Supplementary Eye Field: Representation of Saccades and Relationship Between Neural Response Fields and Elicited Eye Movements

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INTRODUCTION

Schlag and Schlag-Rey (1985, 1987) initially defined the supplementary eye field (SEF) of the macaque monkey as a discrete region of dorsomedial frontal cortex where saccadic eye movements are electrically elicited with low currents. SEF lies just anterior to the supplementary motor area (SMA) from which skeletalmotor movements can be elicited (e.g., Woolsey et al. 1952) and medial to the better known frontal eye field (FEF) from which both saccades (e.g., Bruce et al. 1985; Robinson and Fuchs 1969) and smooth pursuit (e.g., MacAvoy et al. 1991) can be elicited.

Schlag and Schlag-Rey (1985, 1987) also reported that neurons in SEF responded to the appearance of visual stimuli and in conjunction with saccadic eye movements. This basic result has been confirmed by their subsequent studies (e.g., Schlag-Rey et al. 1997) and in other laboratories, including ours (Russo and Bruce 1996; Schall 1991a,b). Moreover, several interesting and complex aspects of SEF activity indicating several possible specializations have since been examined (see DISCUSSION). However, some basic response properties of SEF neurons, and the functional relationship between the saccades electrically elicited from SEF and the activity of SEF neurons, remain unknown. This void exists, at least in part, because research has not been restricted to the SEF but rather reflected recordings from a larger zone of dorsomedial frontal cortex and has involved either no microstimulation to confirm that recordings were from SEF or stimulation with large currents that can elicit saccades from well outside SEF. In addition, some basic functional issues were unresolved because it was initially reported by Schlag and Schlag-Rey (1987) that the saccades electrically elicited from SEF were not always “constant vector” in nature but rather often seemed “goal-directed.” They hypothesized that SEF served to move the eye to particular orbital positions and thus to code saccades in a cranio-centric coordinate system. However, after systematically investigating the orbital dependence of saccades electrically elicited from the low-threshold SEF using arrays of fixation positions and testing FEF using orientation functions of SEF must operate within the context of this fundamental organization.

Russo, Gary S. and Charles J. Bruce. Supplementary eye field: representation of saccades and relationship between neural response fields and elicited eye movements. J Neurophysiol 84: 2605–2621, 2000. The functional organization of the low-threshold supplementary eye field (SEF) was studied by analyzing presaccadic activity, electrically elicited saccades, and the relationship between them. Response-field optimal vectors, defined as the visual field coordinates or saccadic eye-movement dimensions evoking the highest neural discharge, were quantitatively estimated for 160 SEF neurons by systematically varying peripheral target location relative to a central fixation point and then fitting the responses to Gaussian functions. Saccades were electrically elicited at 109 SEF sites by microstimulation (70 ms, 10–100 μA) during central fixation. The distribution of response fields and elicited saccades indicated a complete representation of all contralateral saccades in SEF. Elicited saccade polar directions ranged between 97 and 262° (data from left hemispheres were transformed to a right-hemisphere convention), and amplitudes ranged between 1.8 and 26.9°. Response-field optimal vectors (right hemisphere transformed) were nearly all contralateral as well; the directions of 115/119 visual response fields and 80/84 movement response fields ranged between 90 and 270°, and response-field eccentricities ranged between 5 and 50°. Response-field directions for the visual and movement activity of visuomovement neurons were strongly correlated (r = 0.95). When neural activity and elicited saccades obtained at exactly the same sites were compared, response fields were highly predictive of elicited saccade dimensions. Response-field direction was highly correlated with the direction of saccades elicited at the recording site (r = 0.92, n = 77). Similarly, response-field eccentricity predicted the size of subsequent electrically elicited saccades (r = 0.49, n = 60). However, elicited saccades were generally smaller than response-field eccentricities and consistently more horizontal when response fields were nearly vertical. The polar direction of response fields and elicited saccades remained constant perpendicular to the cortical surface, indicating a columnar organization of saccade direction. Saccade direction progressively shifted across SEF; however, these orderly shifts were more indicative of a hypercolumnar organization rather than a single global topography. No systematic organization for saccade amplitude was evident. We conclude that saccades are represented in SEF by congruent visual receptive fields, presaccadic movement fields, and efferent mappings. Thus SEF specifies saccade vectors as bursts of activity by local groups of neurons with appropriate projections to downstream oculomotor structures. In this respect, SEF is organized like the superior colliculus and the frontal eye field even though SEF lacks an overall global saccade topography. We contend that all specializations of oculomotor functions of SEF must operate within the context of this fundamental organization.
the same methods and subjects, we established that saccades elicited from SEF are basically oculocentric with generally modest orbital position effects that are very similar to what is found in FEF (Bruce 1990; Russo and Bruce 1993). Furthermore we later demonstrated that SEF visual receptive fields are oculocentric, not craniocentric, and that SEF movement fields are oculocentric as well (Russo and Bruce 1996).

Although our conclusion that SEF codes saccades oculocentrically has not yet been unanimously accepted, we set out to further study, in an oculocentric framework, the basic neural mechanisms used by SEF to generate saccadic behavior. We mapped the response fields of SEF neurons, both visual receptive fields and saccadic movement fields, and measured the saccades evoked by activating those neurons and their immediate neighbors via electrical microstimulation. Both response-field mapping and electrical stimulation were performed while the monkeys fixated a centrally located fixation point, and both types of data were analyzed in terms of their polar direction and amplitude. A close correspondence between the neural response fields and the dimensions of elicited saccades would indicate a functional linkage between the discharge of a discrete set of SEF neurons and the generation of specific saccadic metrics, whereas a lack of correspondence would suggest that SEF is functionally specialized for nonspatial or other more complex aspects of saccade programming. We also investigated the overall physiological organization of SEF by analyzing the saccade parameters encoded by adjacent neurons and stimulation sites (especially those recorded within the same electrode penetration or at the same cortical locus) and the mapping of saccade direction and amplitude across the tangential dimensions of SEF.

We found that neural activity in SEF during visually guided saccades is composed primarily of a visual component and a movement component and that the response fields of these two activities were strongly correlated with each other as well as with the saccades electrically elicited from the recording site. Thus the representation of visual stimulus location and saccade metrics were aligned. We also found similar representations of saccade direction along different cortical depths during the same electrode penetration, indicating a columnar organization. Although the total distribution of response fields and elicited saccades suggested that each SEF contains a complete representation of all possible saccades into the contralateral visual hemifield, saccades were not topographically organized across SEF in a simple way. Instead the representation of saccades was fairly patchy with hints of systematic shifts in direction more indicative of a hypercolumnar-type organization. We conclude that SEF participates in the transformation of visual stimulus location into saccadic commands via the punctuated activity of particular groups of SEF neurons that in turn project to downstream oculomotor structures in a topographic manner. In this regard, the basic sensorimotor mechanisms of SEF are similar to those of FEF and the superior colliculus. Thus any functional specializations of SEF must operate within the context of this core neurophysiological framework.

METHODS

Surgical and behavioral protocols were approved by the Institutional Animal Care and Use Committee and complied with United States Public Health Service policy on the humane care and use of laboratory animals.

Single-neuron recording

Three female rhesus monkeys (Macaca mulatta) were prepared for chronic single-neuron recording in three separate aseptic surgical procedures. These three monkeys were the same monkeys used in two previous SEF studies (Russo and Bruce 1993, 1996). During experimental sessions, each monkey sat in a primate chair with its head held stationary by a restraining receptacle fixed to the skull. Eye-position coordinates were obtained with a search coil implanted in one eye (Judge et al. 1980). Neurons were recorded with microelectrodes made from either glass-coated Elgiloy wire (tip exposures, 30–50 μm) or glass-coated platinum/iridium wire (tip exposures, 10–30 μm), which were advanced through the intact dura with a hydraulic microdrive (MO-95, Narishige) mounted on recording chambers. The minimum penetration spacing across the cortical surface was 0.5 mm. However, in cases where multiple penetrations were made at the same microdrive coordinate, the slight curvature of the electrode was used to vary the cortical tissue sampled by rotating the electrode in the microdrive ~90° between experimental sessions. Time-amplitude window discriminators (DIS-1, BAK Electronics) sorted action potentials for sampling by the computer.

