

## Interactions Between Visually and Electrically Elicited Saccades Before and After Superior Colliculus and Frontal Eye Field Ablations in the Rhesus Monkey\*

P. H. Schiller and J. H. Sandell

Dept. of Psychology, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

**Summary.** Recent work has shown that humans and monkeys utilize both retinal error and eye position signals to compute the direction and amplitude of saccadic eye movements (Hallett and Lightstone 1976a, b; Mays and Sparks 1980b). The aim of this study was to examine the role the frontal eye fields (FEF) and the superior colliculi (SC) play in this computation. Rhesus monkeys were trained to acquire small, briefly flashed spots of light with saccadic eye movements. During the latency period between target extinction and saccade initiation, their eyes were displaced, in total darkness, by electrical stimulation of either the FEF, the SC or the abducens nucleus area. Under such conditions animals compensated for the electrically induced ocular displacement and correctly reached the visual target area, suggesting that both a retinal error and eye position error signal were computed. The amplitude and direction of the electrically induced saccades depended not only on the site stimulated but also on the amplitude and direction of the eye movement initiated by the animal to acquire the target. When the eye movements initiated by the animal coincided with the saccades initiated by electrical stimulation, the resultant saccade was the weighted average of the two, where one weighting factor was the intensity of the electrical stimulus. Animals did not acquire targets correctly when their eyes were displaced, prior to their intended eye movements, by stimulating in the abducens nucleus area. After bilateral ablation of either the FEF or the SC monkeys were still able to acquire visual targets when their eyes were displaced, prior to saccade initiation, by electrical stimulation of the remaining intact structure. These results suggest that neither the FEF nor the SC is uniquely responsible for the combined computa-

tion of the retinal error and the eye position error signals.

**Key words:** Frontal eye fields – Superior colliculus – Eye movement – Electrical stimulation

### Introduction

In the rhesus monkey focal electrical stimulation of the superior colliculus (SC) and the frontal eye fields (FEF) elicits saccadic eye movements the directions and amplitudes of which depend predominantly on the site of stimulation within each of these structures (Robinson 1972; Robinson and Fuchs 1969; Schiller and Stryker 1972). Prolonged stimulation produces a staircase of saccades (Schiller and Stryker 1972). These results, as well as those obtained with single unit recordings have led to the suggestion that the SC and the FEF contribute to foveation by computing a retinal error signal (Schiller and Koerner 1972; Schiller and Stryker 1972).

Recently it has been demonstrated that in humans the acquisition of visual targets by saccadic eye movements is accomplished by taking into account both retinal error and eye position information (Hallett and Lightstone 1976a, b). Mays and Sparks (1980b) and Sparks and Porter (1981) have established that this is also the case in the monkey. Trained animals made accurate saccades to briefly flashed targets in the dark even when their eyes, prior to the initiation of the saccade to the visual target, were displaced by electrical stimulation of the SC. For example, when a visual target was presented 10 deg straight above fixation and was immediately followed by collicular stimulation which produced a horizontal 10 deg saccade, the direction of the eye movement subsequent to the stimulation induced displacement was a diagonal upward one which

\* Supported by Grants NIH EY02621 and NIH EY00676-10  
Offprint requests to: Dr. P. H. Schiller (address see above)

landed the fovea correctly at the location where the target had appeared. Had the system computed only a retinal error signal, a 10 deg upward saccade would have occurred after the stimulation induced eye movement. Mays and Sparks, in another set of experiments also found that some cells in the SC signal information about eye position error (Mays and Sparks 1980a). Based on these findings they suggested that in the SC both retinal error and eye position signals are utilized for the generation of commands for saccadic eye movements.

The aim of this study was to determine whether the SC and the FEF are necessary for the generation of saccades based on both retinal error and eye position information. We used the Mays and Sparks paradigm and stimulated either the FEF or the SC before and after the ablation of one of these structures. In earlier work we have shown that the ablation of either the FEF or the SC does not alter stimulation elicited saccades from the remaining structure and that ablation of both structures causes severe deficits in eye movement (Schiller et al. 1980).

## Methods

### *Training Procedure*

Four monkeys were used in this experiment. Prior to training a Robinson type search coil and skull screws were implanted into each animal to enable us to secure the head and to record eye movements during the experimental sessions (Robinson 1963). The animals were then trained to fixate a small visual target and to reacquire this target when it was suddenly displaced in the visual field. The stimuli were presented with the aid of an optic bench on a translucent screen (Polacoat) placed 18–47 cm from the eyes. During initial training the water deprived animals were rewarded with a drop of water whenever they fixated the target briefly (0.12–0.96 deg circular spot). The position of the eyes was monitored with the aid of a search coil and correct eye position was detected by placing an electronic window around the target location; when the eye was held within this window for a specified time period (400–600 ms), the solenoid dispensing the water reward was activated. After this task was mastered, the target was displaced to various positions on the screen. Monkeys learned readily to reacquire these targets for foveal viewing. The next step entailed shortening the duration of the target after it was displaced, eventually to 50–100 ms, which meant that the target was extinguished before the animal was able to initiate his eye movement to it, since the typical reaction time was 150–200 ms. After the monkeys became proficient at this, they were trained to move their eyes to the displaced target in total darkness by having the house light in the experimental chamber go off at the time the target was displaced, to be turned on again upon termination of the trial. We found it undesirable to keep the animals in total darkness throughout the experimental session, mainly because monkeys were quite inaccurate in their initial fixations of the center target under such conditions. Keeping them in darkness during the electrical stimulation and target acquisition period served the purpose of eliminating all possible visual clues as to the position of the eyes.

### *Electrical Stimulation Methods*

The FEF and/or the SC was stimulated with microelectrodes. The SC was reached through an implanted, adjustable tube, and the FEF was reached through an implanted chamber (Evarts 1966). Platinum iridium microelectrodes were used, and typical recordings were undertaken to locate the areas to be stimulated. Most commonly the stimulation was a 300 Hz pulse train lasting 50 ms, although we also examined the effects of longer pulse trains, lasting up to 500 ms. Pulses were negative, with a 200  $\mu$ s width. In some animals we stimulated two brain sites either simultaneously or successively, and in two animals we also stimulated in the area of the abducens nucleus.

