including memories with spatial content. Injury to the hippocampal system, both in humans and in laboratory animals, leads to profound deficits of memory, including navigational memory. In accord with these findings, single-neuron recording in rats has revealed that neurons of the hippocampal system have place fields, encoding the rat's location in its environment, and directional sensitivity, encoding head direction relative to the environment.

SPATIAL COGNITION VERSUS SPATIAL ACTION

We have seen in the preceding sections that spatial information is processed by numerous cortical areas that serve distinct functions, such as motor control, attention, and working memory. Even within the motor system, there appears to be a fractionation of spatial functions, in that neurons controlling movements of the eyes, head, and arm represent the locations of visible targets relative to eye-centered, head-centered, and hand-centered reference frames, respectively. In addition to these distinctions, there may be another fundamental distinction within brain systems mediating spatial functions. Areas mediating conscious awareness of spatial information may be partially separate from those mediating the spatial guidance of motor behavior. These functions may seem inseparable, insofar as one must be aware of the location of a thing in order to look at it or reach for it. However, this is not necessarily the case. An indication that spatial awareness and spatially programmed behavior are distinguishable has come from studies of patients with so-called "blindsight."[85] This condition arises as a result of injury to primary visual cortex. Patients experience a **scotoma**, an area of blindness, in the part of the visual field represented by the injured cortex. The blindness is total in the sense that patients do not report seeing visual stimuli when the stimuli are presented within the confines of the scotoma. Nevertheless, if some patients are asked to look toward or to reach for the unseen stimulus, choosing the target by guesswork, their responses are directed to the correct location.[86] Similar findings have been reported in patients with diffuse pathology affecting widespread areas, including the prestriate visual cortex. When asked to express spatial judgments (for instance, to indicate the size of a visible object by spreading the thumb and forefinger), these patients perform poorly. Nevertheless, when asked to make visually guided movements (for instance, to reach for an object), they accurately adjust the grip size and hand orientation under visual control to grasp the object efficiently.[87,88] The fact that intact visuomotor performance coexists with profoundly impaired visuospatial perception in these patients seems to argue for the existence of distinct brain systems specialized for conscious spatial awareness and motor guidance, respectively.

Summary

Spatial cognition is a function of several different brain areas. No one area is uniquely responsible for our ability to carry out spatial tasks. Nevertheless, some generalizations can be made about the part of the problem that is solved in each brain region.

The parietal lobe plays a crucial role in many aspects of spatial awareness, including spatially focused attention. The representation of space in the parietal cortex takes several forms. Each area within the parietal cortex may have a different kind of representation, designed to help guide different kinds of actions. Beneath the unity of our spatial perception may lie a diversity of specific representations: the frontal lobe transforms spatial awareness into actions; the motor cortex uses a spatial framework to encode intended actions; the premotor cortex contains a set of different spatial representations to generate movement; the prefrontal cortex contains neurons with very high-order, abstract spatial representations and mediates short-term spatial memory; the hippocampus mediates episodic spatial memories, including those which underlie spatial orientation.

The distributed nature of spatial cognition and the many purposes it serves means that we construct internal representations of space not once but many times. A challenge for the future is to understand how these representations function together.

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