Behavioral methods

Visual stimuli were small white spots presented on a 27-in color monitor (CS-2669R, Mitsubishi) located 47 cm from the monkey’s eyes and subtending 66 by 44° of visual angle. Four tasks were used to analyze presaccadic activity and map response fields. In all four tasks, each trial began when the monkey achieved and maintained fixation of a solitary spot for ≥0.5 s. At the end of each correctly performed trial, all remaining visual stimuli were extinguished and the monkey was rewarded with ~0.2-ml of dilute fruit drink.

VISUAL-SACCADE TASK. The appearance of a peripheral visual stimulus coincided with the disappearance of the original fixation target, and the monkey was required to saccade directly to the new target. This task was the simplest way to determine if neurons had saccade-related activity, and an interactive version, wherein the experimenter used a joystick to re-position the peripheral target location between trials, was often the first task used to test each neuron.

VISUAL-PROBE TASK. A visual stimulus was presented in the periphery, but in this task, the fixation target remained on and the monkey was rewarded for simply continuing to fixate it. Conversely the trial was terminated if the monkey incorrectly made a saccade away from the original fixation target. This task was used to map neurons with purely visual responses.

DEFERRED-SACCADE TASK. Shortly after the monkey saccaded to the fixation target, a peripheral target was presented while the fixation target remained on. The monkey was required to saccade to this second target but only after the original fixation target disappeared, usually 0.5–1.0 s after the peripheral target’s appearance. By temporally separating the appearance of the peripheral target from the signal to saccade to it, this task dissociated activity related to the initial presentation of the visual stimulus from activity related to the execution of the saccadic eye movement even though the saccade was visually guided.

MEMORY-SACCADE TASK. The monkey was presented with a brief (0.5 s) visual target in the periphery while fixating a continuously illuminated fixation target. After 0.5–1.0 s, the fixation target disappeared, signaling the monkey to saccade to the location where the peripheral target had previously appeared. This task best dissociated visual activity from movement activity because, in addition to temporally separating the presentation of the stimulus and the execution of the saccade, there was no overt target present when the saccade was made.

The memory-saccade task, performed in complete darkness, was used whenever possible to classify each neuron’s presaccadic activity
as having visual, movement, or both visual and movement components (see Bruce and Goldberg 1985). However, we subsequently mapped a neuron’s response field with the easiest task consistent with the nature of each neuron’s presaccadic activity because in some cases hundreds of trials were required. Thus the visual-probe task was usually used to map neurons with purely visual responses, and the visual-saccade task was usually used to map neurons with purely movement responses. To simultaneously map the visual and movement response fields of neurons with both activities, we used either of the delayed-saccade tasks (memory-saccade or deferred-saccade); however, we generally favored the deferred-saccade task because the monkeys usually would perform more trials of this task than for the memory-saccade task.

**Microstimulation**

After studying a neuron, we tested for electrically elicited saccades by stimulating through the recording microelectrode before advancing it. The stimulation parameters used were the same or similar to the stimulation parameters used in other studies of FEF and SEF. Stimulation consisted of 70-ms trains of 350-Hz biphasic (negative-positive) shocks (thus ~24 shocks per train) with duration of 0.2 ms per phase. Stimulation was applied during fixation of a target at or near the center of the screen, and the threshold of a cortical site was defined as the magnitude of negative-going current necessary to elicit saccadic eye movements on ~50% of trials. Threshold estimation during fixation is quite conservative relative to thresholds measured outside a formal task because attentive fixation raises the threshold for electrically eliciting saccadic eye movements from the FEF (Goldberg et al. 1986) and elsewhere. Although we sought recording sites with low (50 µA) thresholds, sites with slightly higher thresholds (<100 µA) were included in our final analysis if robust presaccadic activity was recorded there and low thresholds for eliciting saccades were eventually obtained, either in the same penetration when the electrode tip was advanced into the deeper cortical layers or in other penetrations at the same coordinates or coordinates not more than 1 mm distant. Sites requiring currents 100 µA to obtain elicited saccades were not included in our population summaries even if they were located within the SEF as determined by the cortical boundary defined by the set of low-threshold sites.

**Data analysis**

Neural discharge rates were computed by estimating the onset and offset of the averaged response using the inflection points of cumulative histograms aligned to either cue onset (visual activity) or saccade beginning (movement activity) and then extracting the trial-by-trial spike rates during this period. The start and end of elicited saccades were found by the computer using an algorithm based on eye velocity.

The optimal polar direction of neural activity was estimated using an array of visual cues all having the same eccentricity but systematically varying in polar direction. The spike rates for each cue direction were fit to the Gaussian function

\[
f(\alpha) = B + R \times e^{-0.5((\alpha-\theta)/\sigma_r)^2}
\]

where \(f(\alpha)\) was discharge frequency, \(\alpha\) was stimulus or saccade direction, \(\theta\) estimates the neuron’s optimal direction, \(\sigma_r\) is an index of the neuron’s tuning with respect to direction, \(B\) estimates its baseline rate, and \(R\) estimates its peak response magnitude. These parameter estimates and their standard error (e.g., \(\theta \pm SE\)) were obtained using the LEASTSQ function in MATLAB (The MathWorks). The optimal direction is designated as \(\theta_n\) when visual activity was fit and as \(\theta_m\) when movement activity was fit. The visual and movement activities of neurons having both activities were analyzed separately.

The angular-angular correlation (\(r_{\theta m}\)) between the optimal direction of neural activity (\(\theta_n\) or \(\theta_m\)) and the median elicited saccade direction obtained at the neuron’s site (\(\theta_s\)) were computed using the formula of Fisher and Lee (Fisher 1993, p. 151). For all statistics and plots, polar directions obtained from left cerebral hemispheres were transformed into a right-hemisphere convention by the formula \(\theta' = 180 - \theta\) so that all contralateral directions lie between 90 and 270° regardless of hemisphere.

Optimal eccentricity (i.e., polar amplitude, radius, or distance) of neural activity was estimated using an array of visual cues all having the same polar direction but systematically varying in eccentricity. These data were fit to the Gaussian function

\[
f(P) = B + R \times e^{-0.5((\ln(P+1)-\ln(p+1))/\sigma_e)^2}
\]

where \(f(P)\) is discharge frequency, \(P\) is the stimulus or saccade eccentricity, \(\rho\) estimates the neuron’s optimal eccentricity, \(\sigma_e\) is a index (dimensionless) of the neuron’s tuning with respect to eccentricity, \(B\) estimates the baseline rate, and \(R\) estimates the peak response magnitude. The natural log transform was used because eccentricity tuning appeared to be logarithmically scaled, similar to what had been found in FEF (Bruce and Goldberg 1985). The optimal eccentricity is designated \(\rho_m\) when visual activity was fit and as \(\rho_m\) when movement activity was fit. In all figures, eccentricity was plotted using a logarithmic scale to maintain sensitivity in the small saccade range.