### *Ablation Methods*

Ablation of the FEF and the SC was accomplished using methods previously described (Schiller et al. 1980). The FEF was ablated aseptically with suction, under visual control. The SC was ablated while the animal was anesthetized (pentothal and a 30–70% mixture of O<sub>2</sub> and N<sub>2</sub>O) and paralyzed with Flaxedil and was artificially respired. The animal was placed into a stereotaxic frame, and the SC was located with a microelectrode relying initially on stereotaxic coordinates. After locating that portion of the SC where the receptive fields of single cells were 5 deg from the fovea on the horizontal meridian, heat lesions were applied with the aid of a thermistor tipped electrode at 4 nearby locations (Schiller et al. 1980). In one animal the FEF was ablated bilaterally preceded and followed by SC stimulation. In another animal the SC was ablated bilaterally, and the FEF was stimulated. In the third animal the left SC was stimulated before and after unilateral ablation of the left frontal eye fields which was followed by electrical stimulation of the FEF before and after right SC ablation. This procedure enabled us to examine the effects of both kinds of lesions in the same animal. No lesions were placed in the fourth animal which in part was used for other purposes. The lesions were verified histologically.

### *Data Collection and Display Methods*

The experiment was controlled with the aid of a PDP11/34 computer. A program written by Sean True and Philip Kohn enabled us to set all experimental parameters, to randomly vary stimulus conditions, to administer electrical stimulation at the desired time in the behavioral sequence, to set window discriminators for the required eye movements to each selected target, to display data on line on a Tektronix 611 storage oscilloscope, to store the data on disk, and finally to analyze and read out the data on an electrostatic printer. The eye-movement data were collected with a 5 ms sample rate and they were displayed either in the conventional form of horizontal and vertical eye-movement traces, or in the form of polar coordinates.

### *Experimental Procedure*

Data collection began on the intact animals after they reached a proficiency level of better than 90% in acquiring briefly flashed targets in the dark, with the size of the electronic windows around the targets set at between 2 by 2 and 3 by 3 deg square. Each experimental session began by lowering a microelectrode to the desired location in the SC, FEF or the abducens nucleus area, and was followed by calibration of the monkey's eye movements to the targets selected. Most commonly we began with four target locations in addition to the initial central fixation point. The

targets, which could be placed anywhere on the screen, were displayed in a random order. During this procedure, while the animal was performing the task, an electronic window was set for each target; animals received a reward only when their eyes entered the appropriate window and remained there for a specified length of time (usually 50 ms for targets other than the central fixation light). Following this the FEF or the SC was stimulated on randomly selected trials at the times chosen by the experimenter. Generally animals were stimulated during 30–50% of the trials. Based on the size and direction of the saccades produced by electrical stimulation, various other target locations were often selected. The intensity and the time of occurrence of the electrical stimulation were systematically varied in these experiments.

## Results

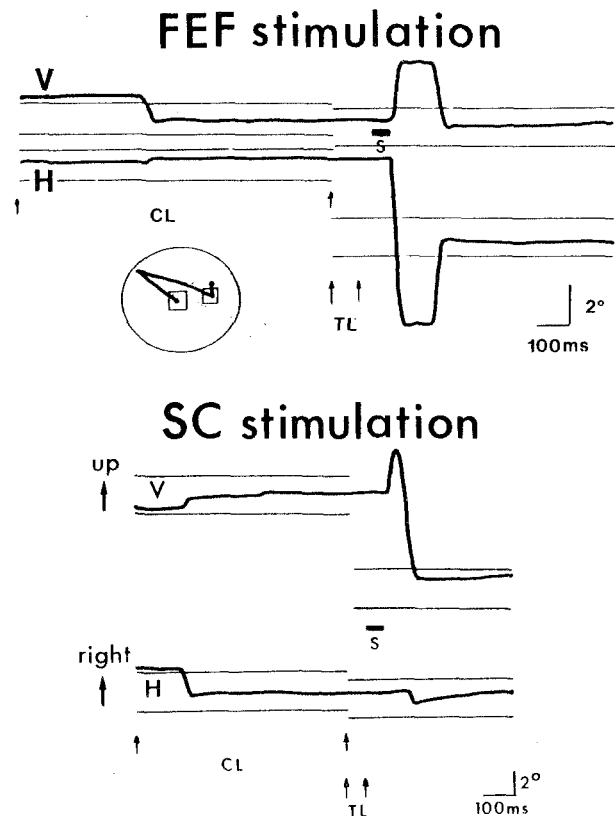
After initial training to fixate a spot of light, the animals were trained for an average of 30 days (> 10,000 trials) to saccade to the location of a briefly flashed peripheral target. In the SC of intact animals, 2,315 stimulation trials were collected (42 penetrations), with current thresholds ranging from 20–90  $\mu\text{A}$ . In the FEF of intact animals 1,221 stimulation trials were collected (19 penetrations), with current thresholds ranging from 40–800  $\mu\text{A}$ . In the region of the abducens nucleus 587 stimulation trials were collected (11 penetrations), with current thresholds ranging from 30–50  $\mu\text{A}$ .

Following bilateral SC ablation in one monkey, 1,988 trials were collected with FEF stimulation (19 sites). Following bilateral FEF ablation in a second monkey, 1,093 trials were collected with SC stimulation (15 penetrations). A third animal received sequential lesions of the left FEF followed 2 weeks later by ablation of the right SC. Following the FEF lesion, the remaining FEF were stimulated to yield 321 stimulation trials (three penetrations) and the remaining SC was stimulated yielding 519 trials (four penetrations). The fourth animal, in which the SC and the abducens areas were stimulated was not ablated.

### *The Effects of FEF and SC Stimulation in Intact Animals*

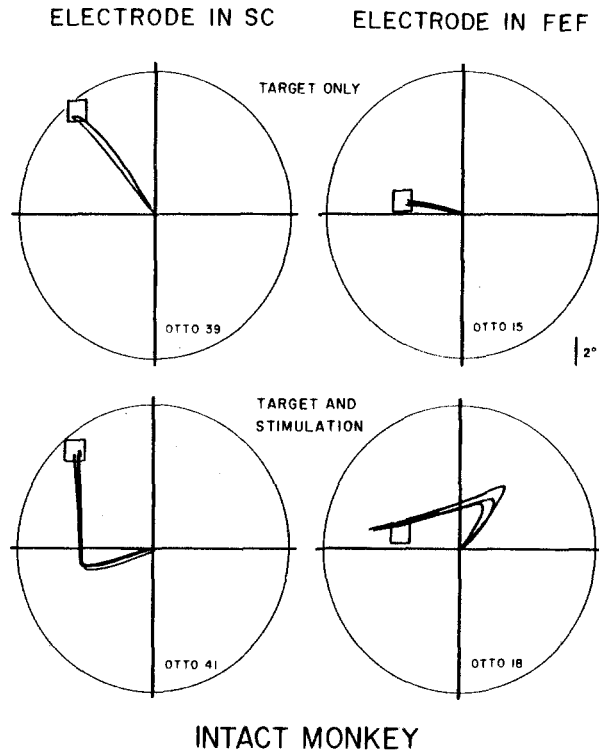
When the eyes were displaced in the orbit as a result of supra-threshold electrical stimulation of the FEF or the SC immediately after the presentation of a peripheral target, on most trials animals compensated for the displacement even though their eye movements were carried out in total darkness. We never observed eye movements following stimulation which could be interpreted to reflect computation of only a retinal error signal.

