Our sense of vision and our eye movements are intimately intertwined. Because high-acuity vision requires foveal inspection, we frequently make rapid or saccadic eye movements to shift images of interest onto the fovea. Visual perception provides information about where to look next and thus directs our saccades, and the resulting saccades move the retinas and therefore influence vision. Understanding how vision and saccades work together instead of in opposition to each other is critical for understanding how we see so effortlessly and efficiently.

It is becoming clear that cognitive processes play key roles in facilitating the cooperation between vision and saccades. By cognitive processes, we mean processes of information manipulation, in contrast to more rudimentary functions of sensory detection and movement execution. Cognitive processes range from the conscious and voluntary (e.g., rehearsal during short-term memory) to the unconscious and involuntary (e.g., procedural learning). In this chapter we concentrate on two cognitive processes important for visuosaccadic behavior and discuss some of the neuronal networks that mediate them.

The first cognitive process is the translation of generalized visual analysis into a specific decision about where to look next. We are usually aware of numerous objects in the visual scene, but we can make a saccade to only one object at a time. An efficient selection process is clearly needed. This first cognitive function, often conscious and voluntary in nature, might be thought of as a forward function in that information about the visual scene influences movement. We call it saccadic target selection, a term encapsulating multiple operations such as shifting attention, deciding where to look next, and preparing to move.

The second cognitive process is that which allows us to maintain a stable visual percept despite all the saccades we make. Saccades move the retinas at high velocity, and if our visual system did not have foreknowledge about these sudden shifts, they would induce the alarming percept of a world constantly jumping around. Our visual system uses advance information about each upcoming saccade to lessen the imminent adverse effects of moving the retinas. This second cognitive function (an unconscious and involuntary one) might be thought of as a reverse function in that information about movement influences vision. We refer to it as a corollary discharge function (after Sperry, 1950), because it involves monitoring an internal correlate of a neuronal movement command. As will be discussed, corollary discharge has other uses as well, such as helping to produce a sequence of movements.

How does the brain accomplish these cognitive functions? We have known that both the cerebral cortex and the brainstem are important components of the visuosaccadic system for over a century (for a historical review see Tehovnik et al., 2000). Since about 1970, moreover, this research has benefited from a growing interest in exploring the neuronal bases of cognitive processes. Currently, it is well understood that many brain regions once thought to be primarily involved in visual processing are, in fact, involved in both and are additionally involved in the cognitive processes accompanying vision and eye movements. One such structure is the superior colliculus (SC), which lies on the roof of the midbrain, and other such structures lie in the cerebral cortex.

The cognitive functions that we consider are mediated by activity coursing in a network distributed throughout the brain; neither saccadic target selection nor corollary discharge arises from activity within a single brain area. As we will discuss, the projections from cerebral cortex to the SC have been studied in great detail, and the results indicate that saccadic target selection develops gradually from earlier, more visually related stages in cortex to later, more movement-related stages in the SC. Furthermore, there are at least two ascending pathways from the SC to cerebral
cortex. One seems to contribute to corollary discharge, and the other may contribute to spatial visual attention.

**The interconnections between cerebral cortex and SC**

Saccades are mediated by a system extending from the retina to the extraocular muscles that has been most extensively studied in the rhesus monkey, the animal model on which we will concentrate. The visuomotoric system can be regarded as having three limbs, two of which are the afferent and efferent limbs (Fig. 98.1,A). The afferent limb provides visual input from the retina. This pathway branches into two main routes, one coursing to the lateral geniculate nucleus and then to striate cortex (also known as V1) and another coursing to the superficial layers of the SC. The efferent limb provides motor output to the extraocular muscles. Motor commands are produced in the saccade generating circuitry in the brainstem, a collection of regions in the pons and midbrain that receives descending input from the SC and other structures.

The third limb is intermediary, connecting the afferent and efferent limbs (Fig. 98.1,B). It is in this vast network of “in-between” areas that activity related to cognitive processes presumably resides, and interconnections between cerebral cortex and the SC are a major component of this network. Several regions of cerebral cortex project monosynaptically to the SC, and the SC reciprocates by projecting disynaptically to many cerebral cortical regions via the thalamus (for reviews of the anatomy, see Leichnetz and Goldberg, 1986; Sparks and Hartwich-Young, 1989).

The SC and certain cortical regions are necessary for saccade generation. Reversible inactivation of the frontal eye field (Fig. 98.1,B, EFF) causes severe deficits in the ability to make saccades to remembered targets (Chaife and Goldman-Rakic, 2000; Dias and Segraves, 1999; Sommer and Tehovnik, 1997), and similar effects have been reported for inactivation of the lateral intraparietal area (Fig. 98.1,B, LIP) (Li et al., 1999). Reversible inactivation of the SC causes deficits in saccade production for all saccades made to either remembered or visual targets (Aizawa and Wurtz, 1998; Hikosaka and Wurtz, 1988, 1987, 1986; Li et al., 1998a; Schiller et al., 1987). Permanent ablation of either the SC or the frontal eye field causes serious deficits for a week or so, after which monkeys largely recover, but combined bilateral lesions of both the SC and the frontal eye field permanently devastate saccadic behavior (Schiller et al., 1980). The influence of many cortical regions seems to depend in large part on their projections to the SC; for example, the ability to evoke saccades electrically from the frontal eye field is severely impaired by inactivating the SC (Haner and Wurtz, 2001), and the ability to evoke saccades electrically from the parietal and occipital lobes is abolished by ablating the SC and the frontal eye field (Keating and Godley, 1987; Schiller, 1985).

In sum, there is good reason to suspect that the overall network composed of the cerebral cortex and the SC is important for saccade generation. In the first half of this chapter, we will review what is known about the signals descending from cerebral cortex to the SC. Investigated so far have been three direct projections emanating from the frontal eye field, the lateral intraparietal area, and the striate cortex (Fig. 98.2,A) and one indirect pathway, a basal ganglia route that relays signals from cortex to the SC via the substantia nigra pars reticulata (Fig. 98.2,B). Then we will discuss the signals flowing in ascending pathways from the SC to cerebral cortex. Two such pathways are staring to be well

**Figure 98.1.** The three limbs of the visuomotoric system in the monkey. **A,** The afferent limb, which provides visual input from the retina, and the efferent limb, which causes muscle contractions. Structures with dashed outlines are subcortical. These are other targets of retinal projections, too, but they are beyond the scope of this chapter. **SC,** superior colliculus (i, superficial layer; ii, intermediate layer); **LGN,** lateral geniculate nucleus; **V1,** striate cortex; **SGC,** saccade generating circuitry. **B,** The intermediary limb, which connects the afferent and efferent limbs. This limb is a network of brain regions; prominent among them are the frontal eye field (EFF) and the lateral intraparietal area (LIP).
characterized, one that reaches the frontal cortex via the mediodorsal thalamus and another that reaches the parietal cortex via the pulvinar (Fig. 98.2C).