For some neurons, the formal testing of optimal direction or eccentricity with uniformly spaced arrays of visual cues could not be completed (usually because the neuron was lost or the monkey stopped working before the neuron could be formally tested). In some of these cases, we successfully estimated their optimal direction and eccentricity by fitting the neural activity recorded during our preliminary test that used an interactive joystick to re-position the visual cue between trials. We fit these data to the general Gaussian function of direction and eccentricity

\[
f(\alpha, P) = B + R \times e^{-0.5((\alpha-\theta)/\sigma_r)^2 +((\ln(P+1)-\ln(p+1))/\sigma_e)^2}}
\]

where \(f(\alpha, P)\) is discharge frequency, \(\alpha\) is the stimulus or saccade direction of each trial, \(P\) is the stimulus or saccade eccentricity of each trial, \(\theta\) estimates the neuron’s optimal direction, \(\rho\) estimates the neuron’s optimal eccentricity, \(B\) estimates its baseline rate, \(R\) estimates its peak response magnitude, \(\sigma_r\) is an index of the neuron’s tuning with respect to direction, and \(\sigma_e\) is a index (dimensionless) of the neuron’s tuning with respect to eccentricity.

For the purpose of analyzing the uniformity of a set of directions represented at nearby SEF sites, the mean vector length \(r\) (Batschelet 1985, p. 10) was used as an index of “directional-concentration,” the formula being

\[
r = \left(\frac{\sum \cos (\theta_i)^2 + \sum \sin (\theta_i)^2}{n}\right)^{1/2}
\]

where \(\theta_i\) is the \(i\)th member of a group of \(n\) saccade directions.

**Histology**

At selected recording sites, electrolytic lesions were made by passing 20 µA of negative current through the electrode for 30 s. Other sites were marked with iron by passing 10 µA of positive current through Elgiloy electrodes for 3 min.

Monkeys AB and SY were deeply anesthetized with pentobarbital sodium and perfused transcardially with saline, followed by 10% formalin in 0.1 M phosphate buffer and a sucrose series. Monkey HK died unexpectedly and could not be perfused. Instead, its brain was fixed by immersion for 7 days in a mixture of 1.25% glutaraldehyde and 1% paraformaldehyde in 0.1 M phosphate buffer followed by 3 days in the same fixative with 30% sucrose. All brains were photographed, blocked in the coronal plane, and sectioned at 50 µm on a freezing microtome. Every other section through the region with electrode penetrations were reacted with ferrocyanide (Perl’s reaction).
for visibility of the iron deposits and counter stained with neutral red. Individual recording and stimulation sites that had been marked with deposits or lesions were identified.

RESULTS

Location of low-threshold SEF

Both hemispheres of two monkeys (AB and SY) and one hemisphere of one monkey (HK) were studied. For each of these five hemispheres, the low-threshold SEF was defined as the contiguous cortical area whose boundary was not more than 1 mm from an electrode penetration coordinate containing at least one site with a low (≤50 μA) threshold for eliciting saccadic eye movements. Using this criteria, the low-threshold SEF was typically found to be located in a small region (10–15 mm²) on the dorsomedial convexity of the frontal lobe with its center ~5 mm anterior to the most posterior level of the arcuate sulcus and 2–3 mm lateral to the lip of the longitudinal fissure. Figure 1 shows the location of electrode penetrations in the right hemisphere of monkey AB using different symbols to denote the lowest threshold found at each penetration coordinate. An example of one electrically elicited saccade from one low-threshold SEF site is also shown along with its histological confirmation. We rarely saw evoked movements other than saccades in the low-threshold SEF: the only exceptions were four electrode penetrations where both evoked saccades and pinna movements were observed. Most electrically elicited pinna movements were evoked at sites posterior and lateral to SEF, whereas skeletal movements were evoked several millimeters posterior to SEF. We did not see any elicited smooth eye movements, such as are elicited from the depths of the arcuate sulcus (MacAvoy et al. 1991).

The low-threshold saccadic SEF is the subject of this report. Our study is based on elicited saccades from 109 stimulation sites and 160 presaccadic neurons, all located within the low threshold SEF as defined in the preceding text. We first present summaries of the stimulation and neural activity data separately, then present data showing how they are related to each other, and finally show how they are organized across SEF.

Electrically elicited saccades

Figure 2 summarizes our elicited-saccade database pooled across the five hemispheres we studied. Saccades were electrically elicited during attentive fixation of a small spot at the center of the monitor (see METHODS). Thresholds ranged from 10–90 μA (Fig. 2, top left), with a median threshold of 40 μA. Elicited saccade data from stimulation sites with thresholds >50 μA but <100 μA were included in our analyses if they were located within the boundary of low-threshold SEF sites. Neurons at these slightly higher threshold sites usually exhibited robust presaccadic activity similar to that found at low-threshold sites. We would expect that these thresholds would be significantly lower if stimulation had been tested while the monkey alertly looked about without any overt fixation targets; however, we did little testing of this type.

The median cortical depth of the 109 stimulation sites was 1.85 mm below the apparent start of neural activity. Only 7 of the 109 sites was at a depth <0.8 mm as we did not find low thresholds (or robust presaccadic activity) until ~1 mm or more below the apparent entry of the electrode into the cortex.

Because threshold currents elicited saccades on only ~50% of trials, we usually increased the current ~10 μA after determining each site’s threshold to quickly obtain representative sets of elicited saccades at fixed currents. These testing currents ranged from 15 to 100 μA, with a median of 50 μA (Fig. 2, middle left).

The latency of electrically elicited saccades, defined as the time from the start of the stimulation train to the start of the saccadic movement, was generally very short (Fig. 2, bottom left). The median latency was 50 ms, with 88% of the stimulation sites having a median latency between 36 and 60 ms. However, the upper tail of the latency distribution is long, and for eight sites, the elicited saccade latency was even greater than the duration of the stimulation train that we used (70 ms). We carefully examined the velocity profiles of elicited saccades and found no indication that elicited saccades with longer latencies were different from elicited saccades with shorter latencies. In particular, they were not prematurely ab-

FIG. 1. Location of supplementary eye field (SEF). Left: dorsal view of the right frontal lobe of monkey AB showing the thresholds for electrically eliciting saccades at different cortical locations in the dorsomedial region of the frontal lobe. - - - , anterior-posterior location of the histological section shown to the right. Top right: coronal section through the right frontal lobe of monkey AB showing the reaction product from iron deposited at 1 SEF stimulation site (AB267) with a 40-μA threshold. Bottom right: saccades electrically elicited from the stimulation site located at the iron deposit shown above. Saccades were elicited with 50 μA during fixation of a centrally located target. The time course of a single representative trial is shown on the left, and the 2-dimensional trajectories of all 6 trials are shown on the right. The median saccade direction, amplitude, and latency were 257°, 16.4°, and 48 ms, respectively. Starting eye position has been aligned to facilitate comparison of trajectories and end points in this and subsequent 2-dimensional plots of eye position. Stim, time of electrical stimulation; H, horizontal eye position; V, vertical eye position; |V|, absolute eye velocity.
breviated by the cessation of 70-ms stimulation train, even when the train ended before the saccade began. Instead, all the saccades electrically elicited from SEF exhibited the classic all-or-none ballistic features originally described for saccades elicited from FEF by Robinson and Fuchs (1969) with consistent amplitudes and directions regardless of latency.

We term the median elicited saccade, taken during central fixation, the characteristic saccade vector for a site. The distribution of characteristic saccade vectors from all 109 sites is shown in Fig. 2, right. For this and subsequent figures, characteristic saccades from left hemispheres are converted to a right-hemisphere convention by mirror reversing them as described in METHODS. For example, elicited saccades with a polar direction of 45° (upward and rightward) obtained from a left-hemisphere site would be converted to 135° (upward and leftward).

All 109 characteristic saccades were contralaterally directed. Their directions ($\theta_c$) ranged from nearly straight up (minimum 97°) to nearly straight down (maximum 262°), and nearly all directions into the contralateral hemifield seem to be represented. However, almost twice as many saccades were elicited into the upper contralateral quadrant (65%) as into the lower quadrant (35%). Characteristic elicited saccade amplitudes ($\rho_c$) ranged from small (1.8°) to large (26.9°), with a median of 13.1°.