FEF and SC stimulation, in conjunction with target presentation, yielded two distinct patterns of



**Fig. 1.** Horizontal and vertical eye movement records obtained for two trials, one when the FEF was stimulated (s) and the other when the SC was stimulated. In both cases a 300 Hz, 50 ms duration burst electrical stimulus was used, applied immediately after the presentation of a 100 ms duration target light (TL). The FEF was stimulated with 400  $\mu\text{A}$  and the SC with 70  $\mu\text{A}$ . The trial begins when a central fixation light (CF) turns on. Thin horizontal lines show electronic windows around the center fixation light and the target light gaze locations. The eye movements have to get into these windows for successful completion of a trial. V = vertical eye movement record, H = horizontal eye movement record. Direction of eye movements shown by arrow at the beginning of the SC eye movement traces. Vertical arrows below the eye movement records show duration of center (CL) and target (TL) lights. Inset shows a polar plot of the trial obtained with FEF stimulation; the squares as the electronic windows set around stimulus locations

eye movements. In the first pattern a brief fixation occurred following the electrically elicited saccade, and then a second saccade took the eye to the location of the already extinguished visual target. The second pattern of eye movements showed no intervening fixation, meaning that the correction was accomplished in midflight. Examples of these two types of corrective eye movements appear in Fig. 1, one of which was obtained with FEF stimulation, and the other with SC stimulation. In both structures corrections of the first type (with the intervening fixation) occurred much more commonly than did midflight corrections, about 90% of the time. Figure 2 shows a polar plot of typical corrections obtained



**Fig. 2.** Polar plot of eye movements obtained during target acquisition with and without electrical stimulation. Each frame shows three trials except for the top left which has two trials. The upper two frames show eye-movement records to two different target locations. The lower frames show eye movements to the same targets when the FEF and the SC were stimulated 80 ms after target onset with 500  $\mu$ A and 60  $\mu$ A, respectively. Other parameters as in Fig. 1. The animal correctly acquires the target in all cases. Direction of the monkey's eye movements are as viewed by the reader

when either the FEF or the SC were stimulated after the presentation of a visual target. The FEF stimulation in this figure resulted in a less accurate correction than did the SC stimulation. This was not a consistent difference between the stimulation effects of the two regions. The greater error in this case was probably produced because the FEF stimulation moved the eyes away from the target and into the contralateral visual field.

The accuracy of corrections depended on a number of factors. These included the motivational state of the animal, the size of the visually triggered eye movement, the size of the electrically triggered eye movement, and the side to which the stimulation moved the eye relative to the target. Large eye movements were associated with greater errors. Accuracy seemed somewhat better when the stimulation and the intended eye movements were to the same side of the visual field.

On a typical day when the SC was stimulated in the intact animal, a total of 111 trials were collected

with stimulation currents sufficiently high to elicit reliable ocular displacement (70  $\mu$ A for this site). The electrical stimulation in the absence of a target produced a 6 deg rightward eye movement. Four peripheral targets were used, placed 6–14 deg from the center fixation light. Each peripheral target was displayed for 50 ms, the houselight was extinguished 30 ms after the peripheral target and the 50 ms stimulation pulse began 20 ms after the peripheral target was turned off, initiating a saccade 30 ms after onset of the electrical stimulus. Thus, the peripheral target and the houselight were extinguished before any visually or electrically triggered eye movements began. Accuracy for the acquisition of the target location was high under these conditions. On 42 of the 111 stimulation trials collected, the monkey came within 2 deg of the target after making his correction and on 40 trials he came within 4 deg of the target location. On 29 of the trials the monkey made no attempt to compensate for the stimulation produced ocular displacement. These were all trials in which the electrical stimulation brought the eyes very close to the fourth peripheral target which was located 6 deg to the right and 3 deg down from the central target. Eye movements based solely on retinal error computation were never observed.

On a typical day with FEF stimulation of the intact animal a total of 58 stimulation trials were collected at current levels sufficiently high to produce reliable ocular displacement (500  $\mu$ A at this site), which without the presentation of a target produced an 18 deg rightward eye movement. The peripheral targets were located 7–16 deg from the center target. Other parameters were similar to the ones described above with SC stimulation. With this large electrically induced ocular displacement only one trial was produced in which the monkey came within 2 deg of acquiring the peripheral target location following stimulation. There were 15 trials when the eyes came within 4 deg, 23 trials when they came within 6 deg, six trials when they came within 8 deg, and one trial when they came within 10 deg of the target. On 12 trials the monkey returned his gaze to the location of the center target. As with the SC stimulation, eye movements reflecting computations based only on retinal error alone were never observed. The greater variation in the accuracy of the compensatory eye movements produced with the FEF stimulation in this situation was due to the fact that the electrically induced eye movements were three times larger for FEF than for SC stimulation in these examples. Further examples on this point will follow below.

These observations are in agreement with those reported by Mays and Sparks for stimulation of the

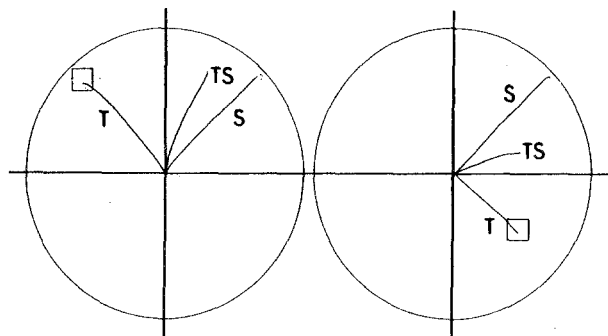


Fig. 3. Interaction between visually and electrically elicited saccades: coincidental timing. Each frame shows three trials, one showing a saccade obtained when only the visual target was presented (*T*), the second when the saccade was produced by electrical stimulation of the FEF without a visual target (*S*), and the third when the two events occurred simultaneously (*TS*). The electrical stimulus was a 50 ms, 300 Hz train at 400  $\mu$ A

SC (Mays and Sparks 1980b) and demonstrate that similar results can be obtained with FEF stimulation.

