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Neuronal Activity Related to Visually Guided Saccadic Eye Movements in the Supplementary Motor Area of Rhesus Monkeys

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SUMMARY AND CONCLUSIONS

1. The purpose of this study was to describe the response properties of neurons in the supplementary motor area (SMA), including the supplementary eye fields (SEF) of three rhesus monkeys (*Macaca mulatta*) performing visually guided eye and forelimb movements. Seven hundred thirty single units were recorded in the dorsomedial agranular cortex while monkeys performed a go/no-go visual tracking task. The unit activity associated with rewarded, task-related movements was compared with that associated with unrewarded, spontaneous movements executed in the intertrial interval or when the task was not running. A number of neuronal response types were identified.

2. Sensory cells were characterized by their response to the visual and/or auditory target stimuli combined with no discharge associated with eye or forelimb movements. New information was provided about the receptive fields of the visual cells; they varied in size and, although many included the ipsilateral hemifield, they tended to emphasize the contralateral. A significant proportion of the visually responsive cells had receptive fields restricted to within 8° of the fovea. The response latency was relatively long (>90 ms) and variable.

3. Preparatory set cells were activated from the appearance of the target until the presentation of the go/no-go cue. This subpopulation ceased firing 50–100 ms before the movement was initiated. These cells tended to respond best in relation to contralateral movements. The response latency was similar to that of the sensory cells, although some of these units began to discharge in anticipation of predictable target presentations. These neurons were not active before unrewarded, spontaneous saccades.

4. Sensory-movement cells comprised the largest population of neurons identified in SMA. They were active from the appearance of the target until after the execution of the saccade. These neurons tended to respond preferentially in association with contraversive saccades. The latency of response to the target was significantly longer than that of the sensory cells. There was a large amount of variability in the time to reach the peak level of activation, and this population of units generally became inactivated shortly after the saccade was initiated. Although there were counterexamples, most sensory-movement cells responded equally in association with visually and auditory guided movements. In addition, these neurons were not active in relation to self-generated eye movements made during the intertrial intervals.

5. Pause-rebound cells were identified by their suppression at the appearance of the target and subsequent discharge associated with the saccade. These units tended to respond preferentially to contralateral targets. Although the onset of the suppression tended to be of sufficiently short latency to be considered anticipatory, the onset of the saccade-related burst did not occur until shortly before the eye movement was initiated.

6. Presaccadic movement neurons were identified by an absence of any modulation associated with the targets combined with a discharge beginning as much as 300 ms before and decaying after the saccade was initiated. Many of these units were omnidirectional, but those that responded preferentially in relation to saccades in one direction usually preferred contraversive eye movements. Furthermore, these neurons were activated only for the task-related saccades and not for spontaneous saccades.

7. Postsaccadic movement cells were recorded infrequently. Detailed analysis of their properties was, therefore, not possible.

8. Eye position cells were characterized by a statistically significant orbital dependence to their modulation. Such units discharged before saccades of different directions and amplitudes that brought the eye to a broadly specified orbital position. These neurons were also active in relation to pursuit eye movements that ended in the particular position. In addition, once the eyes were at the specific angle of gaze, these neurons exhibited a sustained discharge that ceased before any eye movement away from that position.

9. Forelimb movement cells discharged before and during the reaching movements. Even though each of the three monkeys used his right arm to perform the task, these neurons were identified in both hemispheres. The forelimb movement cells typically responded preferentially for movements in one direction. Although a small number of these neurons were studied, the distribution of the preferred directions of movement was different for the units recorded in the left and right hemispheres.

10. No-go–specific neurons were modulated specifically when the monkeys withheld movements in no-go trials. These units tended to be activated in association with not moving into the contralateral hemifield. The response latency of these units was significantly longer than that of the sensory cells.

11. A rough somatotopic arrangement was evident in SMA. Eye movement–related cells tended to be found rostral to forelimb movement–related cells. Units that were active during mouth movements were encountered in between the eye and forelimb regions. The sensory and preparatory set cells appeared to be distributed over the entire region explored.

12. These data provide new information about the involvement of the SMA and its constituent SEF in gaze control. On the basis of the different neuron classes that were identified, it appears that SEF/SMA provides a variety of signals for use in the sensorimotor integration that underlies volitional skeletal and oculomotor movements.

INTRODUCTION

Since the original investigations by Ferrier (1875), it has been recognized that frontal cortex participates in gaze control. During voluntary, conjugate eye movements two loci of elevated blood flow can be distinguished in frontal cortex (Fox et al. 1985; Melamed and Larsen 1979; Orgogozo and Larsen 1979). The lateral locus corresponds to the frontal eye fields (FEF), and the dorsomedial locus corresponds to the rostral end of the supplementary motor area (SMA). Over the years, numerous investigators have demonstrated

the role of the prearcuate FEF in generating saccades in macaque monkeys (reviewed by Bruce 1990; Goldberg and Segraves 1989; Schall 1991a). Evidence that another region of frontal cortex is involved in the generation of conjugate eye movements comes from the original investigations of SMA in humans by Penfield and Welch (1949, 1951) and in monkeys by Woolsey et al. (1952), who described a representation of the eye therein. Furthermore, Brinkman and Porter (1979) and more recently Schlag and Schlag-Rey (1987) described neurons in rostral SMA that were modulated in relation to eye movements. Furthermore, a number of investigators have demonstrated that low-intensity microstimulation of rostral SMA elicits conjugate eye movements (Gould et al. 1986; Mann et al. 1988; Mitz and Godschalk 1989; Schlag and Schlag-Rey 1987). These results indicate that it is useful and appropriate to define rostral SMA as the supplementary eye field (SEF).

The purpose of this study was to obtain more information about the role SMA plays in the generation of sensory-guided movements. This was accomplished by recording single-unit activity in SMA of rhesus monkeys performing a go/no-go visual or manual tracking task. By training the monkeys to withhold their response until given a cue, the task was designed to dissociate the processing involved in identifying the target, planning the movement, initiating or withholding the movement, and executing the movement. It was hoped that this operational dissociation would reveal different groups of neurons responsible for each phase of generating a movement. In addition, by providing a clearly separated task period and intertrial interval, this paradigm provides a test of the recent claim that saccade-related cells in SEF, in contrast to those in FEF, discharge before "spontaneous" saccades (Schlag and Schlag-Rey 1987). Finally, the data obtained from SEF/SMA will be compared directly with similar data recorded in the FEF of the same monkeys in the accompanying paper (Schall 1991b).

Having quite limited information with which to make any predictions of differences between SEF and FEF, my strategy in this investigation was to quantify the spatial and temporal response properties of the units as much as possible. Such quantification provides a basis for comparison between the two cortical regions. In addition, these numbers are necessary for understanding how the activation of these areas leads to the generation of a saccade. Specifically, a detailed description of the temporal patterns of activation and inactivation of the various cell classes will be necessary for understanding the neural basis of saccade latency (Carpenter 1981; Reulen 1984). Finally, sufficient quantification must precede attempts to incorporate these areas into existing models of the oculomotor system (reviewed by van Gisbergen and van Opstal 1989).

A preliminary report of some of these data has appeared (Schall et al. 1987).

METHODS

Subjects

Three juvenile male rhesus monkeys (*Macaca mulatta*) provided the data for this investigation. They will be referred to as *A*, *M*, and *Q*, which is the order in which they were used. The animals were cared for in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals and the guidelines of the Massachusetts Institute of Technology Committee on Animal Care.

Task

By the use of operant conditioning techniques, the monkeys were trained to perform a go/no-go visual tracking task. The monkeys were water deprived in their home cage and were rewarded with apple juice. The animals' fluid intake was closely monitored; if on any day they did not perform the task until satiated, supplemental fluid was given.