To eavesdrop on the dialogue between cerebral cortex and the SC, investigators have identified neurons that talk back and forth between the areas using two methods: antidromic and orthodromic activation. Antidromic activation is used to see if a recorded neuron in one region (e.g., a part of cortex) projects to another region (e.g., the SC). Figure 98.3A shows the logic. If electrical stimulation in region B causes a recorded neuron in region A to fire at a fixed latency, and if other tests including one known as the collision test are successful (see the review by Lemon, 1984), then it is concluded that the neuron in region A is being activated through its own axon; therefore, the neuron projects to region B. Orthodromic activation is used to see if a recorded neuron in one region is receiving input from another region (Fig. 98.3B). If stimulation in region A causes a recorded neuron in region B to fire at a jittery latency and the collision test fails, then it is concluded that the neuron is being activated through synapses; therefore, this neuron receives input from region A. After a neuron’s connections are identified with one or both of these methods, it is then analyzed to determine what signals it is carrying, as discussed next.

**Descending projections from cortex to the SC**

The stages of neuronal activity related to visuosaccadic behavior generating a saccade in response to visual stimulation involves a series of steps including analyzing the visual scene, attending to objects within it, remembering the locations of objects, deciding to look somewhere, preparing a saccade, and executing the movement. It is reasonable to presume that these steps are accompanied at the neuronal level by sequential stages of activity. Figure 98.4 illustrates examples of neuronal activity that may contribute to various stages of visuosaccadic behavior. These examples were recorded from two SC-projecting cortical neurons (a lateral intraparietal area neuron, Fig. 98.4B, top, and a frontal eye field neuron, Fig. 98.4B, middle), both identified using antidromic activation, and from a neuron within the intermediate layers of the SC (Fig. 98.4B, bottom). The neurons were studied while the monkey performed a visual delayed-saccade task (Fig. 98.4A, left). The monkey fixated a spot of light during a baseline period, and then a target flashed in the periphery (Fig. 98.4A, top left). The monkey was required to maintain fixation for an extended delay period (500 to 1000 msec) until the...
A Antidromic Activation

Figure 96.3. Methods for evaluating the signals sent between brain regions. A. In antidromic activation, one region, B, is stimulated while recording from a neuron in another region, A. Stimulation-evoked action potentials travel backward through the axon of the neuron and are recorded at the cell body, A. In orthodromic activation, one region, A, is stimulated while recording from a neuron in another region, B. Stimulation evoked action potentials travel forward through projections and drive the neuron via synapses, and resultant postsynaptic action potentials are recorded at the cell body. (Spike waveform pictures modified from Sommer and Wurtz, 1986.)

B Orthodromic Activation

A Delayed Saccade Tasks

Visual Version

Target Onset

Memory Version

Delay Period

Saccade Onset

B SC-projecting LIP Neuron

Target Onset

Saccade Onset

SC-projecting FEF Neuron

SC Neuron

Visual Response

Delay Activity

Presaccadic Activity

Figure 98.4. Visual, delay, and presaccadic neuronal activity. A. The signals carried by identified neurons typically are characterized using one or more versions of the delayed-saccade task. See text for details. B. Examples of activity recorded from an SC-projecting lateral intraparietal area (LIP) neuron, an SC-projecting frontal eye field (FEF) neuron, and an intermediate layer SC neuron while monkeys performed the visual version of the delayed-saccade task. In each panel the activity is aligned on target onset (left) and saccade onset (right). Racers of dots show individual action potentials (each row is from a different trial). Curves show averaged firing rates (scale at the right). The time scale is 100 ms per tick on the abscissa. At the bottom, the visual responses, delay activity, and presaccadic activity are labeled. (Modified from Wurtz et al., 2001.)

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increases in activity that probably represented commands to move the eyes (Fig. 98.4B, presaccadic activity).

It is the delay activity that is of particular interest to us because it occurs after the initial visual response and before a saccade is made, during the time when saccadic target selection should be occurring. Ever since the discovery of delay activity by Fuster and Alexander (1971), investigators have used a variety of methods to tease out what this activity represents. Studies of neurons throughout the brain have found that delay activity can be a correlate of nearly every cognitive function imaginable, including various types of memory, spatial attention, representation of task rules, operations linked to categorization (e.g., whether a viewed animal is a cat or dog), and movement preparation (for reviews see Fuster, 1997; Miller, 2000). Most of these studies examined neurons without identifying their connections, for example, without determining if they projected to the SC. In the following sections, we will discuss some of these studies that examined neurons explicitly identified as sending delay activity and other signals to the SC.

Signals sent from Frontal Cortex to the SC. The first investigators to examine the signals sent from any cerebral cortical area to the SC in behaving monkeys were Segraves and Goldberg (1987), who used antidromic activation to identify SC-projecting frontal eye field neurons and studied their activity while monkeys performed a variety of tasks that included delayed saccade tasks. The results established that a variety of signals are transmitted from the frontal eye field to the SC, including visual responses, delay activity, and presaccadic bursts of activity. Segraves and Goldberg concluded, however, that the predominant output signal was a movement command represented by the presaccadic burst, implying that earlier visual detection and saccadic target selection functions are performed, for the most part, locally within the cerebral cortex.

To characterize more thoroughly the delay activity sent from frontal eye field to the SC, Sommer and Wurtz (2001a) studied SC-projecting frontal eye field neurons while monkeys performed a go/no-go delayed-saccade task. This task was similar to that diagrammed in Figure 98.4A, except that during the delay period the color of the fixation point changed. In half of the trials (go trials) the color changed to green, instructing the monkey to make a saccade to the target location, after the delay period, and in the remaining trials (no-go trials) the color changed to red, instructing the monkey to maintain fixation after the delay period. This revealed whether delay activity was related to producing saccades. Separate visual and memory versions of the task revealed whether this delay activity was related more closely to working memory, to visual attention, or to movement preparation. They found, first, that delay activity was quite common in the SC-projecting frontal eye field neurons (occurring in ~75% of the neurons) and, second, that the activity clearly did not represent only a single cognitive function. Most prevalent was delay activity related to working memory and to saccade preparation.

This study also revealed that the composition of signals sent from the frontal eye field to the SC was actually very diverse and included purely visual neurons as well as purely movement-related neurons (Sommer and Wurtz, 2000a). Reasons why these results differ from those of Segraves and Goldberg (1987), who found no purely visual neurons and a larger fraction of purely movement-related neurons, are discussed elsewhere (Sommer and Wurtz, 2000a). It is now well established that the signals carried by SC-projecting frontal eye field neurons are similar to those generally found in the frontal eye field (also noted by Everling and Munoz, 2000). This is true not only for the frontal eye field in monkey, but also for the homologous region (area 6) in cat (Weyand and Gaffan, 1998a, 1998b).