#### *The Interaction Between Visually and Electrically Elicited Saccades*

When two sites in the SC or the FEF are stimulated simultaneously, the resultant saccade is the weighted average of the stimulation effect at each site, where the weighting is provided by stimulation intensity (Robinson 1972; Robinson and Fuchs 1969). Thus, if the left and right SC are stimulated, and the former, when stimulated singly, yields a 45 deg right up saccade and the latter a 45 deg left up saccade, simultaneous stimulation of the two areas at similar intensities will produce a straight up saccade. If one progressively increases the intensity of the stimulation in one SC, eye movements will be produced which will progressively approximate those obtained by stimulating that SC alone. A similar weighting occurs when a visually triggered eye movement interacts with an electrically triggered saccade, provided the electrical stimulation is relatively close to threshold and is properly timed with respect to the visually triggered eye movement. Figure 3 shows examples of this for two target locations. For each example three traces appear: one produced by the presentation of the target alone, one produced by stimulation alone, and one produced by both. These traces suggest that when stimulation intensity and the timing are appropriate, the pairing of a visual stimulus with an electrical stimulus produces averaging similar to that observed when two sites are electrically stimulated.

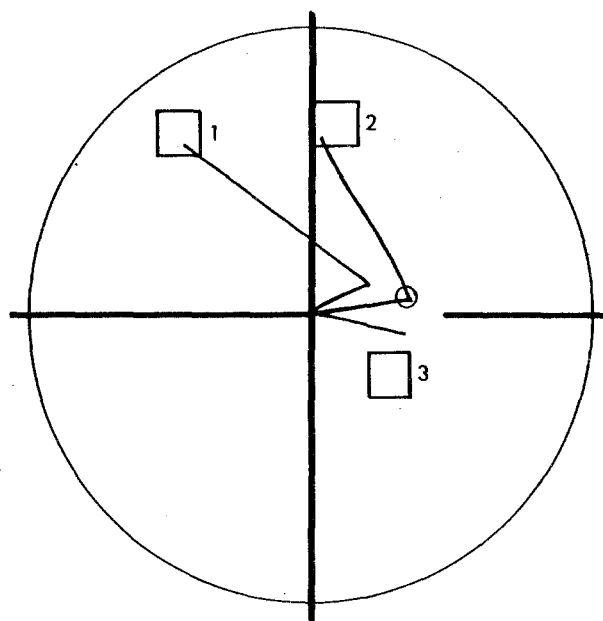


Fig. 4. Interaction between visually and electrically elicited saccades obtained with a temporal offset between the two events. Three trials to three target locations are shown. The direction of the initial, electrically elicited saccade is influenced by the location of the target. No correction is made after the initial eye movement to target 3, probably because the saccade, produced by the combination of self-generated and electrically generated commands, brought the eye to a location which is judged by the animal to correspond to the target location. The *small circle* shows the area to which the eye was moved when the SC was stimulated without the appearance of a target five times. Stimulation parameters: 50 ms duration, 300 Hz pulse trains, 70  $\mu$ A

Interactions between the self-generated and electrically generated saccades can also be observed when the electrical command precedes the self-generated command, as it does most commonly in the Mays and Sparks paradigm. Under such conditions the initial displacement of the eye, attributable to the electrical stimulation, can also be shown to be affected by the self-generated command provided the intensity of the electrical stimulation is not too high. Figure 4 shows that the initial displacement of the eye by electrical stimulation of the SC 70 ms after target onset, takes a different path for each of three target locations shown. When the target is up-left, the initial stimulation elicited saccade is a short up-right movement; when the target is up-right, the trajectory of the stimulation elicited saccade is more horizontal; when the target is down-right, no correction occurs. Failure to correct in the last case is probably due to the fact that the interaction between the self-generated and the stimulation elicited eye movement brings the eye very close to the intended location. Interactions of this sort are commonly observable as long as the stimulation occurs 50–120 ms after target

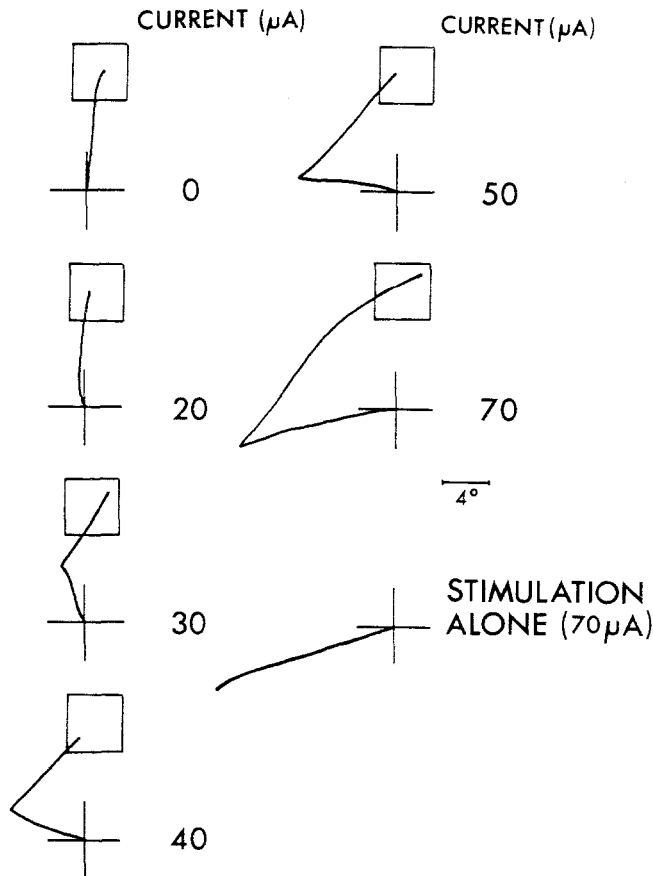


Fig. 5. The effect of stimulation intensity on corrective eye movements. The animal always corrects, but as stimulation intensity is increased it has a proportionately greater effect on the initial component of the eye movement. At the highest current level used ( $70 \mu\text{A}$ ) the initial eye movement is similar to that produced by stimulation of the SC without the presentation of a visual target. Other stimulation parameters as in Fig. 1

onset. Unfortunately one cannot specify the interaction time exactly, since the self-generated eye movement has a variable latency.

#### *The Effect of Varying the Intensity of Electrical Stimulation*

The manner in which the electrical stimulation affects eye movements in the Mays and Sparks paradigm depends, as we have noted, on the intensity of the stimulus. The stronger the current, the more closely will the direction and the amplitude of the initial displacement of the eye resemble the saccade produced by the stimulation alone. This is shown in Fig. 5. For each trace the task and the timing are the same; the animal sees a target  $8 \text{ deg}$  up, and generates commands to acquire it. Eighty ms following target onset the SC is stimulated at various

current levels. As the current is progressively increased, the eye is displaced more and more in the direction specified by the stimulation. This shows once again that visually triggered eye movements and electrically triggered ones interact, where the weighting depends on intensity, as defined by the amount of current passed in the case of electrical stimulation.