The monkey faced a tangent screen in which five light-emitting diodes (LED) were embedded (Fig. 1). The targets for movement were positioned in one of two arrangements: *1*) 15° to either side and 8° above and below a central fixation spot or *2*) on the corners of a 15° horizontal by 8° vertical rectangle centered on the fixation spot. A trial began when the central LED (fixation spot) appeared; initially it was yellow. The monkey was required to fixate the central LED for a specified interval (200–500 ms), after which one of the peripheral stimuli appeared. After the target appeared, the monkey was required to maintain fixation of the central LED for a variable interval (0–1,200 ms), after which the fixation spot changed color. If the fixation spot turned green, the monkey was required to make a saccade to the target (go trial). If the central spot turned red, the monkey was required to continue fixating the central spot for a specified interval (500–1,000 ms) (no-go trial). For *monkey Q* two speakers were also mounted on either side to provide auditory targets (broad-band noise). The task was otherwise the same.

Surgery

All surgical procedures were accomplished with the animal under barbiturate anesthesia (pentobarbital sodium, 30 mg/kg) and with the use of sterile techniques. Initially, a scleral search coil was implanted subconjunctivally and a stainless steel post to restrain the head was attached to the skull with acrylic cement. Once the task was mastered to a criterion of 90% correct, a recording chamber was implanted over a midline craniotomy that exposed SMA.

Data collection

The entire experiment was under the control of a computer (PDP 11/34), which presented the stimuli, collected the eye move-

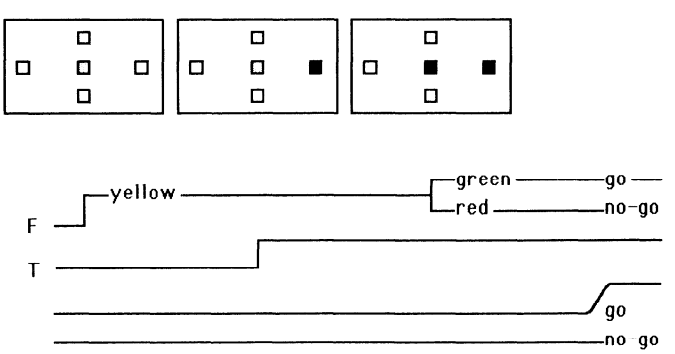

FIG. 1. Go/no-go visual tracking task. *Top*: arrangement and state of the stimuli at different stages of a trial. *Middle*: traces of the central fixation spot (F) and the target (T). *Bottom*: diagrams of eye position traces for the go and no-go trial types. Each trial began when the central spot turned on; initially it was yellow. After a specified interval 1 of the peripheral targets appeared. After a variable interval the central spot changed color to either green or red. If it turned green, the monkey was required to generate a saccade to fixate the target. If it turned red, the monkey was required to continue fixating the central spot.

ments and single-unit activity, and delivered the juice reward. Eye movements were monitored with a scleral search coil (Robinson 1963). Eye position was sampled at 200 Hz. The primate chair included a panel that could be raised to allow forelimb movements. When the panel was raised, the monkeys had learned to perform the same task by touching the appropriate targets. Touches were registered by the use of an infrared scanning device (General Digital), which was sampled at 100 Hz. Electromyographs (EMGs) were not recorded. Single units were recorded by the use of glass-coated platinum-iridium microelectrodes, which were introduced through the dura with a hydraulic microdrive. The action potentials were amplified, filtered, and discriminated conventionally and sampled at 1 kHz. Single units were admitted to the data base according to these criteria: the amplitude of the action potential was sufficiently above background to reliably trigger the window discriminator, the action potential waveshape was invariant, and the isolation could be sustained for a sufficient period to test.

Data analysis

Saccades were detected by the use of an algorithm that searched for significantly elevated velocity. Saccade initiation and termination were defined as the beginning and end of the monotonic change in eye position. Forelimb movements were detected by comparing the coordinates from the infrared scanning device with electronic windows positioned around each target. The onset of movement was defined as the moment when the monkey moved out of the window surrounding the central fixation spot.

Only successful trials were used for the data analysis. Perievent time histograms and rasters were constructed, aligned on the various events of the task. Neuronal modulation was defined by detecting changes in the slope of the cumulative sum of spikes (Falzett et al. 1985). The initiation and termination of modulation (either activation or suppression) were defined by the times at which the inflections in the cumulative sum of spikes occurred. The magnitude of response was given by average discharge rate during the period of modulation.

Because the targets consisted of four immovable LEDs, it was not possible to effectively map the receptive and movement fields of the neurons. Nevertheless, it was possible to quantify the variation in response with target direction. The directional specificity of the neurons was determined by vector summation of the response to each target (Batschelet 1981). The angle of the resultant vector gave the preferred response direction of the cell. Directions ipsilateral to the hemisphere in which a unit was recorded were signified by 0°; contralateral, by 180°. The normalized length of the resultant vector, which could range from 0 to 1, was defined as the response direction bias. A direction bias of 0 indicates equal response for all directions.

As mentioned, for *monkey Q* two speakers were mounted on either side to provide acoustic targets for movements. Thus the responses of cells to the auditory and visual stimuli were compared. A measure of the modality specificity was provided by the following response contrast ratio: (visual response − auditory response)/(visual response + auditory response). This contrast ratio could range from +1, signifying a response only to the visual stimulus, to −1, for a pure auditory response.

A variety of statistical tests were employed as required by the data. I used t tests to determine whether populations of cells differed with respect to specific measures such as response latency. Other statistical tests have been devised to analyze distributions of angles (Batschelet 1981). The V test determines whether a distribution of angles differs significantly from random; a significant test statistic, denoted u, indicates that the distribution is clustered about a given expected value.

Histology

After several months of recording, *monkeys A* and *M* were killed with a lethal overdose of pentobarbital and perfused through the heart with saline followed by buffered 4% paraformaldehyde. Guide pins were inserted with the hydraulic drive into the cortex at specific positions around the recording chamber. The brain was photographed and cut in either the coronal or sagittal plane on a freezing microtome into 50-μm sections that were stained with cresyl violet. Because individual electrode tracks could not be localized, the approximate location of the penetrations was estimated relative to the pins by the use of the original penetration coordinates, correcting for tissue shrinkage. *Monkey Q* has been used in an anatomic tract-tracing experiment, which has been described in preliminary fashion (Parthasarathy et al. 1990).

RESULTS

The location of the recording chamber in *monkey A* is shown in Fig. 2. In *monkey A* the recording chamber was centered at Horsley-Clark coordinate AP25, in *monkey M* at AP28, and in *monkey Q* at AP24. Figure 2 also illustrates the location of the electrode penetrations in one hemisphere. The giant layer 5 pyramidal cells observed caudally indicated the border of primary motor cortex (see Wise and Tanji 1981). A granular layer 4 that gradually became evident rostrally indicated the rostral border of area 6 (Walker 1940). Thus the penetrations were located in the dorsomedial agranular SMA.

A total of 170 penetrations into SMA yielded a total of 733 isolated single units, of which 542 exhibited activity modulated in relation to some element of the task. The cells could be separated into various groups on the basis of the nature and period of modulation in relation to the different events of the task. The number of cells identified in each class is given in Table 1. It is apparent that there was considerable variation between monkeys in the proportions of the different cell types observed. Besides general individual differences, this variation can be attributed to at least two other experimental factors. First, as indicated by the position of the recording chambers, slightly different regions of SMA were explored in each monkey. Second, the task evolved as the recordings progressed. The forelimb movement task was added while recording from *monkey A*, and the go/no-go discrimination was added while recording from *monkey M*.