Two other important signals are also transmitted from the frontal eye field to the SC. First, the projection carries fixation-related activity that sarts when a monkey fixates a spot and continues even if the spot is briefly removed (Segraves and Goldberg, 1987). This activity seems to be sent to the entire SC (Sommer and Wurtz, 2000a), not just to the rostral SC where neurons with similar fixation-related signals are found (Munoz and Wurtz, 1993). Therefore, the descending fixation signals from the frontal eye field may work in parallel with rostral SC fixation signals to inhibit causal, saccade-related SC neurons and keep the eyes steady. Second, the projection from the frontal eye field to the SC carries activity related to preparatory set (Everling and Munoz, 2000). In a task where the monkey was instructed by the fixation point color to make a saccade either toward or away from a suddenly appearing peripheral target, movement-related neurons projecting from the frontal eye field to the SC showed, on average, higher activity during the fixation period and just after target onset when the instruction was to make a saccade toward the target. Therefore, the projection may contribute to larger visual responses in the SC when stimuli are to be targeted for saccades, which may help shorten reaction times. These two issues, of fixation-related activity and preparatory set, are discussed further below.

Although the frontal eye field sends a multitude of signals to the SC, this does not prove that the signals affect the activity of SC neurons. To address this issue of causality, other studies used methods involving orthodromic stimulation. Gritton and Mandell (1974) showed, in paralyzed cats, that stimulating the frontal eye field can increase or decrease the activity of SC neurons. Schlag-Rey et al. (1992) examined the issue in behaving monkeys, stimulating the frontal eye field while recording from SC neurons during delayed-saccade tasks. They found that the sign of the stimulation-
evoked change in SC activity was a function of topography: when the frontal eye field and SC sites represented similar saccadic vectors, frontal eye field stimulation caused SC activity to increase, but if the vectors were mismatched, stimulation caused SC activity to decrease. Because the direct projection from the frontal eye field is presumably excitatory (ghumatergic), the decreases in activity seen in these studies likely were mediated by multisynaptic pathways, for example, via GABAergic interneurons within the SC.

In sum, the projection from the frontal eye field to the SC carries an abundance of signal types and is functionally potent. Besides the frontal eye field, other frontal regions such as the supplementary eye field also project to the SC and contain neurons having visual responses, delay activity, and presaccadic activity (reviewed by Schall, 1997). However, akinetic and orthodromic activation studies still need to be performed to determine precisely how these other areas influence the SC.

Signs Sent from Parietal Cortex to the SC. Peré and Wurtz (1997) provided the first description of signals sent from any area of parietal cortex to the SC. They focused on the lateral intraparietal area, probably the most important parietal region for saccadic behavior. Using standard delayed-saccade tasks (Fig. 98.4), they demonstrated that SC-projecting lateral intraparietal area neurons carry visual, delay, presaccadic, and fixation-related activity. Not surprisingly, given the results already discussed in this chapter, the distribution of signals seemed quite similar to the distribution generally found in the lateral intraparietal area. A go/no-go task identical to that described above was used to study the delay activity in detail, revealing it to be highly diverse. In some neurons the activity seemed related to attending to or remembering the visual target, and in others it seemed more related to preparing the saccade. In all these ways, the SC-projecting lateral intraparietal area neurons were qualitatively similar to SC-projecting frontal eye field neurons. Differences could be detected only quantitatively (Wurtz et al., 2001), as discussed below.

At about the same time, Gnda and Beyer (1998) showed that SC-projecting lateral intraparietal area neurons are tuned for binocular disparity, providing information about visual depth. This was expanded upon by Ferraina et al. (2002), who concluded that the disparity tuning was quite broad. Finally, the latter authors additionally found that some neurons in the adjacent ventral intraparietal area exhibiting strong sensitivity to visual motion also project to the SC (Peré et al., 1999).

Signs Sent Indirectly from Cortex to the SC Via the Basal Ganglia. In addition to the direct connections that carry signals from cerebral cortex to the SC, there is a critical indirect route through the basal ganglia. Many cerebral cortical areas project to the caudate nucleus, which in turn projects to the substantia nigra. Both of these projections are excitatory. The substantia nigra pars reticulata contains GABAergic neurons that project to and inhibit SC neurons. Unlike the signals sent from cortex to the SC, which usually take the form of elevations of activity above a quiet baseline level, the signals sent from the substantia nigra to the SC are usually manifested as decreases in activity below a steady, elevated baseline level (for review see Hikosaka et al., 2000).

Two studies examined SC-projecting substantia nigra neurons, and both found a great variety of signals transmitted. Hikosaka and Wurtz (1983b) concluded that every type of signal present in substantia nigra pars reticulata seems to be sent to the SC. This included visual signals, delay activity, and presaccadic activity. The delay activity was thought to be related to short-term visual memory, although it could have been related to movement preparation as well (experiments systematically manipulating whether a saccade occurred or not, i.e., go/no-go experiments, were not performed). They also found that the visual and presaccadic discharges of SC-projecting neurons often were influenced by the context of the task, being different when saccades were made to remembered as compared to visual targets.

Basso and Wurtz (2000) studied how the activity of substantia nigra pars reticulata neurons varied with the probability of making a saccade. In their task, multiple visual stimuli were presented simultaneously, and the probability that saccadic target selection had to occur for any one of the stimuli was manipulated by varying the number of stimuli (from one stimulus, corresponding to a 100% probability of saccadic target selection occurring for that stimulus, to eight stimuli, corresponding to only a 12.5% probability of saccadic target selection occurring for any particular stimulus). Only a minority of their substantia nigra neurons was identified as projecting to the SC, but they found no obvious differences in this subset as compared to the general sample of substantia nigra neurons examined. They previously had found that the delay activity of intermediate-layer SC neurons varied strongly with probability in this task: the greater the chance that saccadic target selection would occur for a target in the neuron's receptive field, the higher the level of delay activity (Basso and Wurtz, 1998). Surprisingly, however, this was not the case for substantia nigra neurons, which usually maintained the same level of delay activity regardless of the chance of saccadic target selection occurring for the target in the receptive field. This maintained level was only slightly different than the background firing rate. This suggests that one or more of the direct cortical projections to the SC, not the indirect route through the nigra, is primarily responsible for changes in SC delay activity.
During saccadic target selection, Basso and Wurtz did find, however, that the short-latency visual responses of nigral neurons were strongly modulated by the probability of saccadic target selection. Taken together with the results of Hikosaka and Wurtz (1983b) that the visual responses of SC-projecting nigral neurons are sensitive to task context, these data suggest that the major cognitive-related influence of substantia nigra on SC is to cause visual-related changes in activity related to very early stages of saccadic target selection. Presumably these influences are primarily attentional in nature, as they are represented by altered visual responsiveness.