Interactions between self-generated and electrically triggered eye movements occur not only when the timing is close between these two events. They can also be shown to occur when the monkey's intent is to fixate, provided, once again, the stimulation intensity is relatively low. What happens when one stimulates while the monkey attempts to keep his eye on target is shown in Fig. 6. The SC was stimulated in this case while the monkey was in the midst of fixating the initial target. Stimulation of the SC near threshold at this time yielded saccades of a variety of sizes, and sometimes no saccade at all. Most saccades were much smaller than the size elicited from the SC site when either the current level was higher or the monkey's intent to maintain fixation was reduced. As the intensity of stimulation was increased, saccade size reached the size characteristic of the site stimulated at high intensities, and the variability decreased. These observations suggest that close to threshold the electrical stimulation interacts with the intention of not moving the eyes, thereby producing vector averaged saccades, where one vector is the stimulation and the other the fixation (0 vector).

The threshold for effective stimulation is also affected by the spatial relationship between the intended and electrically triggered eye movements. When the intended eye movement toward a target is in the same direction as the electrically triggered saccade, the threshold for the latter is very low. If the directions are in opposition, the thresholds are high. Systematic exploration of this for one stimulation site is shown in Fig. 7.

Examination of the threshold effects showed no significant differences between FEF and SC stimulation.

#### *The Effects of Abducens Nucleus Area Stimulation*

The area of the abducens nucleus was stimulated in two monkeys. Each penetration began by recording neural activity. When eye movement related discharge was observed its characteristics were examined, and then the region was stimulated while we examined what kinds of eye movements were elicited. We inferred that we were affecting the abducens nucleus with the electrical stimulation when (1) the latency of the elicited eye movement

CURRENT

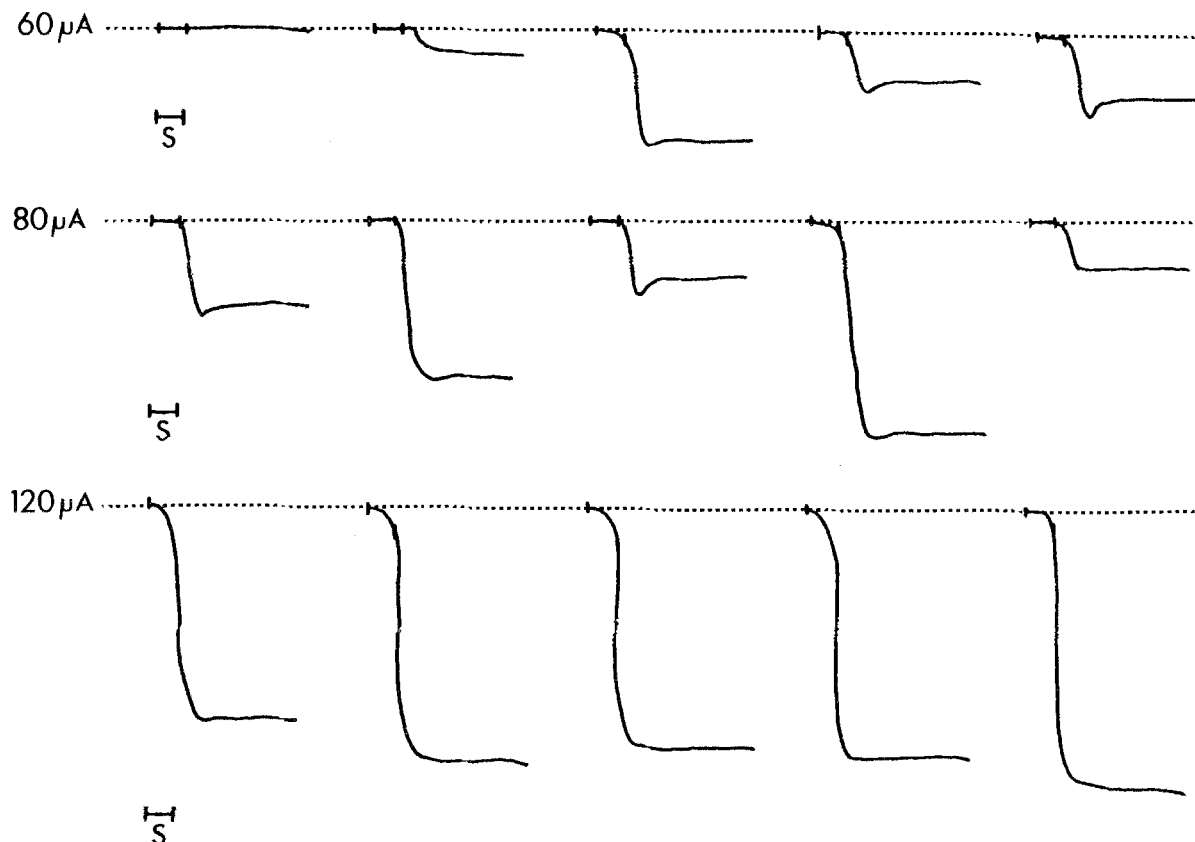


Fig. 6. The effect of stimulation intensity on saccade size when the stimulation is administered during an intended fixation. At low current levels saccade amplitude is both low and variable. At high current levels saccade size is relatively constant. Fixation intent and stimulation effects appear to interact in producing the eye movement. Stimulation parameters as in Fig. 1

SC STIMULATION

CURRENT ( $\mu$ A)	1	2	3	4
15	NE	NE	NE	NE
30	33%	25%	NE	NE
50	50%	67%	17%	NE
80	100%	83%	66%	NE
120	100%	80%	100%	NE
150	-	-	-	NE

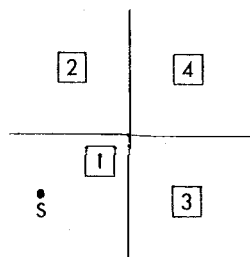


Fig. 7. The percentage of successfully elicited eye movements to electrical stimulation for different target locations and current levels. Electrical stimulation in the absence of a visual target brought the eyes to location S. Electrical stimulation threshold is lowest to the visual target which lies in the same direction as the stimulation elicited saccade and highest for the target which lies in the opposite direction