Sensory cells

One population of SMA cells was identified by their specific response to visual or auditory stimuli. Examples of visually responsive neurons are shown in Fig. 3. Some neurons discharged when the fixation spot appeared (Fig. 3*A*). Because the monkeys fixated the central spot in anticipation of the upcoming trial, such activity indicates that the cell has a foveal receptive field. Most of these neurons also discharged when the central spot changed color, giving the go/no-go cue. In addition, many of the sensory cells with foveal receptive fields responded after the target was fixated by the saccade. Some sensory neurons exhibited a phasic suppression of activity after the onset of the stimulus (Fig. 3*B*). Other units responded to the peripheral targets (Fig. 3*C*); these were interpreted as sensory neurons having peripheral receptive fields. Unfortunately, the visual stimuli

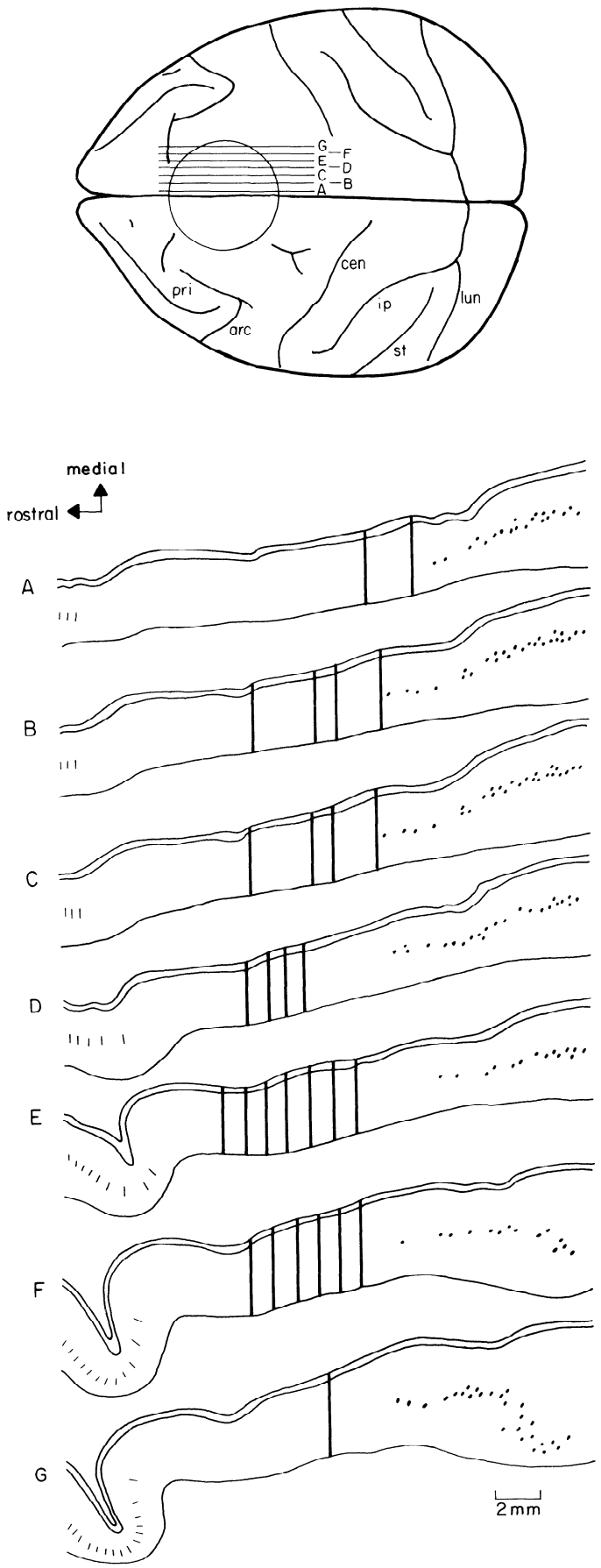

TABLE 1. *Cell types recorded in SMA*

Cell Type	Monkey *A*	Monkey *M*	Monkey *Q*	Total	%
Sensory	5	37	23	65	16
Preparatory set	9	22	17	48	12
Sensory movement	27	47	41	115	28
Pause-rebound	1	9	8	18	4
Presaccadic	34	25	12	71	17
Postsaccadic	6	0	3	9	2
Eye position			3	3	<1
Oral movement	9	7	11	27	7
Forelimb movement	8	5	29	42	10
No-go–specific		3	4	7	1
Suppressed through trial	6	4	17	27	
Modulated but unclear	43	28	39	110	
Unmodulated/inactive	12	3	176	191	

Sensory cells responded to the visual and/or auditory stimuli. Preparatory set cells discharged from the presentation of the appearance of the target until the cue to execute or withhold the movement. Sensory-movement cells discharged from the appearance of the target until the execution of the saccade. Pause-rebound cells were suppressed at the appearance of the target and discharged at the saccade. Presaccadic cells burst before and during saccades. Postsaccadic cells discharged after saccades had been initiated. Eye position cells were modulated by the position of the eye in the orbit. Oral movement cells were active in relation to mouth movements during the juice reward. Forelimb movement cells were active in relation to forelimb reaching movements. No-go–specific cells discharged only after the no-go cue. Suppressed cells exhibited reduced activity throughout a trial but could not be further characterized. Modulated but unclear cells exhibited some apparent modulation, but insufficient data were collected to analyze them further. Unmodulated/inactive cells showed no modulation or discharge during any trial. SMA, supplementary motor area. Percentages represent values of task-specific modulated neurons.

used for the targets could not be moved; consequently, it was not possible to map the receptive fields of these neurons in sufficient detail. Another notable feature of the visual units in SMA is the extreme variability in their response. For many such neurons, the response was robust in some trials, but in others there was no response at all. It must be admitted outright that, because the stimuli were immovable LEDs, it was not possible to determine what degree of this variability was due to not having a stimulus in the most sensitive part of the receptive field.

These illustrated units represent the extreme examples of sensory cells with responses restricted to either the central spot, which was already fixated, or to the peripheral targets. The population of sensory cells was distributed between these extremes, however. For the purposes of this analysis, neurons that exhibited any response to the fixation spot were classified as possessing foveal receptive fields, and the remaining cells were classified as exhibiting peripheral receptive fields.

FIG. 2. Location of recordings in *monkey A. Top*: a dorsal view of the brain illustrating the location of the recording chamber; the principal (pri), arcuate (arc), central (cen), intraparietal (ip), superior temporal (st), and lunate (lun) sulci are labeled. Labeled lines through the right hemisphere indicate the levels at which the corresponding parasagittal sections (*bottom*) were drawn. Giant layer 5 pyramidal cells in primary motor cortex are indicated by solid spots. Short vertical lines show the position of the rostral granular layer. Long vertical lines indicate the location of individual microelectrode penetrations. In this monkey, as in the other 2, the penetrations were restricted to the dorsomedial agranular frontal cortex, which corresponds to SMA.