Presaccadic response fields

We searched for neurons with presaccadic responses while the monkey performed either the visual-saccade or the deferred-saccade task (see METHODS) with the experimenter interactively varying the coordinates of the peripheral visual cue between trials with a joystick. When a SEF neuron with presaccadic activity was isolated, we first performed a set of preliminary tests to estimate the spatial location of the response field and classify its presaccadic activity as visual, movement, or visuomovement. An example of this preliminary testing procedure is illustrated in Fig. 3, A and B. Because a neuron’s response field could be located at any point in the visual field, we first attempted to make a rough estimation of its location using the interactive version of the deferred-saccade task while watching the on-line raster display and listening to audio feedback of the neural response. The response field center of this neuron appeared to be directly downward (~270°) and ~10° eccentric. A retrospective quantitative analysis of these data confirmed that our initial estimate was fairly accurate (Fig. 3A, right). The three-dimensional plot shows the target coordinates of the 25 trials from this interactive task plotted along the x and y axes versus the neural response plotted along the z axis. The surface shows the best fit of these data to the Gaussian function for direction and eccentricity described in METHODS. The peak of the function was 263° in polar direction and 8.1° in eccentricity, fairly close to our on-line estimate of 270° in polar direction and 10° in eccentricity.

After approximating a neuron’s response-field location, we analyzed the composition of its presaccadic activity using the memory-saccade task with a visual cue located at our initial on-line estimate (Fig. 3B). This neuron was classified as having visuomovement activity because it discharged in conjunction with the appearance of the peripheral visual cue and then again in conjunction with the saccadic eye movement.

Next we attempted to formally analyze the spatial location of a neuron’s response field by determining its optimal direction and optimal eccentricity in separate experiments Response-field direction was analyzed by systematically varying the polar direction of the visual cue around our initial on-line estimate while holding eccentricity constant, and response-field eccentricity was analyzed by systematically varying the eccentricity of the visual cue around our initial on-line estimate while holding direction constant. Figure 3, C and D, shows this procedure for response-field direction. Because this neuron exhibited both visual and movement activities in the memory-saccade task (Fig. 3B), the deferred-saccade task was used so that visual and movement activity could be analyzed separately. These data were fit to the Gaussian function described in METHODS to obtain independent estimates of the neuron’s visual activity optimal polar direction ($\theta_v$) and movement activity optimal polar direction ($\theta_m$). Notice that the resulting estimate of $\theta_v$ (258°) is very close to the estimate of 263° obtained by fitting the informal, interactive data described in Fig. 3A. However, the formal testing procedure yielded a smaller SE for the $\theta_v$ estimate. Furthermore this neuron’s $\theta_m$ could not be accurately estimated with this set of interactive data even though it was well estimated with the formal data. Thus the response-field parameters estimated with our formal tests were generally more accurate; however, some neurons mapped only informally were included in our analysis if the data provided good fits yielding a $\theta_v$ and/or $\theta_m$ that agreed with the on-line estimates.

A total of 160 presaccadic neurons in the low-threshold SEF were successfully classified and mapped. The Venn diagram in Fig. 4 summarizes their response classification: overall, 84% of these neurons had visual activity and 57% had movement...
activity. There were 68 (43%) with purely visual responses, 26 (16%) with purely movement responses, and 66 (41%) with both visual and movement responses. The median cortical depths for the three neuronal types were 1.75 mm (visual), 2.18 mm (movement), and 1.68 mm (visuomovement). The null hypothesis of equality of depth across neuron types is unlikely (Kruskal-Wallis $\chi^2_{[2]} = 7.39$, $P < 0.025$).

To illustrate the overall presaccadic responses of SEF, the average response histograms for 104 neurons tested on the memory saccade task are shown in Fig. 4, top (56 of the 160 neurons could not be tested on the memory saccade task because the monkey stopped working or the neuron was lost; they were classified on the basis of activity during the deferred-saccade task). These composite histograms were compiled by first computing histograms of neural activity for each neuron using target locations at or near the optimal location for their presaccadic responses, and then averaging them together. The activity of these 104 neurons aligned to cue onset, fixation offset, and saccade, beginning show that presaccadic activity in SEF is composed of two main components: a burst of activity in response to the appearance of a visual stimulus and a burst of activity preceding and during the saccade. Some tonic mnemonic activity is also evident, indicated by the small but significant elevation in tonic activity (~3 spikes/s) while fixating during the delay period, compared with the period of fixation before the peripheral cue was presented. A very similar pattern of activity was observed when these same neurons were tested with the deferred-saccade task. In general both the deferred-saccade task and the memory-saccade task gave similar results.

When the visual and movement activities of SEF visuomovement neurons were mapped, their response fields were

![Image of the page]

**FIG. 3.** Standard testing procedure performed on 1 SEF presaccadic neuron (SY024, right hemisphere, visuomovement neuron). A: interactive deferred-saccade task used to perform an on-line estimate of the neuron’s response-field location. The 25 target vectors chosen between trials by the experimenter using a joystick are shown to the left. A retrospective analysis of neural activity during these trials is shown to the right. Activity was aligned to the onset of the visual stimulus and the responses (average spike rate for a 182-ms epoch starting 82 ms after visual cue onset) were fit to the Gaussian function of direction and eccentricity described in METHODS. The fit was significant ($F_{[2,19]} = 2.29$, $P < 0.05$), with a peak at 263° in polar direction and 8.1° in eccentricity. Stems above or below each response marker show the difference between the response and the best fit Gaussian function. B: classification of presaccadic activity. Rasters and peristimulus time histograms (PSTHs) of neural activity during performance of the memory-saccade task in the dark with a target located 270° in direction and 10° in eccentricity. The duration of the visual cue was 0.5 s, and the subsequent delay interval was 1.0–1.8 s. Raster and PSTH on the left are aligned to the appearance of the visual cue and sorted by delay-period length. Raster and PSTH on the right are aligned to the beginning of the memory-guided saccade eye movement and sorted by latency relative to the offset of the fixation point. Notice that this neuron responded to both the cue (latency 64 ms) and then again in conjunction with the saccadic eye movement directed to the location where the cue was presented (latency ~68 ms relative to saccade start). ●, beginning of saccadic eye movement; *, offset of fixation point. C: quantitative analysis of visual and movement activity optimal direction using the deferred-saccade task. The visual cues were all 10° eccentric with polar directions spaced 60° apart. The peristimulus time histograms represent 10 trials for each of the 5 cue locations. The PSTHs on the left are aligned to the onset of the visual stimulus, and the PSTHs on the right are aligned to the start of the saccadic eye movement. D: response magnitudes, Gaussian fits, and estimated optimal directions of visual and movement activity. Response magnitudes of visual activity are the spike rates during a 200-ms epoch starting 100 ms after the stimulus appeared. Response magnitudes of movement activity are the spike rates during a 200-ms epoch starting 100 ms before saccade initiation. Thick bars show the mean rate ± SE at each direction; ○, the response rates for each trial. Because single-trial rates in a 200-ms epoch are quantified in steps of 5 Hz, overlapping data points in the visual activity plot were spread out horizontally to show all the points at each direction tested. In the movement activity plot, the monkey’s natural variation in saccade direction minimized overlap, and so only a few overlapping data pairs had to be spread. Both Gaussian fits were highly significant (visual activity: $F_{[5,47]} = 5.613$, $P < 0.00001$; movement activity: $F_{[5,40]} = 4.130$, $P < 0.00001$). Notice that $\theta_v$ and $\theta_m$ are very similar to each other ($258 \pm 4$ vs. $261 \pm 4°$), and to the $\theta_v$ ($263 \pm 7°$) obtained from the retrospective analysis of our informal test data shown in A.
usually closely aligned. Of the 66 visuomovement neurons in our sample, we obtained quantitative estimates of both \( u_v \) and \( u_m \) for 44 of them. Figure 5 shows the relationship between \( u_v \) and \( u_m \) in these 44 neurons. Both visual and movement activity data were obtained from the same trials during the deferred-saccade or memory-saccade task. However, all estimates of \( u_v \) and \( u_m \) were from independent fits of distinct and completely nonoverlapping visual and saccadic bursts. Although some visuomovement neurons exhibited significant differences between \( u_v \) and \( u_m \) (the largest was 57°), the median absolute difference was only 8° and with an extremely strong correlation of 0.95. A linear regression of \( u_m \) on \( u_v \) yielded a slope not significantly different from 1 (1.1 [0.94, 1.17]), and a \( y \) intercept not significantly different from 0 (−14 [−35, 8]), indicating that the visual and movement fields of SEF visuomovement neurons largely overlapped. This congruence of visual and movement response fields is not only a principal finding but also justifies using the mean of \( u_v \) and \( u_m \) as an estimate of a visuomovement neuron’s overall optimal direction (\( u_{vm} \)) as described in the following text.