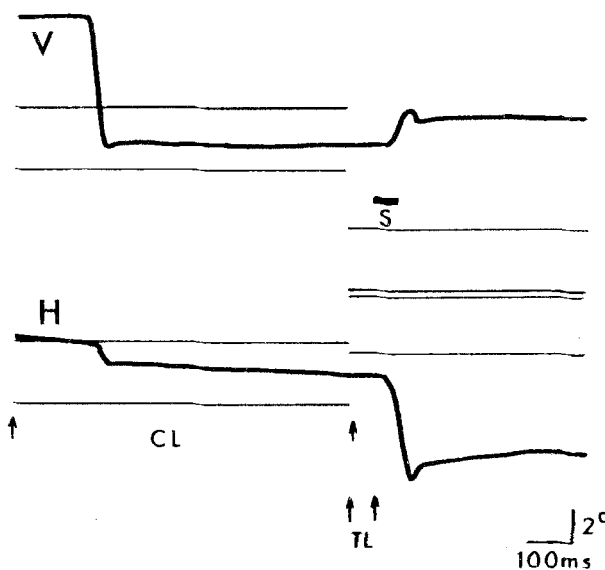
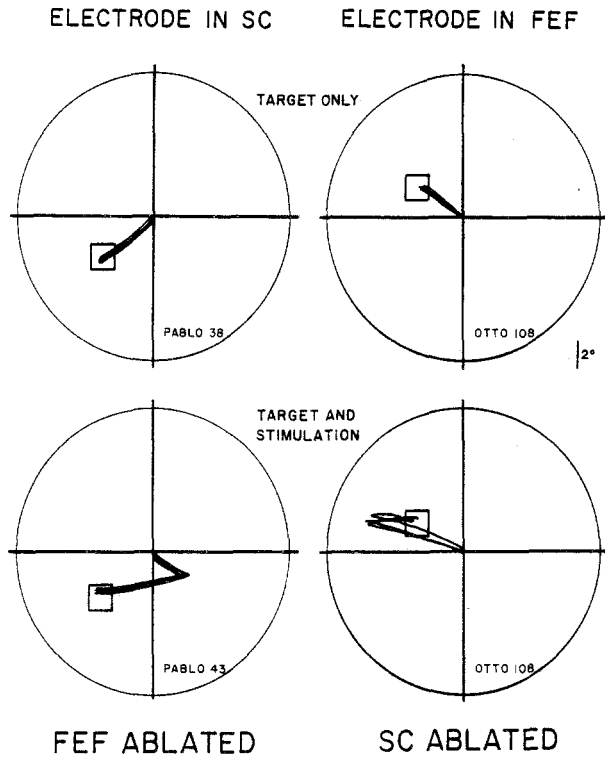
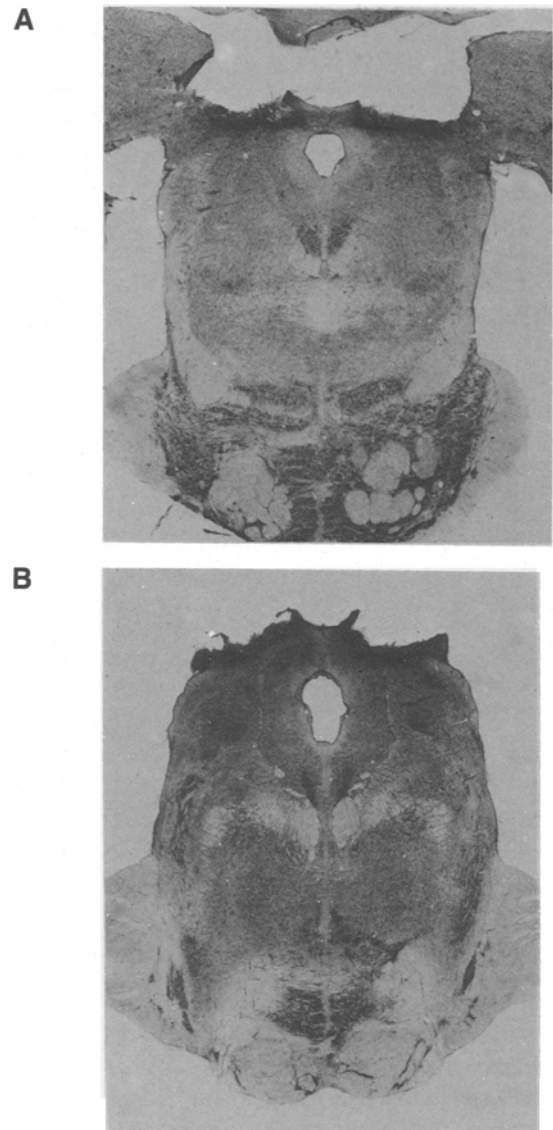


Fig. 8. The effect of abducens nucleus area stimulation. Parameters as in Fig. 1, with a stimulation intensity of 30  $\mu$ A. The monkey fails to make corrective eye movements



**Fig. 9.** The effect of bilateral *FEF* and *SC* ablation on corrective eye movements. The frames on the left show performance after *FEF* ablation with and without *SC* stimulation. The frames on the right show performance after *SC* ablation with and without *FEF* stimulation. Three trials per frame (compare with Fig. 2). Neither ablation interfered with corrective eye movement. Both sites were stimulated with 50 ms duration, 300 Hz pulse trains, administered 20 ms after the onset of the target, using 600  $\mu$ A in the *FEF* and 60  $\mu$ A in the *SC*. Target durations were 120 ms for *FEF* stimulation and 80 ms for *SC* stimulation

was 10–15 ms, and (2) the size of the saccade depended on the duration of the stimulus train. In the immediate vicinity of the abducens nucleus eye movement latency ranged from 10–30 ms, but at all sites stimulated saccade size was a function of stimulus train duration. A total of 11 sites were stimulated, yielding 587 trials. An example of the results of such stimulation near the abducens appear in Fig. 8. The monkey failed to acquire the target. The eye movement produced by the stimulation shows not only a horizontal but also a small vertical (upward) component. This, we believe, was due to the fact that the fixation point was below the horizontal meridian. Thus, contraction of the lateral rectus muscle, therefore, caused the eye to move laterally upward. As would be expected, stimulation at the same site with the initial gaze position above the horizontal meridian yielded a lateral eye movement with a small downward component.



**Fig. 10.** Two photomicrographs in the area of the *SC* ablation. **A** Anterior portion of *SC*; **B** posterior portion of *SC*

Stimulation of the abducens nucleus area in these experiments virtually never yielded corrective eye movements. In fact in most cases the animal did not seem to make eye movements which could be interpreted as attempts to look at the target. Rather, the animal seemed to become confused; after some delay he typically made several small eye movements which did not reflect calculations based on either retinal error or eye position error signals. Histological analysis did not permit us to determine the exact location of all the stimulation sites because of the large number of penetrations and because of the long survival time (1–5 months) following these experi-