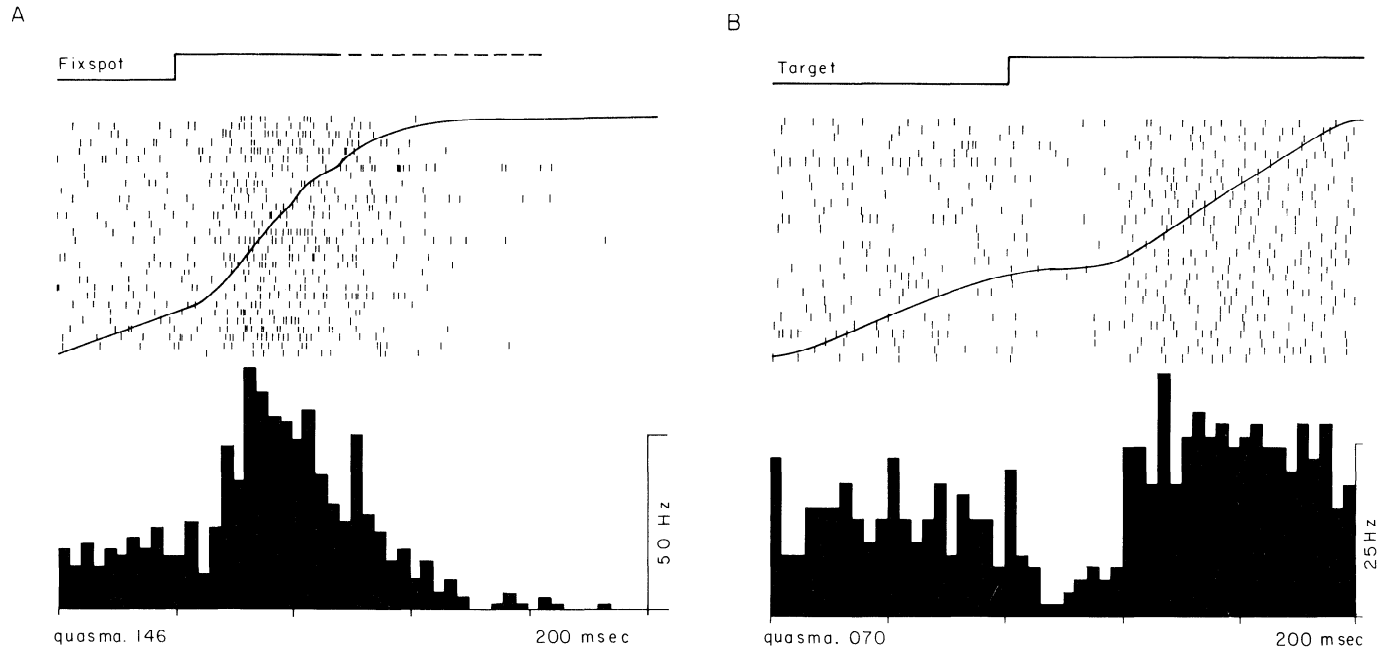

FIG. 3. Sensory neurons. *A*: visually responsive cell with a foveal receptive field. Trace of the central fixation spot is shown on *Top*. In all of the illustrated trials, the monkey was fixating the central LED when it was illuminated. *Middle*: a raster display of neuronal activity, including the cumulative sum of the spikes. Change in neuronal activity is revealed by the change in slope of the cumulative sum of spikes. *Bottom*: poststimulus time histogram. Rasters and histogram are aligned on the onset of the central spot. This cell responded to the fixated LED but not to the peripheral target LEDs. *B*: sensory cell with suppressed activity. Rasters and histogram are aligned on the presentation of the target. *C*: visually responsive cell with peripheral receptive field. Each raster represents the activity of the cell after the onset of the visual target in 1 of the 4 different positions. Trace of the target and arrangement of the stimuli are drawn above each raster. This unit did not respond when the fixated central LED appeared. Receptive field of this cell is restricted to the left hemifield; this cell was recorded in the right hemisphere.

Out of 65 sensory cells recorded, 47 units included the fovea in their receptive field, and 19 had peripheral receptive fields. Sixty-three of the cells exhibited elevated activity after target appearance, and only 2 cells were suppressed. Sufficient data were collected from many of these cells to allow various quantitative analyses. For 51 cells the variation in the response as a function of the direction of the target was calculated; the response direction biases of these cells are illustrated in Fig. 4*A*. Not surprisingly, sensory cells with peripheral receptive fields tended to be more biased than those with foveal receptive fields. For example, the foveal sensory cell illustrated in Fig. 3*A* had a direction bias of 0.13, whereas the peripheral sensory cell illustrated in Fig. 3*C* had a direction bias of 0.79. Whereas 53% of the cells that had peripheral receptive fields exhibited a direction bias >0.2, only 17% of the cells with foveal receptive fields were so biased. The mean ± SE response direction bias for cells with peripheral receptive fields was 0.32 ± 0.06 and for cells with foveal receptive fields was 0.12 ± 0.02. The fact that some of the neurons with receptive fields that included the fovea exhibited a degree of response direction bias can be interpreted to indicate that the receptive fields of these units extended across the visual field while being more sensitive in one quadrant.

The preferred target direction was determined for those sensory cells that exhibited a response direction bias >0.2 (Fig. 4*B*). Although neurons were encountered that responded for all target directions, there was a significant tendency for sensory cells to respond best to contralateral stimuli (mean angle = 175°; *V* test $u = 3.11$, df = 23, $P < 0.001$). To summarize, the results of this spatial analysis indicate that the receptive fields of visual neurons in SMA range in size, some restricted to within the central 8° and others extending ≥15° from the fovea. The peripheral receptive fields may extend into the ipsilateral hemifield but tend to emphasize the contralateral hemifield.

The temporal parameters of the sensory cell responses were also analyzed. Figure 4*C* shows the distribution of the response latencies for 58 sensory neurons. Four of these units became active before the target actually appeared, although this anticipatory activity was not as robust as what was observed in the other neurons classes that responded to the target (see below). The average response latency was 92 + 4 ms. The distribution of the delay from the time of response onset to the time of peak activation is illustrated in Fig. 4*D*; the mean rise time was 84 ± 6 ms. The distribution of times after target appearance at which the activity decayed is shown in Fig. 4*E*; the mean value was 275 ± 11 ms.

The contrasts in response to the visual and auditory stimuli for the sensory cells with foveal and peripheral receptive fields from *monkey Q* are shown in Fig. 4*F*. Those cells that responded to the peripheral stimuli but included the fovea in their receptive field tended to respond equally to the peripheral visual or auditory stimuli; the visual/auditory contrast ratio ranged from 0.02 to 0.36. Cells that spared the fovea tended to respond more selectively for either auditory or visual stimuli; the visual/auditory contrast ratio ranged from −0.20 to 0.53, with four of seven having a contrast ratio greater than or equal to ±0.20.

The spatial distribution of sensory cells in *monkeys M*

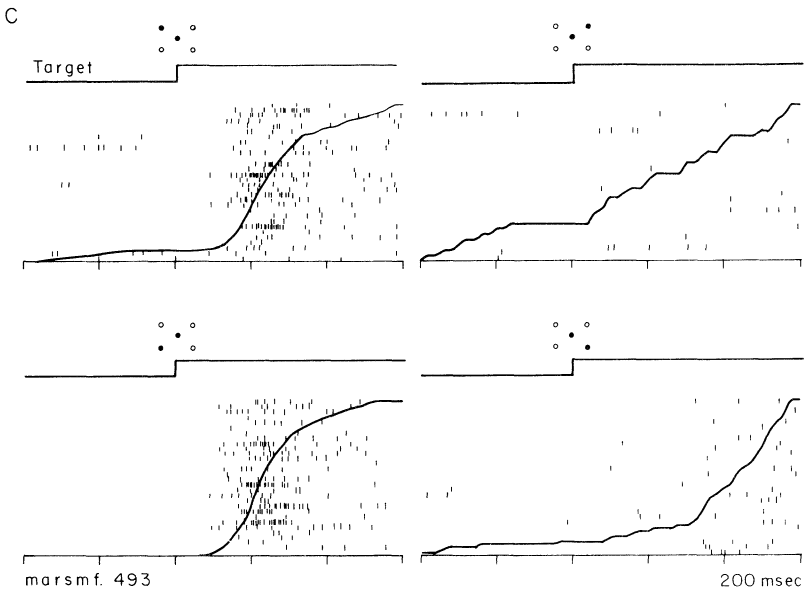

FIG. 3. (*continued*)

and *Q* is shown in Fig. 5, *A* and *B*. Sensory cells tended to be found throughout the region of SMA explored. There was no clear segregation or clustering of visual, bimodal, and auditory cells in *monkey Q*, nor was any topography evident for cells with foveal and peripheral receptive fields (not shown).

Preparatory set cells

Another population of neurons had more prolonged activity than the sensory cells; they became active after the presentation of the peripheral target and decayed after delivery of the go/no-go cue signaling the monkeys to execute or withhold the movement. These units were called preparatory set cells because they were specifically active during the period in which the monkey could prepare the movement (see Evarts et al. 1984; Kornblum and Requin 1984).