Figure 6 shows the optimal response-field vectors for all 160 SEF neurons considered in this report. The direction of each neuron’s response field was based on its estimated \( u_v \), \( u_m \), or \( u_{vm} \). The eccentricity of most response fields were based on their optimal stimulus eccentricity (\( r_v \)) or optimal saccade amplitude (\( r_m \)) obtained using the log-Gaussian fits described in METHODS (and detailed in the following text) or their mean if both were computed (\( r_{vm} \)). However, satisfactory estimates of \( r \) could not be computed for 50 of the 160 neurons using either the formal or interactive tests. For these 50 neurons, we used our initial on-line estimate of response-field eccentricity for the plots in Fig. 6; however, these data were not included in further analyses of \( r \) (e.g., Fig. 11). As with the electrically elicited saccades, the optimal response-field vectors of left-hemisphere neurons were transformed into a right-hemisphere convention. Compilation of all single-neuron data in this way provides a comprehensive sample of the neural representation of saccades in SEF. Notice that this collection of 160 optimal saccade vectors encompasses virtually all possible contralateral saccades, similar to the analogous plot of elicited saccade vectors (Fig. 2). Unlike the elicited saccades which were all contralat-
stimulated through the recording electrode. The 50% threshold for eliciting saccades at this site during central fixation was 20 μA, and the set of 10 elicited saccades shown in Fig. 7A, bottom, were obtained using 25 μA. The median elicited saccade direction (θ) was 185°, very similar to the θ recorded at this stimulation site.

Figure 7B illustrates a similar analysis for a neuron with presaccadic movement activity and no visual response. This neuron was tested with the memory-saccade task using an array of eight visual cue directions. The optimal saccade direction for the neuron’s movement activity was 119°. The saccades subsequently elicited by stimulation using 30 μA had a median direction of 126°. Notice how θ is very close to θm. Also notice that the elicited saccades are slightly more horizontal than the neuron’s optimal direction.

Figure 8 summarizes the relationship between the response-field optimal direction of 77 SEF neurons and electrically elicited saccade direction. As in Fig. 6, a single neuron’s optimal direction was derived from estimates of θv, θmv, or θvm. The correlation between neural activity optimal direction and elicited saccade direction was highly significant (r = 0.92). A separate analysis of visual and movement activity (using estimates of θv from visual and visuomovement neurons and estimates of θm from visuomovement and movement neurons) yielded similarly strong correlations (visual activity: r = 0.94, n = 59; movement activity: r = 0.88, n = 42).

Although SEF neural activity and elicited saccade directions were highly correlated, the precision of their alignment was not uniform across the visual hemifield. In fact, the median absolute difference for the 77 neurons in Fig. 8 was nearly 17°. Although some of this discrepancy could be due to errors of measurement (our estimates of θv and θm typically had an SE <10°), there was a conspicuous trend for sites with neurons that had response fields nearly upward and downward to yield elicited saccades that were slightly more horizontal. This trend was confirmed by computing the linear regression of elicited saccade direction on response-field direction. The slope of the regression line was 0.79 [0.71, 0.87], significantly less than unity inasmuch as its 95% confidence interval does not include 1. Furthermore the complete regression equation predicts that sites where neurons have response fields directly up (90°) will yield elicited saccades that are 107° in polar direction, and sites where neurons have response fields directly down (270°) will yield elicited saccades that are 248° in polar direction. Thus neurons at sites representing vertical directions should yield elicited saccades rotated toward the horizontal an average of ~20°. An example of this phenomenon is shown in Fig. 9. This neuron’s θv and θm was nearly straight down (258 and 261°, respectively); however, the median elicited saccade direction was 233°, thus rotated ~27° contralateral from the neuron’s response field.

**Relationship of presaccadic activity optimal eccentricity to electrically elicited saccade size**

Similar to the relationship between the optimal direction of neural activity and the direction of saccades electrically elicited from the recording site, we found a relationship between a neuron’s optimal eccentricity and the amplitude of subsequent electrically elicited saccades. However, this relationship was less precise than what we found for polar direction. Figure 10

![Graph](image)
shows the neural recording and electrical stimulation at three different SEF sites. The visual neuron in Fig. 10, left, preferred moderate visual cue eccentricities ($\rho_v = 12.4 \pm 1.0^\circ$), and medium-sized saccades were subsequently elicited ($\rho_e = 8.5 \pm 1.0^\circ$). The visual neuron in Fig. 10, middle, preferred large eccentricities ($\rho_v = 29.6 \pm 1.1^\circ$), and fairly large elicited saccades were subsequently elicited ($\rho_e = 17.1 \pm 0.7^\circ$). The movement neuron in Fig. 10, right, clearly preferred very large saccades but had very poor tuning for saccade size ($\rho_m = 47.5 \pm 11.3^\circ$), and the subsequent elicited saccades were very large ($\rho_e = 25.9 \pm 2.5^\circ$). Figure 11 shows the optimal eccentricity of 60 neurons plotted against the median saccade amplitude electrically elicited from their recording sites. The correlation coefficient ($r = 0.49$) is highly significant, but only about half the correlation that was observed for the analysis of response field versus elicited saccade direction. As in the analysis of saccade direction, similar results were obtained when visual and movement activity were considered separately. $\rho_v$ obtained from visual and visuomovement neurons were significantly correlated with $\rho_e$ ($r = 0.48$, $P < 0.005$, $n = 44$), as were $\rho_m$ and $\rho_e$ obtained from visuomovement and movement neurons ($r = 0.39$, $P < 0.05$, $n = 26$).

Notice that most of the data points in Fig. 11 were below the $x = y$ diagonal, indicating that estimates of optimal eccentricity were generally larger than elicited saccade amplitude. One reason is that many SEF response fields were open ended with responses that fell off very gradually, if at all, with increasing eccentricity. As a result, the estimates $\rho_v$ and $\rho_m$ for these eccentric response fields generally had a correspondingly larger SE (see Fig. 10), making it difficult to obtain a single accurate estimate of response-field optimal eccentricity that could be considered truly “optimal.” Similar observations of open response fields have been made in the superior colliculus (Munoz and Wurtz 1995) and the FEF (Bruce and Goldberg...
Like \(v\) and \(u\) of visuomovement neurons, \(r\) and \(u\) were also highly correlated (\(r = 0.84, P < 0.005, n = 15\)). Such a small sample of visuomovement neurons with both \(r\) and \(u\) estimated again reflects the difficulty in estimating the optimal response-field eccentricity of SEF presaccadic activity.