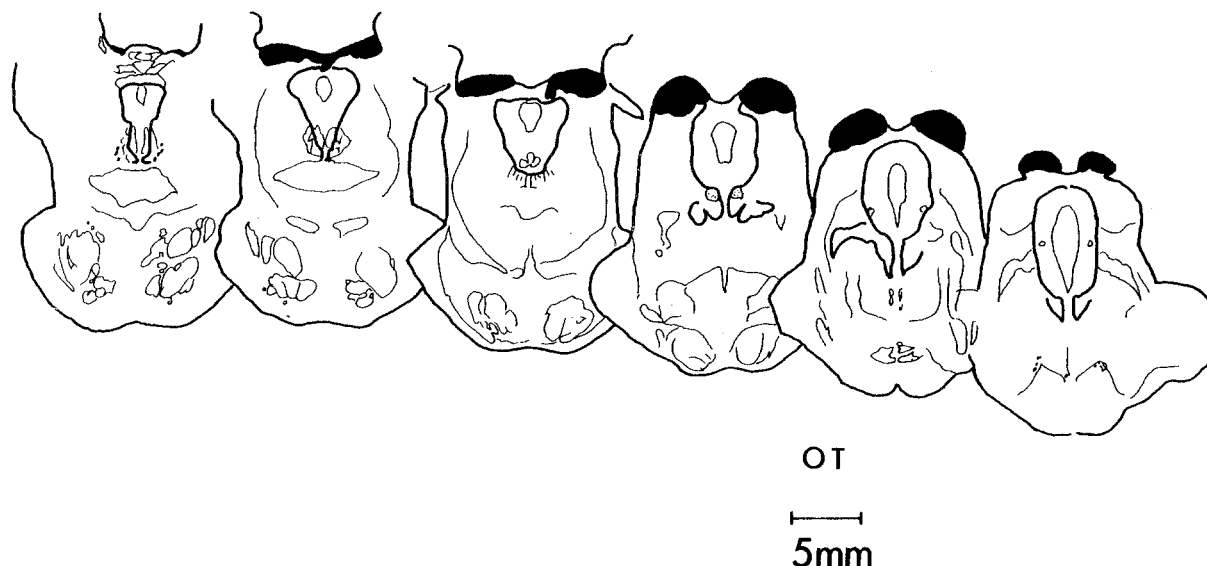


Fig. 11. Reconstruction of brain tissue showing SC ablation for the same tissue displayed in Fig. 10

ments. Individual penetrations after such a time interval are not usually recoverable in our experience; however, general disruption and gliosis were observed in the vicinity of the abducens nucleus.

#### *The Effects of SC and FEF Ablations*

The major question we wished to answer in this study was whether the ablation of either the SC or the FEF would disrupt the animal's performance in the Mays and Sparks paradigm. We found that after an initial period of recovery our animals without either the FEF or the SC were still capable of performing appropriate corrections when their eyes were displaced by electrically stimulating the remaining structure. Examples are shown in Fig. 9. On the left is shown the performance of a monkey whose FEF was ablated bilaterally, and on the right a monkey whose SC was removed bilaterally. Both animals corrected for the electrically induced displacements and brought their eyes close to the location of the targets.

Although the animals still made corrections following FEF and SC lesions, their performance was poorer than pre-operatively. Most of the deficits we observed were similar to those reported previously (Schiller et al. 1980): following SC lesions spontaneous eye movements were fewer, and the accuracy of target acquisition was somewhat impaired. This was especially notable during the initial periods of recovery, and animals were, therefore, tested over extended time periods. Use of the Mays-Sparks paradigm uncovered another deficit in these animals:

they had great difficulty making saccades to the briefly flashed targets. This was true for both the SC and FEF lesioned animals. Considerable retraining was required to ameliorate this deficit, and monkeys did not reach pre-operative levels of proficiency even after more than 5 weeks, during which they ran more than 7,000 trials. The animals were able, however, to perform close to their pre-operative levels when the target durations were increased to 80–120 ms (as compared with 50–60 ms preoperatively). Other aspects of their performance were unaffected: thresholds, corrections and averaging between electrically induced and self generated saccades were similar to those obtained prior to the lesions.

An example of a typical day's performance using SC stimulation 71 days after bilateral FEF ablation resulted in collecting 82 trials during which the current levels used produced a reliable ocular displacement (60  $\mu$ A). In the absence of a target the stimulation produced a 6 deg rightward eye movement. Four target locations 6–10 deg from the fixation point were used, and each target appeared for 120 ms. Other parameters were as described earlier with SC stimulation. Of the 82 trials, 53 resulted in corrections which brought the eyes within 2 deg of the target, 23 trials came within 4 deg. On six trials no compensatory eye movements occurred.

On a typical day when the FEF was stimulated 129 days following SC ablation 36 trials were collected. The stimulation in the absence of a target produced an 8 deg eye movement. Of the 36 trials 27 resulted in corrections which brought the eyes within 2 deg of the target, and four trials on which the eyes

came within 4 deg of the target. Five stimulation trials were ineffective.

### *Histological Reconstructions*

The FEF and SC lesions were reconstructed by examining sectioned brain tissue stained either with cresyl violet or silver (Merker 1979). The FEF lesions were similar to those reported previously (Schiller et al. 1980), and the histology disclosed that this structure was successfully removed in our animals. Figure 10 shows two photomicrographs of the bilateral SC lesion. The lesion is reconstructed in Fig. 11. We believe that most of the SC was removed in this animal.

### **Discussion**

Evidence gathered over the past several years about the manner in which visually guided saccadic eye movements are generated has yielded several theoretical formulations. Electrical stimulation and recording studies of the SC and the FEF in the rhesus monkey in the last decade suggest that these structures are involved in calculating saccades in a retinotopic framework (Robinson 1972; Robinson and Fuchs 1969; Schiller and Stryker 1972). Thus, one theory held that the acquisition of a visual target for foveal viewing is the product of a computation which determines where the target is relative to the fovea irrespective of the position of the eye in orbit.

This view was challenged recently by the observation that eye position signals are also an integral part of the computations which enable the system to foveate targets. In both man and monkey the information about eye position is combined with the information about target location for the generation of a saccade (Hallett and Lightstone 1976a, b; Mays and Sparks 1980b). This study confirms these observations: visual targets are correctly foveated even when the eyes were displaced involuntarily by electrical stimulation of either the SC or the FEF following the presentation of the visual target.

How is one to reconcile this observation with the results of the earlier work? Several possibilities may be considered:

(1) The first possibility is that visual targets are correctly acquired without utilizing the available eye position signal. What happens in the Mays-Sparks paradigm is that upon perceiving the visual target a central motor command is generated. The brief electrical stimulus, added to the central program, momentarily deflects the eye during the execution of

this command, after which the movement continues in its original path as set up initially by the central command. This is a simple, attractive hypothesis, but we believe that it is probably incorrect for two reasons: (a) In the majority of cases the electrical stimulation of the FEF and SC produces a saccade followed by a fixation, with the eye in an inappropriate location relative to the target. Then a second, corrective saccade occurs which brings the eye to the location of the already extinguished target. Thus, it cannot be argued that the perturbation is momentary. The hypothesis would seem to require that all corrections occur midflight which was clearly not the case. (b) This hypothesis would predict similar results for stimulation at any stage of the oculomotor system. Yet stimulation of the abducens nucleus fails to yield corrective saccades as also noted by Mays and Sparks (pers. commun.).