An example of a set cell is shown in Fig. 6. The rasters in the *left panels* of Fig. 6 represent the activity of the neuron while the monkey was performing the task using eye movements. The unit began to discharge after the target was presented, and the duration of the activity was correlated with the delay of the cue: the longer the delay, the more prolonged the activity. Figure 6, *B* and *C*, shows the relation-

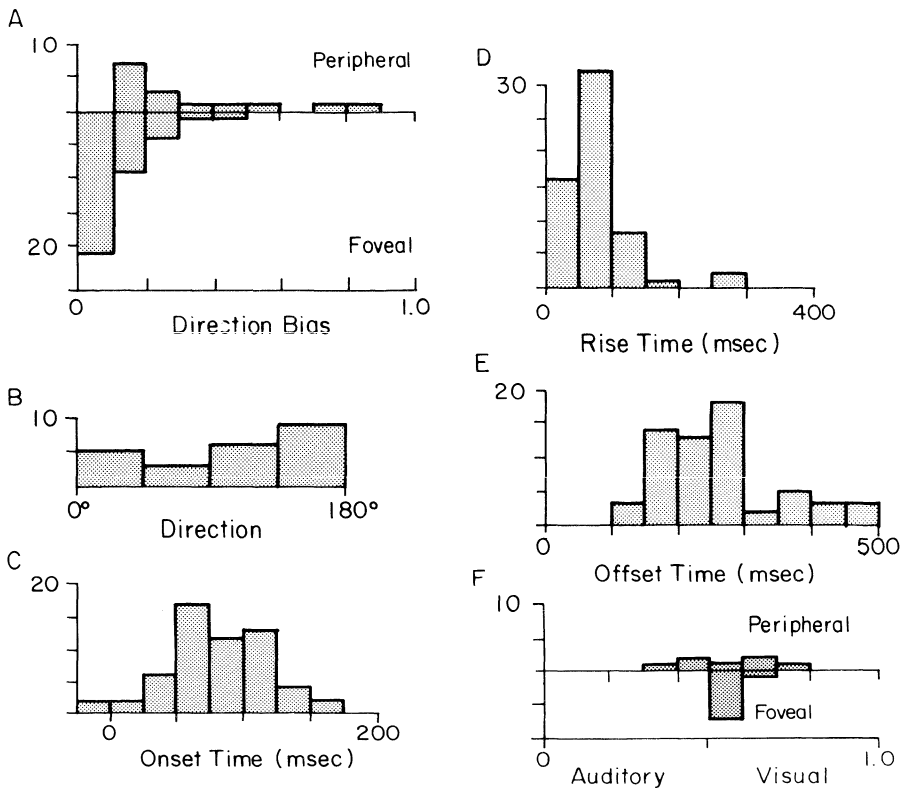

FIG. 4. Quantitative measures of sensory cell activity. *A*: distribution of direction biases, which measure the relative response to targets in each direction; values can range from 0 to 1, with 0 indicating equal response for all directions. Separate histograms for cells with foveal and peripheral receptive fields are shown. *B*: distribution of preferred directions. Ipsilateral is represented by 0° and contralateral by 180° in relation to the hemisphere in which the unit was recorded. *C*: distribution of onset times, defined as the time of the inflection in the cumulative sum of spikes measured after the target appeared. *D*: distribution of rise times, defined as the delay from the onset time until the peak of activity, i.e., largest slope of the cumulative sum. *E*: distribution of response termination times, defined as the moment of the final inflection in the cumulative sum relative to target onset. *F*: distribution of visual/auditory response contrast ratio, computed as the difference divided by the sum of the response to visual and auditory targets. Values can range from −1 for auditory to +1 for visual. Separate histograms are shown for cells with foveal and peripheral receptive fields. Results are described in the text.

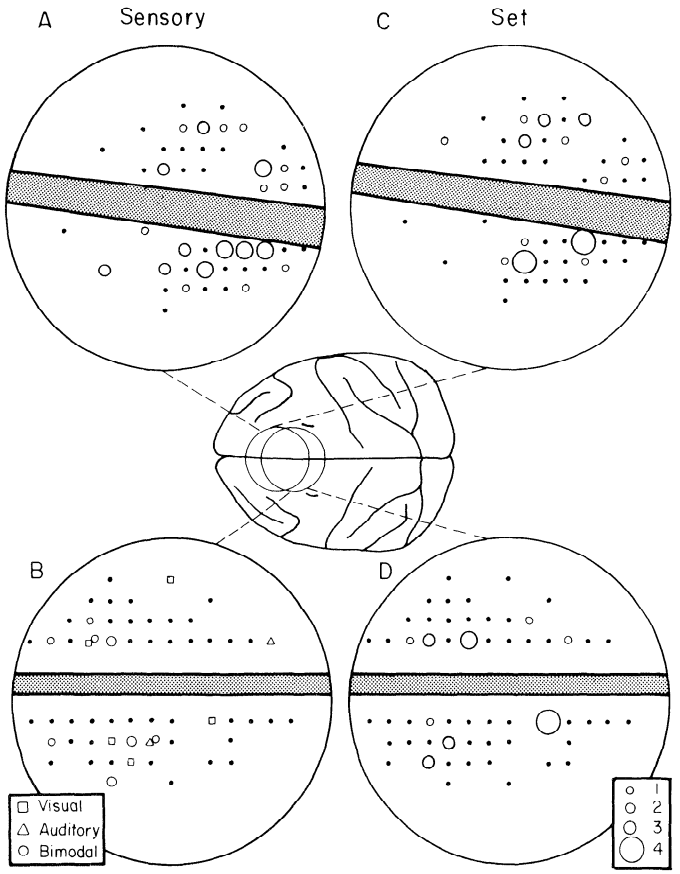

FIG. 5. Spatial distribution of sensory and set cells in *monkeys M* and *Q*. *A* and *B*: distribution of sensory cells; *C* and *D*: distribution of preparatory set cells. Penetrations were spaced in a 1-mm grid. *A* and *C*: distribution in *monkey M*, which had the rostrally positioned recording chamber shown on the dorsal view of the brain; *B* and *D*: distribution in *monkey Q*, which had the caudally positioned recording chamber. Solid points signify penetrations in which no sensory or set cells were encountered. Different symbols represent responses of different sensory components as shown in the legend. Size of the symbol represents the number of such cells encountered, as shown in the other legend. No clustering of either sensory or set cells was evident.

ship of the cessation of activity to the presentation of the cue and the execution of the saccade. As was characteristic of all of the preparatory set cells studied, in general this unit quit firing after the cue but before the saccade. It appears, however, that the termination of activity was more closely related to when the saccade was initiated than to when the cue to move was given. For example, this cell quit discharging before the cue on those few trials in which the monkey made anticipatory saccades.

The rasters on the *right side* of Fig. 6 represent the activity of the same cell recorded while the monkey was performing the task using forelimb movements. Fig. 6, *E–G*, indicates that the cessation of activity of this neuron is related to the saccade and not to the reaching movement. In contrast to what was observed during the eye movement task, however, there appeared to be a significant elevation of activity before the target appeared in the reaching task. As can be seen by the eye position traces, though, the monkey was making saccadic eye movements before presentation of the target; these gaze shifts were directed at the different possible target positions as the monkey anticipated where the next target for movement would be. In fact, on those trials in which the monkey happened to maintain fixation of the central LED, the unit did not begin to discharge until after the target was presented. Thus it seems as if this cell was activated in association with the scanning eye movements the monkey was making in anticipation of the upcoming trial. This pattern of results was observed in two other set cells.

This explanation, however, does not hold for certain other preparatory set cells that became active before the presentation of the target in both the eye movement and the forelimb movement tasks. For example, anticipatory activity was evident in five set cells during the eye movement task, in which the monkey was required to maintain fixation of the central spot until the cue to move was given. In another five set cells anticipatory activity became evident only when the delay between the presentation of the fixation spot and the onset of the target was prolonged such that the monkey could anticipate when the target would be presented.

A total of 48 preparatory set cells were recorded. The response direction biases of 44 of these cells are shown in Fig. 7*A*. It is evident that most of the cells exhibited a significant degree of directionality; the average response direction bias was 0.28 ± 0.03, and 48% exhibited a bias >0.2. These values were not significantly different from those of sensory cells with peripheral receptive fields. The preferred directions of the significantly biased set cells are shown in Fig. 7*B*. All directions were represented, but there was a significant tendency for these neurons to respond preferentially in relation to contraversive movements (mean angle = 133°, $u = 1.96$, df = 37, $P < 0.05$). The contralateral bias was no different from that of visual sensory cells.