Signals sent from striate cortex to the SC. The final direct projection from cerebral cortex to the SC that has been investigated emanates from striate cortex. Unlike the other projections we have discussed, all of which target predominantly the intermediate layers of the SC, the projections from striate cortex target primarily the superficial layer (Kosopers and Lawrence, 1967; Ogren and Hendriks, 1976). The SC superficial layer also receives direct projections from the retina (Cowey and Perry, 1980; Hendriks et al., 1970), and neurons in this part of SC are visually responsive, with no presaccadic bursts of activity. Because it has been shown recently that striate cortical activity is influenced by attention (Haenny and Schiller, 1988; Motter, 1993; Posner and Gilbert, 1999) and may have delay activity related to short-term visual memory (Super et al., 2001), it is possible that signals in the projection from striate cortex might play some role in saccadic target selection. Whether this is true, however, remains unclear. The only study to examine this, in cat, found that SC-projecting striate cortical neurons often have enhanced visual responses when a visual stimulus is used as the target for a saccade as opposed to when it is viewed passively (Weyand and Galka, 2001). In principle, this could represent spatial visual attention. It was not determined, however, whether the enhancement occurred only when saccades were made toward the target; for comparison, Wurtz and Mohler (1976a) showed that enhancement effects in monkey striate cortex are independent of saccade direction and therefore cannot represent a spatially localized shift of attention. The modulation might represent a general arousal or vigilance effect (or other effects beyond the scope of this discussion; see Weyand and Galka, 2001).

Earlier studies of SC-projecting striate cortical neurons used anesthetized, paralyzed animals (cat: Palmer and Rosenquist, 1974; monkey: Finlay et al., 1976). These studies were valuable in describing the visual characteristics of SC-projecting striate cortical neurons (the neurons were typically binocular, complex, and orientation- and direction-tuned, with large receptive fields), but they did not address cognitive issues.

Also of interest in considering the relationship between visual cortex and the SC, at least with respect to cats, is the Sprague effect (Sprague, 1966): after ablation of visual cortex (including virtually all occipital visual areas, not just striate cortex), cats fail to orient to contralateral visual stimuli, but recovery occurs if the SC contralateral to the ablated cortex is lesioned or if the collicular commissure is cut. In a series of experiments, Rosenquist and colleagues showed that this recovery is likely due to disinhibition of the SC caused by interruption of fibers in the collicular commissure coming from the substantia nigra pars reticulata and from the pedunculopontine region (for a summary, see Durmer and Rosenquist, 2001). The Sprague effect has not been investigated in monkeys because the recovery of visual orienting is so fast following lesioning of visual cortex (in this case limited to striate cortex) that no subsequent interventions at the level of the SC are required for nearly complete recovery of orienting saccadic eye movements (Mohler and Wurtz, 1977).

Gradual progression of saccadic target selection from cortex to the SC. As discussed above, neurons in the frontal eye field and the lateral intraparietal area send to the intermediate layers of the SC a wide range of signals related to visuosaccadic behavior, which leads to two questions. First, are the signals leaving these two cortical regions similar to each other or radically different from each other? And second, how do the signals sent from these cortical areas compare with signals in the recipient structure, the SC? To answer these questions, Wurtz and colleagues studied SC-projecting frontal eye field neurons, SC-projecting lateral intraparietal area neurons, and intermediate layer SC neurons using identical tasks, equipment, and analytical techniques (for detailed analysis, see Wurtz et al., 2001). They found that, qualitatively, the signals carried by SC-projecting neurons in both cortical areas were quite similar to each other and to the signals within the SC. Neurons in all three populations exhibited visual responses, delay activity, and presaccadic activity in nearly every possible combination.

When the signals were analyzed quantitatively, however, important differences were uncovered. First, the delay activity was examined to see if it was more strongly influenced by the visual target or by the upcoming movement. To gauge the influence of visual stimulation on the delay activity, the activity was compared in the visual and memory versions of the standard delayed-saccade task (Fig. 98.4A). It was found that delay activity in the SC-projecting neurons of both cortical regions was strongly enhanced by visual input (to a similar degree in both regions), whereas delay activity in the SC intermediate layers was much less visually related, being equal whether a target remained in the receptive field or disappeared. To measure the influence
of upcoming movement on the delay activity, the activity was compared in the go and no-go trials of the go/no-go delayed-saccade task described above. Delay activity in the SC was much more strongly enhanced by upcoming movement than was delay activity in SC-projecting neurons of either cortical population.

Next, the visual responses and presaccadic activity of the neurons were compared. Visual responses in the three populations of neurons were not markedly different. The presaccadic activity, however, was much more intense in SC neurons (nearly always 200 to 600 spikes per second) than in cortical output neurons (rarely >200 spikes per second). Also, when the two populations of cortical output neurons were compared, SC-projecting frontal eye field neurons often were found to have presaccadic activity as their only signal (so-called pure movement neurons), whereas this was never seen in the SC-projecting lateral intraparietal area neurons.

In sum, this investigation answered both questions posed above. First, signals leaving the two cortical areas are not radically different from each other; they are similar, with only limited differences. Second, signals sent to the SC intermediate layers and signals within the SC intermediate layers are similar, except for important quantitative differences. Compared to the cortical output neurons, the SC neurons are more movement-related and less visually related. From cortex to the SC intermediate layers, there seems to be a gradual change in signal content corresponding to a progression in saccadic target selection processes from more visually related (i.e., processes of attention and visual memory) to more movement-related (i.e., processes of saccade preparation).

Other, less direct comparisons of cortical and SC activity support this idea. Everling and colleagues (Everling and Munoz, 2000; Everling et al., 1999), for example, examined neurons in the SC intermediate layers and in the frontal eye field using identical techniques. Here we consider their total sample of frontal eye field neurons, the projections of which were not identified except for a minority shown to project to the SC (results pertaining specifically to these SC-projecting neurons were discussed above). Neurons in both the frontal eye field and the SC had higher activity throughout trials when monkeys had to make saccades toward, as opposed to away from, a visual stimulus in the receptive field. Furthermore, activity in both areas predicted reaction time and the occurrence of errant saccades, indicating that the activity was strongly related to saccade production. The investigators concluded, however, that although these effects were similar in the two areas, they were weaker in the frontal eye field than in the SC.

Several other studies have examined cognitive-related activity in the SC intermediate layers as well (for detailed reviews see Basso, 1998; Wurtz et al., 2000). Glimcher and Sparks (1992) were the first to examine systematically SC delay activity. They presented two peripheral visual stimuli, one within and one outside of the neuron's receptive field, and instructed monkeys by means of a central color cue which stimulus would be the saccadic target. They found that shortly after the monkeys were instructed to make their eventual saccade into a neuron's receptive field, activity of the neuron increased dramatically. Building on this result, Basso and Wurtz (1998) and Dorris and Munoz (1998) showed that the intensity of cognitive-related activity in SC neurons is directly correlated with the graded probability of making a saccade to a particular visual stimulus. In these and similar studies (Dorns et al., 1997; Everling et al., 1998, 1999), it was repeatedly found that cognitive-related SC activity predicted saccadic reaction times and the production of errant saccades, indicating that it was strongly movement-related. In contrast, Sommer and Wurtz (2001a) showed that delay activity sent from the frontal eye field to the SC does not seem to predict either reaction time or errant saccades. Taken together, these studies reinforce the model of a gradual progression in saccadic target selection processes that becomes more movement-related from cerebral cortex to the SC.