**Relationship of presaccadic activity type to electrically elicited saccade threshold**

We compared the likelihood and ease of obtaining elicited saccades at the sites of purely visual neurons, visuomovement neurons, and movement neurons. Low-thresholds are more likely where FEF neurons have movement activity (Bruce et al. 1985); however, we were surprised to find that microstimulation was uniformly effective in eliciting saccades at SEF sites, regardless of the type of presaccadic activity there. Of the 68 SEF sites where visual neurons were recorded, 51 were tested with electrical stimulation. Of these tests, 82% (42/51) elicited saccades, and the median threshold (regarding threshold at the 9 unexcitable sites as large) was 52.5 \(\mu\)A. Of the 66 SEF sites where visuomovement neurons were recorded, 53 were tested with electrical stimulation and 85% (45/53) elicited saccades with a median threshold of 55 \(\mu\)A. Of the 26 SEF sites where movement neurons were recorded, 21 were tested with electrical stimulation and 86% (18/21) elicited saccades with a median threshold of 52.5 \(\mu\)A. A \(\chi^2\) test failed to indicate that these percentages of elicited saccades differ significantly across neuron types (\(\chi^2[2] = 0.0239, P > 0.5\)), and a Kruskal-Wallis test failed to indicate that thresholds differ across neuron types (\(\chi^2[2] = 0.7575, P > 0.5\)).

**Topographic organization**

The representation of saccades in SC has long been known to have a straightforward topography, with small saccades represented anterior, large saccades posterior, upward saccades medial, and downward saccades lateral (Robinson 1972). In FEF saccade amplitude is also topographically organized with large saccades represented dorsomedially and small saccades ventrolaterally, but the representation of saccade direction is more complex with gradual changes in saccade direction as an electrode is advanced parallel to the cortical surface resembling a hypercolumnar organization (Bruce et al. 1985). To determine what type of saccade

**FIG. 8.** Relationship between the optimal direction of SEF response fields and the direction of electrically elicited saccades. The response-field optimal direction of 77 SEF neurons computed from visual (\(\theta_v\), red), movement (\(\theta_m\), green), and visuomovement (\(\theta_{vm}\), blue) activity are plotted vs. the median direction of saccades electrically elicited at the recording site (\(\theta_e\)). \(\theta_{vm}\) is the mean angle of the independently computed estimates of \(\theta_v\) and \(\theta_m\), for neurons with both visual and movement activity (see Fig. 6). All directions are right-hemisphere transformed. The dashed line with unity slope is drawn to emphasize the overall similarity between neural response field and electrically elicited saccade direction. The solid line shows the linear regression of elicited saccade direction on response-field direction. Notice the systematic departure from equality for saccade representations near the vertical. Length and placement of plot frame indicates range of data along each axis.

**FIG. 9.** SEF site where 1 presaccadic neuron (SY024, right hemisphere) with nearly vertical (downward) visual and movement response fields yielded oblique electrically elicited saccades. Top: polar plots showing response magnitudes, Gaussian fits, and estimated optimal polar directions for visual (left) and movement activity (right). Response magnitudes of visual activity are the spike rates during a 200-ms epoch starting 60 ms after the stimulus appeared. Response magnitudes of movement activity are the spike rates during a 200-ms epoch starting 100 ms before saccade initiation. All other conventions are the same as Fig. 7. Notice that \(\theta_v\) and \(\theta_m\) are both \(-10^\circ\) rotated away from straight down (270\(^\circ\)), but \(\theta_e\) is rotated \(-37^\circ\) from downward. This neuron is the same neuron used to illustrate our basic testing procedure in Fig. 3.
topography, if any, the low-threshold SEF has, we analyzed neural response-field vectors and electrically elicited saccade dimensions with respect to the relative location of the electrode tip within the cortex. Although we did not find a systematic global topographic organization of saccades across SEF, there was continuity of saccade direction across short distances and evidence of columnar and hypercolumnar organization with respect to polar direction.

As the electrode was advanced perpendicular to the cortical surface, neural response fields and elicited saccades represented similar saccade directions, indicating a columnar organization with respect to saccade direction. One example of this finding for neural activity is illustrated in Fig. 12, top left. In this electrode penetration, two superficially located neurons that were mapped simultaneously had response-field directions of 140° and 143°. Furthermore a neuron 0.45 mm deeper that was also mapped during the same experimental session had a response-field direction of 147°, very close to the response-field direction of the two neurons recorded above them. Similar

![Fig. 10. Relationship between the optimal eccentricity of neural activity and the amplitude of subsequent electrically elicited saccades at 3 different SEF sites.](image-url)
trode penetration. The characteristic elicited saccade direction of saccades elicited from two different sites in the same electrode system (see METHODS). Thus the conservative conclusion is that representation of saccade direction across the surface coordinates along the z axis. A planar regression was highly significant (r = 0.60, F[69,66] = 18.4, P < 0.0001), with the slope indicating a 55° change in polar direction per millimeter from the upper contralateral visual quadrant in anterior penetrations to the lower contralateral visual quadrant in posterior penetrations. Similar zones of systematic change in saccade direction along the anterior-posterior axis were also found in the left hemisphere of monkey AB and the right hemisphere of monkey HK. For all three hemispheres with significant regressions, the partial regression coefficients of saccade direction on anterior-posterior location were significant with 95% confidence, but the partial regression coefficients of saccade direction on medial-lateral location were not significant. No systematic change was evident in the left and right SEF of monkey SY, but these had the fewest electrode penetrations.

Although three hemispheres showed orderly progressions of saccade direction, their monotonic anterior-posterior pattern did not appear to describe a global SEF topography. Instead there were multiple horizontal saccade representations along the anterior and posterior extent of SEF in monkeys AB and HK (with unclear trends in SY), suggesting a hypercolumnar representation of saccade direction similar to what has been seen in the FEF with multiple representations of directions in a somewhat cyclical fashion. We illustrate this possibility in Fig. 14, bottom, by a least-squares fit of all the data from the right-hemisphere of monkey AB to a sinusoidal function. The fit is significant (F[69,66] = 1.715, P < 0.02) and appears to roughly model the change in direction along the anterior-posterior extent of SEF. Several incongruous points in this plot could reflect entry point inaccuracies in the microdrive/microelectrode system (see METHODS). Thus the conservative conclusion is that representation of saccade direction across the
tangential extent of SEF is orderly but is not a straightforward global topography. Finally we did not find any systematic changes in saccade amplitude across SEF.

DISCUSSION

Our previous work showed that SEF cortex encodes eye movements in oculocentric coordinates, both in its response fields (Russo and Bruce 1996) and its efferent organization as judged by electrically elicited saccades (Russo and Bruce 1993). The present study builds on this model of SEF function by further examining the types of SEF presaccadic neurons, the relationship between visual and motor response fields, the relationship between neural response fields and the metrics of saccades elicited by electrical stimulation at their recording sites, and the local and global topography of saccade representations across SEF cortex. Our analyses were based on data obtained from the low-threshold SEF, that is, the region from which electrical stimulation at low currents reliably elicits a saccade.

To summarize, we found that neurons in SEF share several properties with both the superior colliculus (SC) and the frontal eye field (FEF). Like these regions, SEF has a representation of saccades to virtually all points in the contralateral visual hemifield, and each neuron and site appear to code a specific saccade vector. SEF contains neurons with purely visual activity, purely movement activity, and both visual and movement activity. When visuomovement neurons were analyzed, the visual and response fields were generally congruent, as is true of visuomovement neurons in SC and FEF. When neurons and elicited saccades at the exact same site were studied, the response fields of the neurons matched the metrics of the saccades subsequently elicited with electrical stimulation, revealing a direct functional linkage between the activity of groups of SEF neurons and the generation of specific saccadic eye movement metrics. Finally, SEF visual activity, movement activity, and its efferent (elicited saccade) organization, have a columnar arrangement with respect to both polar direction and response field. Polar direction is generally a continuous representation across the SEF surface; however, it is not a singular representation as in the SC. Instead polar direction appears to be cyclically represented in a hypercolumnar fashion as in FEF. These results and some of their implications are discussed in the following text.