(2) The second possibility is that eye movements are generated by computing, at the level of the SC or higher, both a retinal error signal and an eye position error signal. It has been reported that both signals are available at the level of the SC and that the animal may utilize them in generating commands for eye movements (Mays and Sparks 1980a). It has also been shown that the majority of neurons in the SC which discharge prior to saccades also discharge in association with corrective eye movements (Sparks and Porter 1981): For example, if a collicular eye-movement cell has been found to discharge to a 10 deg leftward saccade made to a visual target at that location, that same cell will also discharge when the 10 deg leftward saccade is a corrective eye movement made in total darkness without the animal ever having been exposed to a target 10 deg to the left. Such data suggest that retinal error and eye position error signals are combined at the SC or earlier. Our study suggests, however, that neither the SC nor the FEF are essential for such a combined computation, as ablation of either of these structures did not interfere with the animal's ability to produce corrective eye movements in the Mays and Sparks paradigm.

(3) The third possibility is that the FEF and the SC compute a retinal error signal which combines with an eye-position error signal somewhere in the brainstem. This must occur prior to the level of the abducens nucleus area, as stimulation there fails to produce corrective eye movements. In this regard it is notable that the burst neurons in the pons appear to be driven by a motor error signal which is the difference between instantaneous eye position and the desired eye position (Van Gisbergen et al. 1981).

We would suggest that the FEF and the SC are involved predominantly in generating retinotopically coded signals, as proposed earlier (Schiller and Koerner 1972; Schiller and Stryker 1972) and that these signals are subsequently combined with the eye position error signal to produce the desired saccade. This hypothesis is not reconcilable, however, with the above noted observation that the majority of SC neurons discharge with corrective eye movements in the Mays and Sparks paradigm (Sparks and Porter 1981).

(4) The last, perhaps unlikely possibility is that neither the FEF nor the SC are directly involved in the generation of saccadic eye movements. The neural signals recorded in these structures related to eye movement may be the product of input from other brain structures involved in the generation of saccades. This input then is utilized by the FEF and the SC for purposes other than actually generating the eye movements. If this were the case one would have to assume that the low current levels required to produce saccadic eye movements by stimulating these structures is the result of antidromic activation of axon collaterals whose other branches connect with oculomotor centers in the brainstem. The observation that ablation of neither the FEF or the SC results in a dramatic loss of visually triggered eye movements may be considered to be in favor of this hypothesis (Schiller et al. 1980; Wurtz and Goldberg 1972). On the other hand it has been shown that paired ablation of the FEF and the SC produces a clear loss in the ability to acquire visual targets with saccadic eye movements (Schiller et al. 1980). One interpretation of this last finding is that the FEF and the SC form two parallel pathways for the control of visually guided eye movements; ablation of either structure alone is not devastating, but when both pathways are eliminated so is the ability to acquire visual targets for foveal viewing.

These observations would seem to favor a hypothesis which accepts a role of the FEF and the SC in saccade generation but proposes, in addition, that some of the neurons in these structures receive a feedback signal from the brainstem. Such neurons would then be active during corrective eye movements.

While we prefer the third possibility of the four described, at this time one cannot unequivocally reject any of these hypotheses. Of the many experiments needed to clarify FEF and SC function, especially important would be ones which could determine whether the eye movement-related neural activity recorded in the SC represents feed-forward or feed-back signals.

The utilization of retinal error and eye position error signals for saccade generation is an essential feature of the oculomotor system. The eyes have to reach targets in space whose presence is made evident not only through the visual system but also through the auditory and somatosensory systems. These systems are obviously well integrated. We have found, for example, that when brief auditory stimuli are presented at various spatial locations using the Mays-Sparks paradigm, monkeys, after SC stimulation make corrections similar to those obtained with visual targets. It would seem that the easiest way to keep the auditory and visual systems in spatial synchrony is to have available an accurate eye position signal. Since this signal is available extremely quickly, it probably does not have a proprioceptive source. It is more likely to originate from neurons which are in close proximity to the final common path to the eye muscles. The majority of oculomotor neurons accurately reflect the position of the eye in orbit (Robinson 1970; Schiller 1970). The exact localization of the structure(s) which are involved in the combining of the retinal error and eye position error signals is one of the important future tasks of research in this area.

## References

- Evarts EV (1966) Methods for recording individual neurons in moving animals. In: Rushman RF (ed) *Methods in medical research*. Year Book Med. Publ., Chicago, pp 241–250
- Gisbergen JAM van, Robinson DA, Gielen S (1981) A quantitative analysis of generation of saccadic eye movements by burst neurons. *J Neurophysiol* 45: 417–442
- Hallett PE, Lightstone AD (1976a) Saccadic eye movements toward stimuli triggered by prior saccades. *Vision Res* 16: 99–106
- Hallett PE, Lightstone AD (1976b) Saccadic eye movements to flashed targets. *Vision Res* 16: 107–114
- Mays LE, Sparks LD (1980a) Dissociation of visual and saccade-related responses in superior colliculus neurons. *J Neurophysiol* 43: 207–232
- Mays LE, Sparks LD (1980b) Saccades are spatially, not retinocentrically coded. *Science* 208: 1163–1165
- Merker B (1979) Protocol for silver staining Nissl substance. M.I.T. Psychology Dept. Res. Paper
- Robinson DA (1963) A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Trans Biomed Eng* 10: 137–145
- Robinson DA (1970) Oculomotor unit behavior in the monkey. *J Neurophysiol* 33: 393–404
- Robinson DA (1972) Eye movements evoked by collicular stimulation in the alert rhesus monkey. *Vision Res* 12: 1795–1808
- Robinson DA, Fuchs AF (1969) Eye movements evoked by stimulation of frontal eye fields. *J Neurophysiol* 32: 637–648
- Schiller PH (1970) The discharge characteristics of single units in the oculomotor and abducens nuclei of the unanesthetized monkey. *Exp Brain Res* 10: 347–362

- Schiller PH, Koerner F (1972) Discharge characteristics of single units in the superior colliculus of the alert rhesus monkey. *J Neurophysiol* 34: 920-936
- Schiller PH, Stryker M (1972) Single unit recording and stimulation in the superior colliculus of the alert rhesus monkey. *J Neurophysiol* 35: 915-924
- Schiller PH, True SD, Conway JL (1980) Deficits in eye movements following frontal eye-field and superior colliculus ablations. *J Neurophysiol* 44: 1175-1189
- Sparks DL, Porter JD (1981) Utilization of an eye position signal by saccade-related burst neurons in the monkey superior colliculus. *Neurosci Abstr* 7: 132
- Wurtz RH, Goldberg ME (1972) Activity of superior colliculus in behaving monkey. IV. Effects of lesions on eye movement. *J Neurophysiol* 35: 587-596

Received July 9, 1982