To see if delay activity in the SC really does influence saccadic target selection, Kustov and Robinson (1996) combined single-unit recordings with electrical stimulation to evoke saccades. They used tasks in which a peripheral or central cue elicited a shift of attention to one of two possible targets, one of which was located in the part of the visual field represented by the site studied in the SC. Monkeys exhibited decreased reaction times in making saccades to the cued targets, indicating that they shifted their attention as expected. The investigators found that delay activity in the SC increased during the attentional shifts and that when the SC was stimulated, evoked saccades were deviated toward the locus of attention. Hence, not only is the activity of SC neurons correlated with attentional shifts, but also it seems to affect the saccadic system such that electrically evoked saccades are altered. Similar conclusions were reached in a recent frontal eye field study (Moore and Fallah, 2001). In that experiment, subthreshold stimulation for evoking saccades in the frontal eye field caused enhanced performance in a spatial attention task, but only for attended targets located in the part of the visual field represented by the frontal eye field site. In summary, these studies confirm the underlying assumption that delay activity, at least in the SC and the frontal eye field, is in fact vital for the act of selecting a saccadic target.

Finally, Munoz and colleagues found neurons in the rostral pole of the SC that seem to inhibit, rather than facilitate, saccade production (for a review, see Wurtz et al., 2000). Whereas neuronal activity in more caudal SC is low during fixation and increases prominently just prior to
saccade production, activity in the rostral pole is high during fixation and decreases just prior to saccade production. Using orthodromic stimulation within the SC, they showed that the rostral pole’s influence on neurons of the caudal SC is inhibitory (Munoz and Istvan, 1998). Therefore, some of the increased delay activity in caudal SC neurons during the experiments described above might be due in part to disinhibition caused by rostral SC afferents. Of course, this begs the question of what controls the rostral SC neurons; some of their input likely comes from cerebral cortex (Sommer and Wurtz, 2000a), but beyond that, little is known.

**Ascending pathways from the SC to the cortex**

The SC sends projections downstream, to the brainstem saccade-generating circuitry, and also upstream, to the thalamus. Ascending projections from the SC to the thalamus were identified anatomically decades ago (e.g., Benevento and Fallon, 1975), and it has long been presumed that these projections terminate on relay neurons that in turn project up to the cerebral cortex (e.g., Benevento and Rezak, 1976; Goldman-Rakic and Porrino, 1985). Very recently, these disynaptic pathways from the SC to cortex via the thalamus have been elucidated more directly using a novel anatomical method in which herpes viruses that pass retrogradely through synapses were injected into cerebral cortex. Primary and secondary labeling was detected in thalamic nuclei and the SC, respectively (Glover et al., 2001; Lynch et al., 1991).

Two major ascending pathways exist: one from the intermediate SC to the mediodorsal nucleus of the thalamus to the prefrontal cortex, and another from the superficial SC to the pulvinar region of the thalamus to extrastrate cortex. We will discuss the mediodorsal nucleus pathway in this section and the pulvinar pathway in the next.

**The Ascending Pathway through the Mediodorsal Nucleus to the Prefrontal Cortex**

Even before its presence was demonstrated explicitly by Lynch et al. (1994), a disynaptic pathway from intermediate SC to prefrontal cortex was posited and there was much speculation regarding its possible function. Is it a feedforward route through which visual signals, some of which might be attentionally modulated, are relayed from the SC to prefrontal cortex (as hypothesized by Goldberg and Bushnell, 1981; Suzuki and Azuma, 1983; Wurtz and Mohler, 1976a)? Or is it a feedback route, through which prefrontal cortex is informed of the saccadic commands produced by the SC?

Evidence supporting both hypotheses was obtained in the first exploration of single neurons in primate visuomotor thalamus (Schlag and Schlag-Rey, 1984; Schlag-Rey and Schlag, 1984). Neurons located in or near the lateral edge of the mediodorsal thalamus, where SC-to-prefrontal cortex relay neurons are found (Lynch et al., 1994), were shown to exhibit both visually related and saccade-related activity. The connections of these neurons were not physiologically identified, however, and thus it was unknown whether they actually projected to prefrontal cortex or received projections from the SC.

Recently, a set of studies used both identified neuronal recordings and reversible inactivation techniques to examine the pathway from SC to mediodorsal thalamus to frontal eye field (Sommer and Wurtz, 1998, 2000b, 2001b, 2002; Wurtz and Sommer, 2000). Every neuron in these experiments was shown with antidiromic and/or orthodromic activation to be part of this ascending pathway. Three populations of neurons were studied: SC neurons projecting to the mediodorsal thalamus, mediodorsal thalamus relay neurons, and frontal eye field neurons targeted by the pathway. The conduction speed in this pathway is very fast: orthodromic and antidiromic activation latencies confirmed that it only takes ~2.3 ms for signals to reach the frontal eye field from the SC through this route.

To characterize the signals carried by these neurons, delayed-saccade tasks were used, as described in previous sections. Neurons at every level of the pathway were active during these tasks, with most neurons having both a visual response and a presaccadic burst of activity and others having only one or the other signal. Therefore, both of the hypotheses noted above were supported in that the pathway definitely carries both visually related and movement-related discharges. Little delay activity was found in the ascending pathway, and therefore this activity was not characterized in detail using go/no-go or similar tasks.

Although the hypothesis that this pathway carries movement information was supported by the recording results, the results could not distinguish between two alternative possibilities regarding the function of these movement signals. Were they used as feedback, that is, corollary discharge, to inform the cerebral cortex about impending saccades, or were they used in a feedforward way to help in the execution of saccades? Both possibilities were supported by the characteristics of the neuronal activity in that the presaccadic bursts began ~100 ms prior to saccade onset and encoded specific vectors of saccades (i.e., the neurons usually had restricted movement fields).