The target response latency for all 48 set cells is shown in Fig. 7*C*. As discussed above, a number of cells consistently exhibited an elevation of activity before the presentation of the target. The average onset time for the remaining set cells was 106 ± 12 ms. The latency of preparatory set cells was not significantly different from that of sensory cells, but the variability in the onset times for set cells was greater than that of sensory cells. This result suggests that activation of preparatory set neurons is not determined entirely by the presentation of the target. In fact, I noticed that when the task was made more predictable and the animal's performance became more consistent, then the activity of most set cells became more uniform across trials.

The distribution of activation rise times is shown in Fig. 7*D*. This time measure was also relatively long and variable. The average value was 187 ± 12 ms, which was significantly longer than that of sensory cells ($t = 7.79$, df = 105, $P < 0.001$).

The distinguishing feature that defined preparatory set cells in this study was the time at which their activation was terminated, after the cue but before the movement. This observation is illustrated by comparing Fig. 7*E*, which shows the distribution of times that the set cell activity terminated relative to the cue for movement, with Fig. 7*F*, which shows the times of cessation relative to the initiation of the saccade. The average termination time relative to the cue was 137 ± 10 ms. It is important to note that in this task

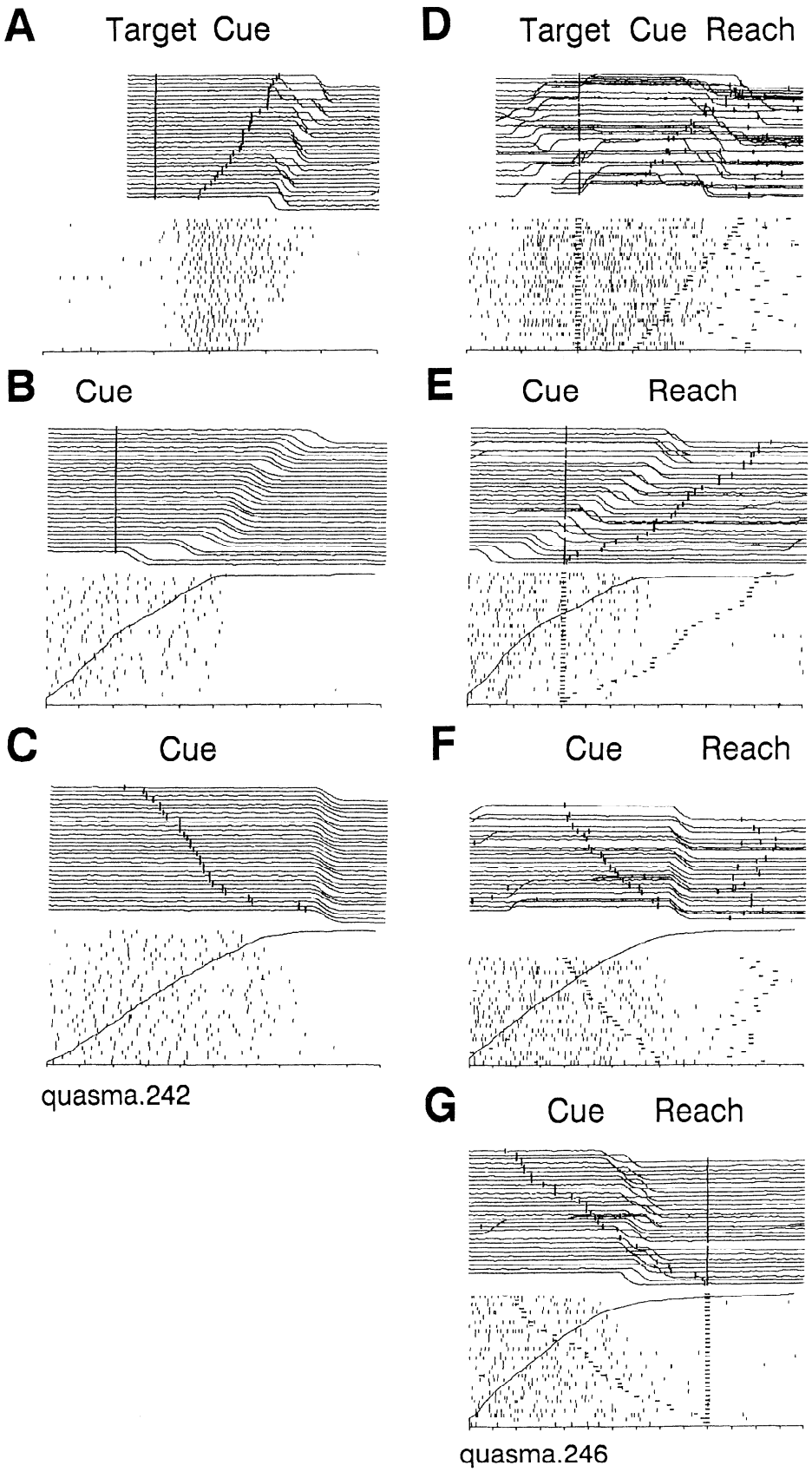

FIG. 6. Preparatory set cell. Each panel illustrates the horizontal eye position traces and raster display of action potentials. Trials were sorted according to the duration of either the target-cue delay or the reaction time. Vertical tick marks in the eye position traces represent the events as labeled. Each tick mark on the time scale in *A* and *D* represents 200 ms; the time scale for the remainder is 50 ms. *Left*: activity of this unit collected during the eye movement task; *right*: activity of the same neuron collected during the reaching task. Eye position traces and rasters in *A* and *D* are aligned on the time the target was presented; those in *B* and *E*, on the time the cue was given; those in *C* and *F*, on the time the saccade was executed; and those in *G*, on the time the reach was made. Note that this neuron began to discharge after the target was presented and ceased to fire after the cue to move was given but before the saccadic eye movement was initiated.

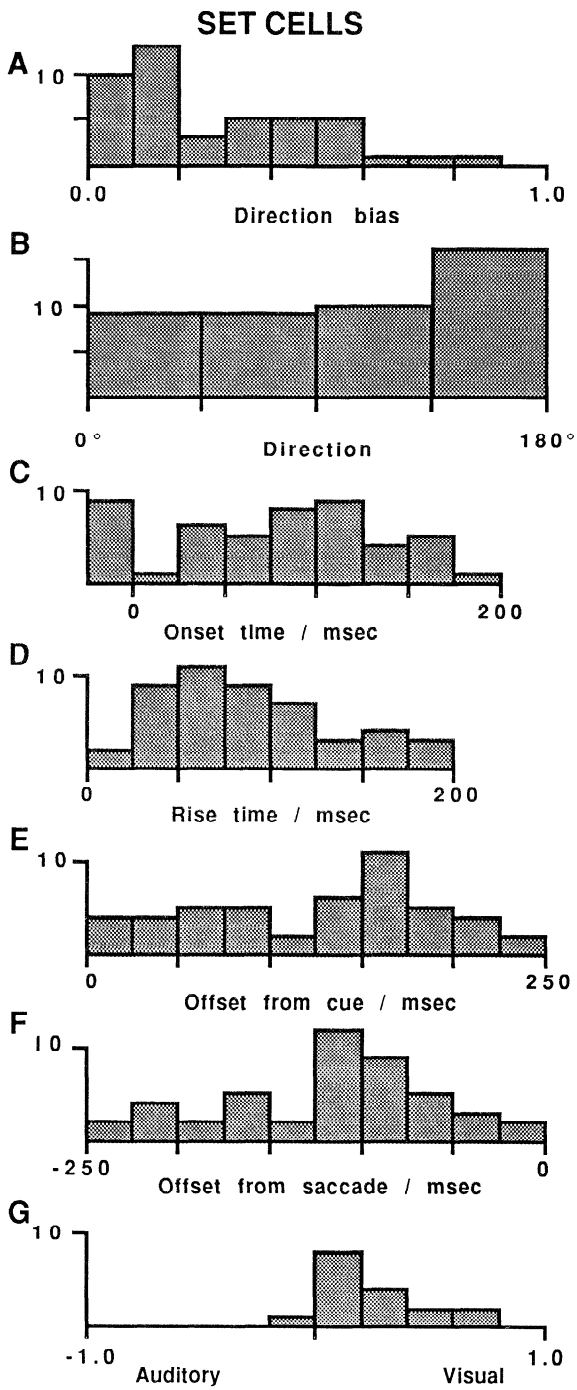

FIG. 7. Quantitative measures of preparatory set cells. *A*: direction biases. *B*: preferred direction. *C*: onset times. Cells with anticipatory activity are indicated by the bin <0. *D*: rise times. *E*: response termination time relative to the cue. *F*: response termination time relative to the saccade. *G*: visual/auditory response contrast ratio.

the typical saccade latencies ranged from 200 to 250 ms; thus the preparatory set cells, which began firing when the target was presented, quit firing before the target was extinguished or was moved off of the receptive field by a saccade. The average time relative to the saccade was -112 ± 9 ms. Comparing the distribution illustrated in Fig. 7*F* with that shown in Fig. 12*E* reveals the fundamental distinction between preparatory set cells and the sensory-movement cells described below. By the time that the saccade is launched, set cells have ceased firing.