Common functional properties of SEF, FEF, and SC

Overall SEF appears to code specific saccade metrics via the activation of locally organized groups of neurons that project to downstream oculomotor centers in a topographic manner. In this respect, SEF seems remarkably similar to both the primate SC and FEF. Indeed, the present results show that SC and FEF share many of the same neurophysiological properties of SEF. For example, both the SC (Schiller and Stryker 1972; Wurtz and Goldberg 1972) and FEF (Bruce and Goldberg 1985) contain neurons with purely visual activity, purely movement activity, and both visual and movement activity. In our study, we showed that single SEF neurons could also be classified on this basis, and the composite activity in SEF during saccades followed this pattern. Furthermore neurons in SC (Schiller and Stryker 1972; Sparks and Mays 1980; Sparks et al. 1976; Van Opstal et al. 1990; Wurtz and Goldberg 1972) and FEF (Bruce and Goldberg 1985) discharge maximally in conjunction with visually guided saccades of a particular size and direction, indicating that only a specific subpopulation of neurons are activated in conjunction with a particular saccadic eye movement. In the present study, almost all SEF neurons had an optimal direction, and most also had an optimal eccentricity.
although this property could not always be quantified because many SEF neurons were broadly tuned for eccentricity and often still had strong responses beyond the maximum eccentricity we could test from central fixation (33° horizontal and 22° vertical). Moreover the saccade vector associated with the largest neural response at any particular site in SC (Schiller and Stryker 1972; Sparks and Mays 1980; Van Opstal et al. 1990; Wurtz and Goldberg 1972) and FEF (Bruce et al. 1985) corresponded to the saccadic vector evoked with subsequent electrical stimulation, supporting a direct causal role for the activity of specific neuron subpopulations in the generation of particular saccadic eye movements metrics. The strong correlation we found between the optimal direction and optimal eccentricity of neural activity and subsequent direction and amplitude of electrically elicited saccades is also comparable to the correspondence found in the SC and FEF.

Finally, like the SC and FEF, all possible saccades into the contralateral visual hemifield seem to be represented within SEF. This includes vertical saccades, which are represented bilaterally in SEF as they are in FEF and SC. Interestingly there was a significant trend for recording sites with nearly vertical response fields to yield elicited saccades rotated somewhat more horizontal (see Figs. 8 and 9). This could simply reflect the fact that electrical stimulation activated only one hemisphere, whereas naturally occurring vertical saccades would entail SEF activity in the vertical representations of both hemispheres. It could also reflect current spread into neighboring columns, representing obliquely contralateral saccades. Regardless, this can be viewed as a systematic perturbation of electrically elicited saccades, analogous in some ways to the orbital perturbation of SEF-elicited saccades, which we previously described and postulated similar explanations for (Russo and Bruce 1993).\(^1\) In both cases we argue that the small but systematic discrepancy between the neuronal response field and the elicited saccade vector is explained by careful consideration of the details and artifactual nature of single-electrode microstimulation. In fact, this systematic contralateral perturbation of saccades elicited at vertical representations should be canceled by having the monkey fixate contralateral to the stimulated hemisphere (e.g., site RAB103 of Fig. 6 in Russo and Bruce 1993). We also would predict a similar contralateral perturbation at the vertical representations in FEF.

In summary, their common neurophysiological properties suggest that all three oculomotor structures have at least some common oculomotor functions that use similar neural mechanisms. Thus SEF, SC, and FEF specify the dimensions of saccadic eye movements via the activation of a functionally distinct subset of output neurons that project to downstream destinations.
oculomotor structures in a topographic manner. Chemical inactivation of small zones in SC (Hikosaka and Wurtz 1985; Lee et al. 1988; Quaia et al. 1998) and FEF (Dias et al. 1995) results in saccadic eye movement deficits into the visual field location represented by the inactivated region. The present data predict that inactivation in SEF would produce similar results. Permanent and total SEF lesions do have much smaller and shorter-lived effects than permanent, total FEF lesions according to the sensitive synchrony test used by Schiller and Chou (1998); however, this may simply reflect the much larger overall size of FEF (see following text), and local inactivation effects might be more comparable.2

Location and size of SEF

The present study targeted the SEF cortex as discovered by Schlag and Schlag-Rey (1987), where saccades are electrically elicited with low-threshold stimulation currents. The thresholds and latencies of elicited saccades reported here generally agree with that report and thereby help confirm that we are studying the low-threshold SEF Schlag and Schlag-Rey (1987) so definitely described. However, the estimates of threshold for eliciting saccades in the present study are conservative relative to Schlag and Schlag-Rey’s report (1987) because we always stimulated while monkeys fixated a visual target (to consistently elicit saccades from the same starting eye position used to map response fields), whereas they usually stimulated while the monkeys explored a blank screen. Fixation consistently increases the threshold for electrically eliciting saccadic eye movements from FEF (Goldberg et al. 1986) and elsewhere. We decided to use sites with thresholds >50 μA because our fixation requirement raises the thresholds, robust presaccadic activity was present at these sites, and low thresholds for eliciting saccades were found at other sites on the same penetration or in other penetrations with the same or nearby electrode coordinates. Even when the 50-μA criteria was modestly relaxed, the SEF in the present study were still only ~10–15 mm2, similar to the extent of Schlag and Schlag-Rey’s SEF.

Many other studies of SEF have used similar microstimulation criteria to locate it (Huerta and Kaas 1990; Mushiake et al. 1996; Schlag-Rey et al. 1997; Tian and Lynch 1995, 1996). However, the small size of SEF reported in those studies and the present report contrasts with studies of the dorsomedial frontal cortex (DMFC) wherein a much larger electrically excitable area has been described (Bon and Lucchetti 1992; Lee and Tehovnik 1995; Mann et al. 1988; Mitz and Godschalk 1989; Tehovnik and Lee 1993; Tehovnik and Sommer 1997). For example, using a different set of stimulation parameters that included 400 μA of stimulating current and 400-ms stimulation trains, Tehovnik and Lee (1993) elicited saccades from an area ~50 mm2. They report saccadic “termination zones” that were contralateral when rostral sites were stimulated and straight-ahead or ipsilateral when caudal sites were stimulated. Given their stimulation parameters and absence of eye movement records, it is unclear whether just one saccade or multiple saccades was made. Regardless, it is possible that the low-threshold SEF studied in the present paper corresponds to (or at least lies within) the rostral area of Tehovnik and Lee (1993); however, as shown in Russo and Bruce (1993), saccades elicited from the low-threshold SEF are best characterized as a vectors rather than contralateral “termination zones.”

Topographic organization of SEF

The primate SC presents an exquisite topographic mapping of the contralateral visual hemifield in its superficial laminae with an isomorphic mapping of saccades across its intermediate layers (Robinson 1972). In FEF, saccade size is topographically organized with large saccades represented dorsally and small saccades represented ventrally and in the depths of the arcuate sulcus (Bruce et al. 1985; Robinson and Fuchs 1969). The representation of saccade direction is more complex, however, with small shifts in saccade direction accompanied by small advances of an electrode down the anterior bank of the arcuate sulcus and multiple representations of direction across FEF (Bruce et al. 1985). In contrast, Schlag and Schlag-Rey (1987) characterized SEF as having no topographic organization but instead appeared to be “patchy,” and no subsequent report has demonstrated topographic mapping in SEF to the contrary.