To distinguish between these possibilities, reversible inactivation experiments were performed (Sommer and Wurtz, 2002) (Fig. 98.5.4). The relay neurons were inactivated with the GABA agonist muscimol while monkeys performed either standard single-saccade tasks or else a double-step task that required corollary discharge information (Becker and Jürgens, 1979; Duhamel et al., 1992; Gaisnard et al., 1994; Heide et al., 1995; Mays and Sparks, 1980). It was found that single saccades were not affected by inactivation, indicating that saccade-related signals in the ascending pathway...
Figure 98.5. Test of the hypothesis that the ascending pathway through mediodorsal thalamus carries a corollary discharge signal. A, Muscimol was injected at the site of previously recorded mediodorsal thalamus relay neurons to inactivate them. B, Schematic of the double-step task. See text for details. T1, T2: first and second flashed targets, respectively; S1, S2: first and second saccades; CD, corollary discharge; Contra, contraversive to the injection site. C, Example results from a single injection. First saccades were shifted upward slightly as an artifact of being made in complete darkness (Gnadt et al., 1991). The differences in average locations, during versus before inactivation, were tested in both the horizontal and vertical directions for the three fixation locations, the first saccade end points, and the second saccade end points. The only significant difference was a horizontal contraversive shift in second saccade end points as predicted by loss of corollary discharge. n.s.d., not significantly different. D, Histogram of the horizontal shifts in second saccade end points for all cases (i.e., all the during vs. before pairs of saccadic sequences) in all injections. In nearly every case there was a contraversive shift. The mean shift was significantly greater than zero, as indicated, and many of the cases had an individually significant contraversive shift. The significance level is p < .05, which is Bonferroni-corrected from p < .05 because the data were tested in two directions. Ipsi, ipsiversive shift; Contra, contraversive shift. E, In contrast, first saccade end points were not shifted horizontally by inactivation (hence, the second saccade end-point shifts are not artifacts of prior first saccade end-point shift). F, Histogram of the severity of deficits for all cases that had an individually significant shift. See text for a description of measuring severity of deficit. The mean deficit is indicated. (Adapted from Sommer and Wurtz, 2002.)

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were not important for the general execution of saccades. However, consistent deficits were found during the double-step task, indicating that corollary discharge was impaired, as described next.

In the double-step task, a monkey fixated a spot and then two sequentially flashed targets were presented briefly in the periphery (Fig. 98.5B, upper left). The monkey had to look at the locations of the targets in the order in which they had appeared (Fig. 98.5E, upper right). Hence, to make the second saccade correctly, the monkey had to know whether it made the first saccade correctly. There was no visual feedback because the targets disappeared before saccades were initiated. proprioception plays little or no role in the on-line control of saccades, so it could not help the monkey in keeping track of its first saccade. (Bridgeman, 1995; Guzrie et al., 1983; Lewis et al., 2001; Steinbach, 1987). To perform the task, therefore, the monkey had to monitor a corollary discharge representation of the first saccade. If inactivation did not affect corollary discharge, then during the inactivation the monkey would make its first saccade and know that it did so; therefore, the second saccade would go straight up to the second target location from the end point of the first saccade, just as it did before inactivation (Fig. 98.5B, lower left). If inactivation totally eliminated corollary discharge, however, then during inactivation the monkey would make the first saccade and not know that it did so; hence, the second saccade would be made as if the monkey were still looking at the center of the screen, and it would go up at an angle so that its end point would be shifted contraversely (rightward) (Fig. 98.5B, lower right). This is in fact what happened: as shown in the example (Fig. 98.5C) and in the population data (Fig. 98.5D), there was a consistent contraversely shift in the end points of second saccades during inactivation. First saccades end points were not shifted on average, however (Fig. 98.5E), and neither were the initial fixation locations. In the vertical dimension there were no mean shifts in second saccade end points, first saccade end points, or initial fixation locations. Surprisingly, the deficits were partial, not total; in the example case, for instance, there was a 2.5 degree shift when a 10 degree shift had been expected, representing a 25% deficit. Overall there was a mean deficit of 19% (Fig. 98.5F), and thus although the effect was consistent, it was modest in magnitude. This suggests that other pathways, unaffected by the inactivations, also carry corollary discharge signals.

In summary, the results support two hypotheses regarding the function of this fast-conducting ascending pathway through mediiodorsal thalamus. First, the pathway carries visual signals. Although the meaning of this finding is not yet fully understood, it demonstrates that visual signals in the frontal eye field do not arrive only in afferents from extrastriate cortex, as seems to be commonly believed. They also arrive from the intermediate layers of the SC, raising the possibility that some interesting attributes of frontal eye field visual neurons (e.g., their ability to discriminate visual targets from distractors; reviewed by Schall, 1997) might be due in part to antecedent processing in the SC. Second, the pathway carries presaccadic discharges to frontal cortex, and reversible inactivation of the pathway demonstrated that these are corollary discharge signals. The corollary discharge signals contribute to the ability to make sequences of saccades. They may also contribute to visual scene stability during saccades, although this possibility has yet to be explicitly tested.

The Ascending Pathway through the Pulvinar to the Visual Cortex While the SC intermediate layer have a prominent projection to cerebral cortex through mediiodorsal thalamus, the superficial layers of the SC project to the cortex primarily through a pathway that includes the pulvinar nucleus of the thalamus (Cleer et al., 2001). Neuronal activity in the SC layers that contribute to these two pathways are different: neurons in both the superficial and intermediate layers exhibit short-latency responses to visual stimulation of the retina (about 40 to 60 msec; Wurtz et al., 1985) and nearly always have clear receptive fields (for reviews, see Sparks and Hartwich-Young, 1989; Wurtz and Albano, 1980), but in contrast to intermediate layer neurons superficial layer neurons show no presaccadic burst of activity. There is some overlap in the distribution of these visual and visual-movement neurons in that both are found in the lower levels of the superficial layers (the stratum opticum; Ma et al., 1991), but the extent to which neurons in this ventral superficial region contribute to one ascending pathway, to the other, or to both remains unknown. In this section, we will concentrate on the neurons with visual receptive fields but not presaccadic activity, and the term SC neurons in this section will refer to these superficial visual neurons. The major inputs to these neurons are from the retina and striate cortex, as discussed above. It is reasonable to assume a prior that the signals sent from superficial SC up to cortex are visual in nature, but since recordings in the pulvinar of the monkey (Bender, 1981; Petersen et al., 1985) have not physiologically identified the source of any of the inputs to the neurons, and because there are inputs to pulvinar from visual cortex (Ogren and Hendrickson, 1976; Ungerleider et al., 1983, 1984), at this point we can only estimate the signal content in this pathway by reviewing studies of the general population of neurons in the superficial SC, the pulvinar, and the parietal cortex.

This ascending pathway from the SC to cortex has been referred to as a second visual pathway or second visual system (Diamond and Hall, 1969; Schneider, 1969), and it has been considered important not only as a phylogenetically older pathway but also as one that may provide an alternative
route for visual information to reach cortex. Such an alternative route takes on particular importance in explaining the residual visual abilities (Mondino, Stooig and Cowey, 1997; Weiskrantz et al., 1974) and the residual visually related neuronal activity in extrastriate cortical areas (Gerard et al., 1992; Rodman et al., 1989, 1990) that persist after removal of striate cortex.

Currently, there appear to be two major types of signals that could be conveyed through the pathway from the superficial SC to cortex via the pulvinar. One type is a visual response modulated by corollary discharge input, and this will be discussed first. The other is a visual response modulated by attention, discussed second.