During the delay period the monkey does not know whether he will be given the go cue to execute the movement or the no-go cue to withhold the movement. Once the cue is given, however, his response is dictated. Does the activity of set cells reflect the declaration of go versus no-go trials? In other words, is the activity of a set cell after the cue different when the cue results in a saccade versus when it does not? Figure 8 compares the response of a set cell during go and no-go trials. It is evident that the neuron quits firing ~100 ms after either the go or the no-go cue. In the entire population there were no differences between the time that the activity was terminated after the go cue in the eye movement task (147 ± 12 ms) or the forelimb movement task (127 ± 16 ms) and the termination time after the no-go cue in the eye movement task (142 ± 18 ms) or the forelimb movement task (181 ± 24 ms). Hence, preparatory set cells in SMA do not appear to behave differently in go and no-go trials, at least with respect to the time course of their activation.

Because set cells could exhibit anticipatory activity and ceased discharging before the target was removed from their receptive field, it was of interest to determine whether they required the actual presentation of the target to become active. Therefore, in selected blocks of no-go trials randomly interspersed in normal go and no-go trials, the target stimulus was not turned on. Even though the go/no-go distinction was compromised in these trials and no movement was ultimately required, the activity of the set cells tested remained essentially unchanged, as illustrated in Fig. 8. In the six preparatory set cells that provided sufficient data of this type, there was no change in the level of modulation between the many trials in which the target appeared and those few in which it did not. However, each of these particular neurons exhibited a significant degree of anticipatory activity in the normal go trials. Even so, these data further indicate that the response of at least these preparatory set cells is not stimulus bound but rather may reflect the temporal properties of the task that the overtrained monkeys have learned.

The contrast ratio of set neuron responses to visual and auditory stimuli is shown in Fig. 7*G*. The mean value (0.04 ± 0.055) was not significantly different from 0. Thus preparatory set cells in SMA were bimodal, responding equally to visual and auditory targets.

The spatial distribution of set cells in SMA of two monkeys is illustrated in Fig. 5, *C* and *D*. This population of neurons was found throughout the region of SMA explored. There was no obvious clustering or segregation, but the small number of units contributing to this analysis must make this result tentative.

Saccadic eye movements can be made under a variety of circumstances, ranging from those made in response to verbal commands (e.g., "Look right") to those made scanning some informative display (e.g., reading) to those made in a relaxed, absent-minded state. In the present experimental paradigm the monkeys made eye movements in at least two conditions, the first while performing the task and the second in the intertrial interval or when the task was not run-

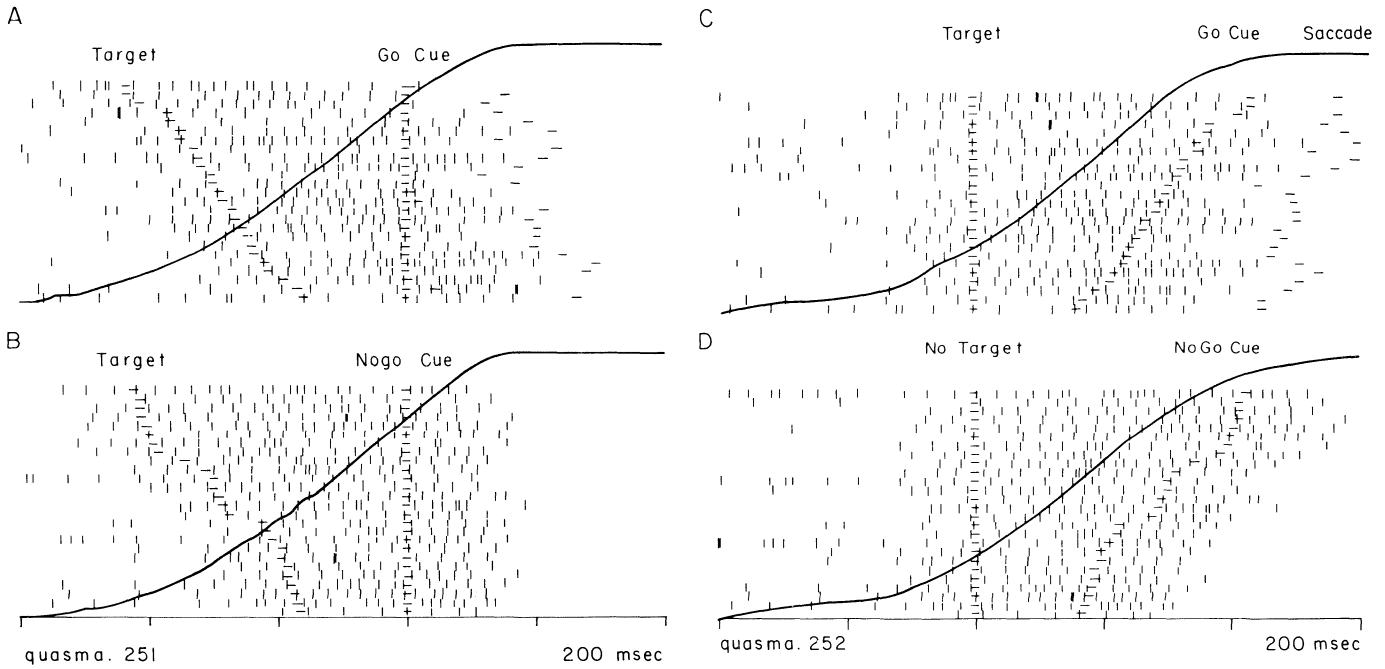

FIG. 8. Decay and onset of preparatory set cell activity. *A* and *B*: decay of activity of preparatory set cell after go cue (*A*) and no-go cue (*B*). The 1st horizontal tick mark on the *left* indicates the time of presentation of the target, the 2nd tick mark indicates the time of the go/no-go cue, and the last tick mark indicates the time of the saccade. Both rasters are aligned on the time of the cue. Cumulative sum of the spikes is superimposed on each raster. These data were collected from the same cell illustrated in Fig. 6. There is essentially no difference in the decline of activity in the 2 cases. *C* and *D*: activity of the preparatory set cell in trials in which the target appeared (*C*) and in interleaved no-go trials in which the target was not turned on (*D*). There is no significant difference in the neuronal activity in the two cases.

ning. The saccades generated in this latter condition will be referred to as *spontaneous* or *self-generated*, and they are distinguished from the *goal-directed* eye movements made during the task primarily by the fact that the reward was in no way contingent on where they directed the eyes.

The activity of a set cell associated with goal-directed and spontaneous saccades is compared in Fig. 9; it is evident that this cell was modulated little if at all in relation to spontaneous, unrewarded saccades. It is important that this analysis use self-generated saccades of an amplitude and direction comparable with those of the goal-directed, task-related saccades. Because of the idiosyncratic nature of the eye movements each monkey made in the intertrial interval, it was sometimes difficult to collect a significant number of such self-generated saccades. Nevertheless, in every case in which a sufficient number of similar self-generated and goal-directed saccades were compared, the level of activation associated with the spontaneous saccades was significantly less. The few remaining set cells were also not clearly activated in association with the occasional spontaneous saccade having the correct vector.