Our data elaborate on the patchy organization of SEF initially described by Schlag and Schlag-Rey (1987). Clearly SEF has a columnar organization with respect to polar direction. For both presaccadic activity and electrically elicited saccades, polar direction, which was readily quantifiable, generally remained constant on a given electrode penetration from the cortical surface down to the white matter. Of course, some neurons in the column did not have a presaccadic response. However, such a finding does not detract from a columnar organization, in the same way that neurons in layer 4 of striate cortex with concentric receptive fields and no orientation tuning do not disprove a columnar organization of striate cortex with respect to orientation. We could not examine the columnar organization of SEF with respect to response-field eccentricity because independent measures of response-field eccentricity were seldom obtained at different recording sites in a single-electrode penetration.

Interestingly, microstimulation was equally effective at eliciting saccades in SEF regardless of the type of presaccadic activity (visual or movement) recorded at the stimulation site. This finding contrasts with FEF, where the lowest thresholds were found at sites of neurons with movement activity (Bruce et al. 1985). We are not sure why SEF did not exhibit this property. Perhaps the slightly higher currents generally used in the present study stimulate a greater volume of cortical tissue, reducing the importance of exactly where the microelectrode tip resided. This explanation is consistent with our finding that visual, visuomovement, and movement SEF neurons did have significantly different cortical depth distributions, perhaps because single-neuron recording has a much finer spatial resolution than electrical stimulation.

Polar direction was organized across the SEF tangential dimensions as well, but not simply. When the topography of saccade direction in each SEF was analyzed, we found zones where direction changed in a fairly monotonic manner for a few millimeters. These progressions were statistically significant despite the presence of some large discrepancies (which could reflect small differences in the electrode’s actual cortical entry point between experimental sessions). However, these sequences did not encompass the entire SEF. Instead our data seemed more indicative of a hypercolumnar or cyclical orga-

2 However, Sommer and Tehovnik (1999) found that reversible inactivation of macaque “dorsomedial frontal cortex” had much smaller effects on oculomotor performance than similar inactivation in FEF.
orization of polar direction with multiple representations for some or all directions, similar to how saccades seem to be represented in FEF. Resolving this issue will be challenging because the low-threshold SEF is so small, and its location makes electrode penetrations parallel to the cortical surface difficult.

We did not find any systematic changes in either the optimal eccentricity of neural response fields or the amplitude of electrically elicited saccades. However, the same difficulties in studying the topographic organization of saccade direction applied to sac-

We did not find any systematic changes in either the optimal eccentricity of neural response fields or the amplitude of electrically elicited saccades. However, the same difficulties in studying the topographic organization of saccade direction applied to saccade amplitude as well. Furthermore, the range of saccade size represented in SEF seems more constricted than in FEF. In the present study, the size of saccades elicited from SEF ranged from 1.8 to 26.9°, with 78% of the SEF sites between 5 and 20°. In contrast, Bruce et al. (1985) found that the size of FEF elicited saccades ranged from <1 to >30°, and Fig. 2 of MacAvoy et al. (1991) shows that such extremely large and extremely small elicited saccades can be obtained on a single-electrode penetration through FEF. Such a difference would not be too surprising given the small size of SEF (<10 mm²) compared with FEF (~100 mm²). Another possibility, however, is that saccade size is coded in part by the duration of presaccadic bursts. More research is needed to resolve these issues.

**Does SEF have a unique role in saccade generation?**

The present study finds that SEF, FEF, and SC use similar neural mechanisms for generating saccadic eye movements. The existence of multiple oculomotor areas, however, suggests that each structure evolved to solve specific problems in ocu-
omotor control. As a result, several functional specializations for SEF have been proposed. For example, Schlag and Schlag-Rey (1987) observed that some SEF stimulation sites yielded elicited saccades that appeared to converge toward a particular orbital position when evoked from different initial eye posi-
tions, and they hypothesized that SEF codes saccades in a cranio-orbital coordinate system. However, a quantitative analysis and comparison of saccades elicited from both SEF and FEF using the same methods in the same monkeys showed that the average convergence of saccades elicited with SEF stimulation was modest and did not significantly differ in this regard from saccades elicited with FEF stimulation (Russo and Bruce 1993). Furthermore, SEF response-field mapping from multiple eye positions showed that overall SEF neural activity coded saccades as ocular or orbital displacements relative to the current point of fixation (Russo and Bruce 1996) similar to the FEF, SC, parietal eye field in the intraparietal sulcus and the saccade generator circuitry in the reticular formation of the midbrain and pons. Although a cranio-orbital representation of saccades may seem an adaptive proficiency in some situations, it may be more critical for the network of interconnected saccade structures to converge using the same neural code. In fact, the current study indicates that the basic functional activity in the SEF is remarkably similar to SC and FEF.

More recently other specializations of SEF have been proposed. Olson and Gettner (1995) reported SEF neurons with "object-centered direction selectivity". Chen and Wise (1995a,b, 1996, 1997) reported that SEF neurons are most active during conditional oculomotor learning and that some SEF neurons change their optimal direction within the context of a conditional oculomotor learning task. A special role in learning has also been described to the larger dorsomedial frontal cortex region by others (e.g., Mann et al. 1988). It has also been hypothesized that SEF has a special role in generat-
ing internally guided as opposed to sensory-guided saccades. For example, there is evidence in humans that SEF is special-
ized for programming sequences of saccades (Gaymard et al. 1990; Müri et al. 1995) and for controlling saccades made during head or body movements (Pierrot-Deseilligny et al. 1993). Schlag-Rey et al. (1997) found that SEF neurons respon-
ded especially vigorously for antisaccades.3

These hypotheses suggest that the efferent output of SEF is relatively independent of its visual inputs. The close alignment between visual and movement response fields of SEF visual-movement neurons demonstrated in the present report seems contrary to this idea; however, the neural activity used to construct visual and movement response fields was clearly generated independently. Thus their alignment may merely reflect the default option of simple visually targeted saccades. Whether or not the alignment of visual and movement response fields are altered during performance of tasks where the visual stimuli instructing saccades and the saccades themselves are dissociated (e.g., anti-saccades or learned-saccades) or whether cortical connectivity between visually responsive and movement-related neurons is modified without actually shifting response fields is unclear. Obviously such an experiment would necessitate careful measurement of response fields in experimen-
tal and control (visually guided) conditions.

Another line of study is suggested by the idea that the evolution and functional specializations of multiple oculomo-
tor areas is dictated by the functional specializations of the different skeletal-motor regions lying adjacent to it (Bruce 1990). Skeletal movements are orders of magnitude more complex than saccadic eye movements, and there are now known to be several somatic movement fields located in the frontal and parietal lobe (reviewed in Kalaska et al. 1997). SEF may have evolved because the medial skeletal-motor areas were too distant from FEF. Another possibility is that SEF is primarily concerned with only medium-sized eye movements that are made in conjunction with forelimb movements and not fine eye movements concerned with intensive visual analysis nor large eye movements in response to visual and auditory targets in the far periphery. Such a supplementary function may be reflected in the relatively small size of SEF. Understand-
ing the nature of SEF response fields and their exact relationship to the eye movements generated by their outputs will facilitate the design and interpretation of studies concern-
ing these and other functions of SEF.

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3 Furthermore SEF function may not solely concern saccades. Mushiake et al. (1996) and Bon and Lucchetti (1991) suggest that SEF may be specialized for combined arm-eye movements, and there are reports of SEF neural activity in conjunction with smooth pursuit eye movements (Heinen and Liu 1997) and smooth eye movements elicited with electrical stimulation of SEF (Tian and Lynch 1995).
REFERENCES