One of the earliest investigations of the effect of a corollary discharge on visual processing in the primate was on superficial layer SC neurons (Robinson and Wurtz, 1976). The test for the effect of a corollary discharge was simply to determine if the neurons responded the same way when a saccadic eye movement swept their receptive field across a stationary stimulus as when the stimulus was swept across the receptive field while the eye was stationary. Many superficial layer SC neurons did not respond to the stimulus during the saccade, which was interpreted to be the effect of an extraretinal input to the SC present during the eye movement but not during the stimulus movement. This is in contrast to the lack of any such evidence for an extraretinal input to striate cortex neurons (Wurtz, 1969).

In principle, the extraretinal signal used by superficial SC neurons could have come either from a corollary discharge or from proprioceptive inflow from the eye muscles. To determine which, Richmond and Wurtz (1980) paralyzed the eye muscles and determined when eye movements were attempted by recording in the brainstem motor nuclei. Even in the absence of actual movement, modification of the visual response still occurred, leading the investigators to conclude that corollary discharge was sufficient for this modulation. Subsequent experiments on neurons in the pulvinar showed that their visual responses, too, were modified by eye movements (Robinson and Petersen, 1985). Given that the pulvinar receives afferents from the SC, this modulation could be a reflection of activity sent from the SC.

Thus, in the pathway from the superficial SC to the pulvinar, there is an indication of the influence of an extraretinal signal, which is the case of SC neurons, has been demonstrated to involve corollary discharge. Note, however, that these neurons acted as if they received corollary discharge signals, as exhibited by changes to their visual responses. Where these particular corollary discharge signals come from, remains unknown. In contrast, in the other ascending pathway, via medial dorsal thalamus, neurons carry a corollary signal that is sent up to the cerebral cortex, and we know that this signal comes from the SC intermediate layers.

Neuronal signals related to attention also have been studied in the SC-pulvinar pathway. When the monkey selects a target for its next saccade that lies in the receptive field of an SC neuron, the visual response of the neuron is frequently enhanced compared to the case in which the monkey selects a target well outside the receptive field of the neuron (Goldberg and Wurtz, 1972). This enhancement is consistent with a shift of attention to the visual target for the impending saccade, and such enhancement has been seen clearly in a number of regions including frontal cortex, parietal cortex, and the substantia nigra pars reticulata (for reviews, see Hikosaka and Wurtz, 1989; Wurtz et al., 1980).

The relation of the enhancement to the generation of the saccade differs between the areas, however, as determined by comparing modulation of neuronal activity when the monkey must use the stimulus as the target for a saccade as opposed to holding its eyes steady and reaching out to touch the stimulus. This distinction was first made in the SC (Wurtz and Mohler, 1975c), where the enhancement accompanying saccades to a target was absent with a reach to the target. The same was true for neurons in the frontal eye field (Goldberg and Bushnell, 1981). In the parietal cortex, however, neurons showed an enhanced response with both saccades and reaching (Bushnell et al., 1981), suggesting that the modulation represented a movement-independent visual attention. Enhancement found in the SC and the frontal eye field, in contrast, is more appropriately regarded as a correlate of target selection specifically related to saccade generation (Wurtz et al., 1980, 1983).

Garasch and Desimone (1996) tested whether enhancement of superficial SC visual neurons really was inextricably linked to saccade generation using a different method (as a caveat, they indicated that some of their neurons may have been in the pulvinar). They used the monkey with a peripheral stimulus falling inside the visual receptive field of the neuron but required the monkey to make a visual discrimination at the site of the cued stimulus instead of making a saccade to the stimulus. The neurons showed an enhanced visual response when the cue was in the receptive field as opposed to when it was not. The enhancement was present even in the absence of the saccade, suggesting that it is dissociable from saccade generation. However, when they then used a symbolic cue at the fixation point, they found no such enhancement even though saccades still were not produced. This implies that the monkey may have been planning a saccade in response to the peripheral cue even though one was not executed; such a planned but withheld saccade would not be expected for symbolic cues at the fixation point. The results therefore do not seem to refute the idea that enhancement in the SC is devoted to saccade generation.

This link between enhancement of visual responses in the SC and saccade generation is further supported by the
observation that as the time at which a saccade is made shifts closer to the time of the visual response, the enhancement increases (Wurtz and Mohler, 1976b). It is as if the presaccadic activity in the SC intermediate layers acts on superficial layer neurons to facilitate the enhancement. This remains entirely hypothetical, however. No such connection has been verified either anatomically or physiologically, although connections from superficial to intermediate layers are now clearly established (e.g., Isa and Saito, 2001; Lee et al., 1997). At this point, the exact mechanism causing the enhancement remains unknown.

Many superficial SC neurons are known to convey visual information to the pulvinar, as shown using antidromic activation (Marrocco et al., 1981). Because that study used paralyzed monkeys, attentional effects on the visual responses leaving the SC could not be assessed. Attention has been studied, however, within the structure receiving these projections. The retinotopic maps of the inferior and lateral pulvinar regions have been clearly delimited (Bender, 1981, 1982), and neurons showing changes in activity related to saccadic eye movements or visual modulation have been found primarily in the inferior area (PI) and in another visually responsive area (Pdm) of the lateral pulvinar (Petersen et al., 1985; Robinson et al., 1986). These neurons showed visual enhancement for stimuli in the contralateral visual field similar to that seen in the SC, but with the striking difference that enhancement occurred regardless of whether an eye movement to the target was made or a lever press was made (Petersen et al., 1985). Because the enhancement did not depend on the motor modality, it was an extremely sound candidate for mediating visual attention.

That these neurons contribute to shifts of attention made by the monkey was demonstrated conclusively by Petersen et al. (1987), who inactivated the region of the pulvinar where neurons were modulated by attention. First, they recorded neurons in this area and found that they were enhanced during an attentional task in which monkeys had to detect the dimming of a target in the neuron's receptive field. Then they inhibited the neurons with muscimol while monkeys performed a task in which a peripheral cue elicited attentional shifts, as measured by improvements in manual reaction time. In valid trials (Fig. 98.6d, top), the peripheral cue and the subsequently presented target appeared in the same hemifield and the reaction time to release a lever in response to target onset was relatively short, presumably because attention was drawn to the target location by the preceding cue (other experiments showed similar reaction time decreases when a central symbolic cue was used, demonstrating that these effects probably were not related to covertly preparing a saccade to the peripheral cue; Bowman et al., 1993). In invalid trials (Fig. 98.6d, bottom), the peripheral cue and the target appeared in opposite hemifields and the reaction time was longer, presumably because attention was drawn away from the target location. During pulvinar inactivation, there was no effect on reaction time if both cue and target were presented ipsilaterally to the injection site (Fig. 98.6b, top: ipsilateral valid cue). However, if both the cue and target were presented contralaterally to the injection site, the reaction time was substantially increased (Fig. 98.6b, bottom: contralateral valid cue). The deficit appeared to represent an impairment in the ability to shift attention contravertively in response to the cue. On the other hand, injection of a GABA antagonist, bicuculline, did not seem to cause swifter attentional shifts (Fig. 98.6b, bottom); this may be a floor effect caused by the monkeys being so well trained that they could not possibly shift their attention faster. For brevity, results from invalid cue trials are not discussed here, but they further supported the conclusion that inactivation caused impairment of attentional shifts.

To summarize, currently we know that some pulvinar neurons show visual enhancement, that the enhancement is not dependent upon the execution of an eye movement, and that inactivation of the pulvinar impairs attention.

While anatomy suggests that the regions of the monkey pulvinar studied lie on the pathway to cerebral cortex (Benevento and Fallon, 1975), a remaining caveat is that the extent to which various regions of pulvinar convey information from the SC to cortex is still unknown (e.g., Stepniewska et al., 1999). Also not known is the extent to which the pulvinar-to-cortex projection modifies neuronal activity in cortex, particularly in the lateral intraparietal area considered previously in this chapter. As noted above, Bushnell et al. (1981) found movement-independent visual enhancement in parietal cortex similar to what was seen in the pulvinar. More recent experiments in parietal cortex (Robinson et al., 1995) showed enhancement using a peripheral cuing task similar to that used in the pulvinar inactivation experiments described above. Again, we do not know whether these parietal neurons received input from pulvinar, but anatomically this was quite possible. Another set of attention experiments in parietal cortex studied the effects of attentive fixation on the visual response of neurons (Mountcastle et al., 1981, 1987), and a recent study verified these observations and showed similar effect in the pulvinar (Bender and Youskow, 2001). Exactly what the SC-pulvinar pathway contributes to attentional activity in parietal cortex (and in other extrastriate areas; see reviews by Desimone and Duncan, 1995; Maunsell, 1995) remains a critical question.

In net, while the possible functional contributions of the pathway from the SC to cortex via the pulvinar have received more attention over a longer period (Diamond and Hall, 1969; Schneider, 1969) than has the pathway from the SC to cortex via the medio-dorsal thalamus, the function of
Figure 98.6. Test of the hypothesis that the ascending pathway through pulvinar carries an attention signal. A, Diagram of the task. The monkey fixated the fixation point and had to keep its eyes within the eye position window at all times. Then a cue stimulus was flashed, a cue-target interval ensued, and a target was presented. The monkey's task was to report detection of the target by manually depressing a lever. During valid cue trials (top), the cue and target appeared in the same hemifield; during invalid cue trials (bottom), they flashed in opposite hemifields. Ipsilateral and contralateral are with respect to the injection site. B, Effects of inactivating pulvinar on reaction times during valid cue trials. There was no effect of inactivation when the cue and target were presented ipsilaterally (top), showing that the monkey still could shift its attention in that direction. However, when the cue and target were presented contralaterally (bottom), the reaction time was abnormally slow during inactivation (muscimol data). Also shown are the results of bicuculline injection, which caused no deficits. (Adapted from Petersen et al., 1987.)
the pulvinar pathway is less well specified. Identified recordings in behaving animals are still needed to determine explicitly the signals conveyed in this pathway. The current data strongly suggest that neuronal activity along the pathway is related to attention, changing from being more saccade-specific in SC to being more visual, that is, more motor modality-independent, in pulvinar and cortex.

Finally, it should be noted that an additional ascending pathway appears to course from the superficial SC layer, reaching tecto-hypothalamic neurons in the lateral geniculate nucleus that presumably project, in turn, to striate cortex (for a review, see Hendry and Reid, 2000). Visually related activity certainly must be relayed in this pathway, but as tecto-hypothalamic neurons are extremely heterogeneous, it is difficult to speculate further about these ascending signals.

Conclusions

In this chapter, we described what is currently known about the dialogue between the cerebral cortex and the SC during visuosaccadic behavior. Figure 98.7 shows a summary diagram of the descending and ascending signals.

Four descending routes have been investigated using antidromic activation techniques (Fig. 98.74). The projections richest in signals related to saccadic target selection emanate from the lateral intraparietal area and the frontal eye field. Both projections send visual responses, cognitive-related delay activity, and presaccadic activity to the intermediate SC. The basal ganglia pathway via the substantia nigra relays strong visual and presaccadic signals to the intermediate SC, but delay activity in this projection seems related only weakly if at all, to target selection. Striate cortex sends visual signals that are potentially interesting, but still poorly understood, to the superficial SC. Ascending pathways (Fig. 98.7B) are more challenging to study. Best characterized is the pathway from the intermediate SC to the fronto-parietal cortex (via mediodorsal thalamus), which carries visual signals and presaccadic activity that appear to serve a corollary discharge function. The pathway from the superficial SC to parietal cortex (via pulvinar) is presumed to carry mostly visual signals that are highly modulated by attention.

We want to emphasize that there are numerous other descending and ascending connections between cerebral cortex and the SC, some of which might also be crucially important for saccadic target selection, corollary discharge, or other cognitive functions. This chapter focused only on interconnections for which there are currently at least some satisfactory physiological results related to cognitive issues.

Our goal has not been to consider just one particular brain region, but instead to determine what can be learned from analyzing the functional relation between areas, specifically between cerebral cortex and the SC. Our focus on visuosaccadic behavior provides only a limited glimpse of brain organization, but it does offer the opportunity to look at the neuronal basis of several cognitive functions using techniques that allow the functional identification of a part of the underlying circuitry. A few general conclusions are worth pointing out explicitly.

First, when we compare the signals leaving cortex, within the SC, and in the ascending pathways, we never see a strict segregation of function between areas. There is no level of visuosaccadic processing in one area that is absent in the next. Instead, there is always an overlap between the signals seen in one area and those in the next, with a gradual shift in signal content. There appear to be progressive sensorimotor transformations rather than abrupt changes.

Second, the recognition that signals are conveyed up to cortex with very short latencies emphasizes that the neuronal
activity seen in cerebral cortex represents not just signal processing within the cortex but also processing directed back to the cortex from brainstem areas. The cortical and subcortical areas have to be regarded as a whole unit, not as a serial chain, just as is the case for cortical areas that also are reciprocally interconnected.

Finally, our most significant generalization concerns the nature of the information conveyed to cerebral cortex from the SC. What we find striking is that the information conveyed upstream is probably not critical for extracting information about the world. Instead, ascending information from the brainstem makes its important contribution to interpreting the visual input in the context of an animal’s actions. The pulvinar pathway appears to inform the cortex of the relative behavioral importance of objects (as expressed by enhanced visual responses). In the medio temporal thalamic pathway, signals inform the cortex about what saccade will be made next. This cycladic discharge information probably allows the visual system to distinguish between actual full-field motion of the external world and full-field motion that is a trivial artifact of making a saccade. In sum, our perception of the visual world is a result of the visual input to cerebral cortex and the interpretation of that input, and key parts of that interpretation may depend upon information relayed up from the SC through the thalamus.

REFERENCES


EYE MOVEMENTS