Sensory-movement cells

Another population of the neurons in SMA exhibited a longer period of activation than either sensory or set cells. These cells were active from the presentation of the target until the monkey initiated the movement. Because they responded in this fashion, they have been called sensory-movement cells. The present data do not indicate whether or not independent sensory and motor components are expressed in these units.

The pattern of activation of sensory-movement cells is shown in Fig. 10. The panels on the *left* depict the activity collected during the eye movement task. As shown in Fig. 10, *A* and *B*, the sensory-movement cell begins to discharge after the target is presented, whether it is visual or auditory. However, the buildup of activity is somewhat more variable than that observed in most of the sensory cells. Unfortunately, the experiment was not designed to test the response of these units in trials in which the monkeys were instructed to make no saccade, so it is not possible to distinguish whether these neurons carry an independent sensory signal.

These units cease to fire when the saccade is initiated (Fig. 10, *C* and *D*). A similar pattern of modulation was observed when the monkey performs the task using forelimb reaching movements (Fig. 10, *E–G*). In the example illustrated, there is a slow decay of activity that begins with the saccade and continues until after the reaching movement.

In interpreting the modulation of this cell, it is important to remember that the monkey looks before he reaches, so the cell activity cannot be dissociated from the saccade. In fact, most of the sensory-movement cells appeared to be more intimately related to saccades than to forelimb movements. Thus they ought to be called more properly sensory–eye movement cells. In contrast, an example of a sensory–arm movement cell is shown in Fig. 11. The unit was modulated during the forelimb movement task but not the eye movement task. Because this cell became active after the target appeared and peaked before the eye movement made

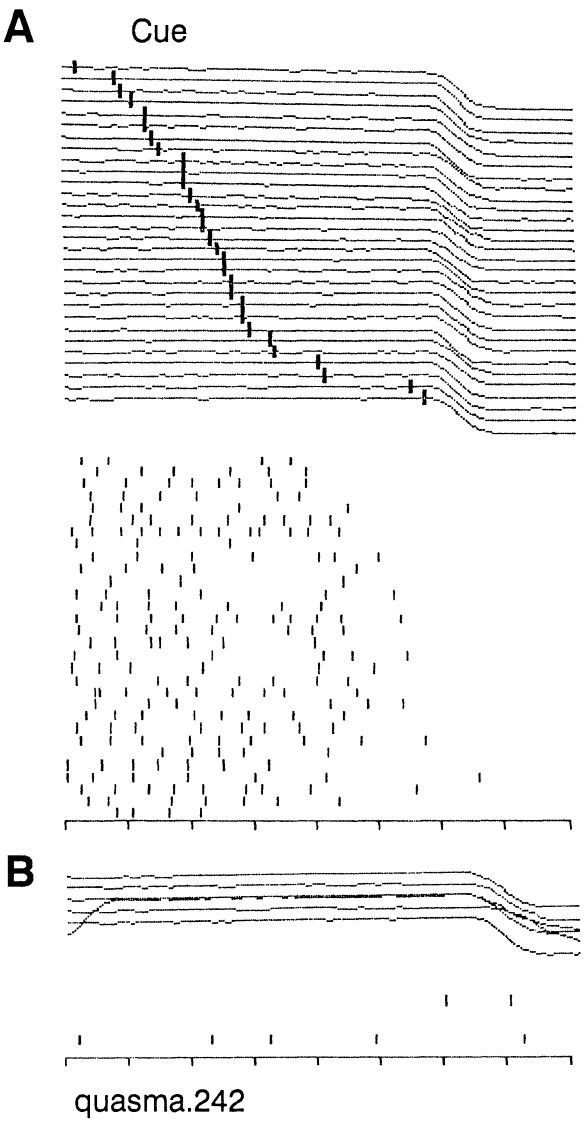

FIG. 9. Preparatory set cell activity associated with goal-directed (*A*) and spontaneous (*B*) saccades. Eye position traces and rasters are aligned on the saccade. Time scale tick marks represent 50 ms. *Top*: same data illustrated in Fig. 6, collected during the eye movement task. *Bottom*: activity associated with spontaneous, unrewarded saccades made during the intertrial interval that were matched for amplitude and direction to the goal-directed eye movements. Note the absence of modulation associated with spontaneous saccades.

before reaching, it seems appropriate to interpret its activity as being associated with some skeletomotor activation preceding the reaching movement, perhaps related to head turning (Biguer et al. 1982; Bizzi et al. 1971). Only four sensory–arm movement cells of this type were recorded, all in a single penetration in the caudal portion of the region of SMA explored.

Sensory–eye movement cells comprised the largest population of task-related neurons recorded; a total of 115 were identified. Figure 12*A* shows the response direction bias of 99 sensory–eye movement cells. The mean bias was 0.20 ± 0.03; 38% exhibited a direction bias >0.2, which was not different from that of set or sensory cells with peripheral receptive fields. There was a significant tendency for the biased cells to respond best in association with movements toward contralateral targets (mean angle = 172°, $u = 2.49$, df = 78, $P < 0.01$), as illustrated in Fig. 12*B*.

The target response latency is shown in Fig. 12*C* for 105 sensory–eye movement neurons. Some exhibited anticipatory activity (see below). The average onset time for the remainder was 116 ± 6 ms. The latency of sensory–eye movement cells was significantly longer than that of sensory cells ($t = 2.71$, df = 162, $P < 0.005$) but was not different from that of preparatory set cells. As illustrated in Fig. 12*D*, there was a large amount of variability in the rise times of sensory–eye movement cells; the mean value was 219 ± 11 ms. The mean rise time of sensory–eye movement neurons was significantly longer than that of sensory cells ($t = 8.70$, df = 162, $P < 0.0005$) and was marginally longer than that of set cells ($t = 1.75$, df = 151, $P < 0.05$). Sensory–eye movement cells tended to exhibit reduced activity very soon after the saccade was initiated, as shown in Fig. 12*E*. The average time of cessation of discharge was 94 ± 8 ms.

Because sensory–eye movement cells were active until the saccade was executed, it was of interest to determine the nature of their response during no-go trials in which the monkeys were required to withhold the saccade. Figure 13 compares the activity of a sensory–eye movement cell during go and no-go trials. In the go trials it is evident that the activity decays after the saccade is completed. In contrast, in the no-go trials the discharge decays sooner and faster. For all sensory–eye movement cells with sufficient data to be tested ($n = 69$), the activity terminated significantly sooner after the no-go cue (229 ± 14 ms) than after the go cue (290 ± 10 ms) ($t = 3.45$, df = 631, $P < 0.001$). Ten of the 69 sensory-movement cells submitted to this analysis exhibited the sharp suppression in activity that is illustrated in Fig. 13*B*; the remainder decayed more gradually.

It was also of interest to determine whether the response of sensory–eye movement cells required the actual presentation of the visual or auditory target. As described above, it was possible in certain no-go trials not to present a target. Figure 13, *C* and *D*, compares the response in go trials with a visual or auditory target to that in selected no-go trials in which no target was turned on. There was considerable activation anticipating the appearance of the target in both go and no-go trials; moreover, the level of response in no-go trials in which no target stimulus was presented was no less than that in the go trials. In seven of seven cells with sufficient data to be tested in this fashion, there was no reduction in activity in no-go trials in which no target appeared; however, each of these units showed anticipatory activity in at least one block of trials. These data indicate that the response of at least these sensory–eye movement cells, like preparatory set cells, is not stimulus bound. Thus it may be more appropriate to describe the activation of these units as *preparatory* rather than *sensory*.

The contrast ratio of responses to visual and auditory stimuli is shown in Fig. 12*F*. Although there were examples of visual- and auditory-specific cells, most sensory–eye movement cells responded equally for visual and acoustic stimuli (see Fig. 10, *A* and *B*). An example of an auditory-specific sensory–eye movement cell is shown in Fig. 14. In contrast to this modality specificity, the cell illustrated

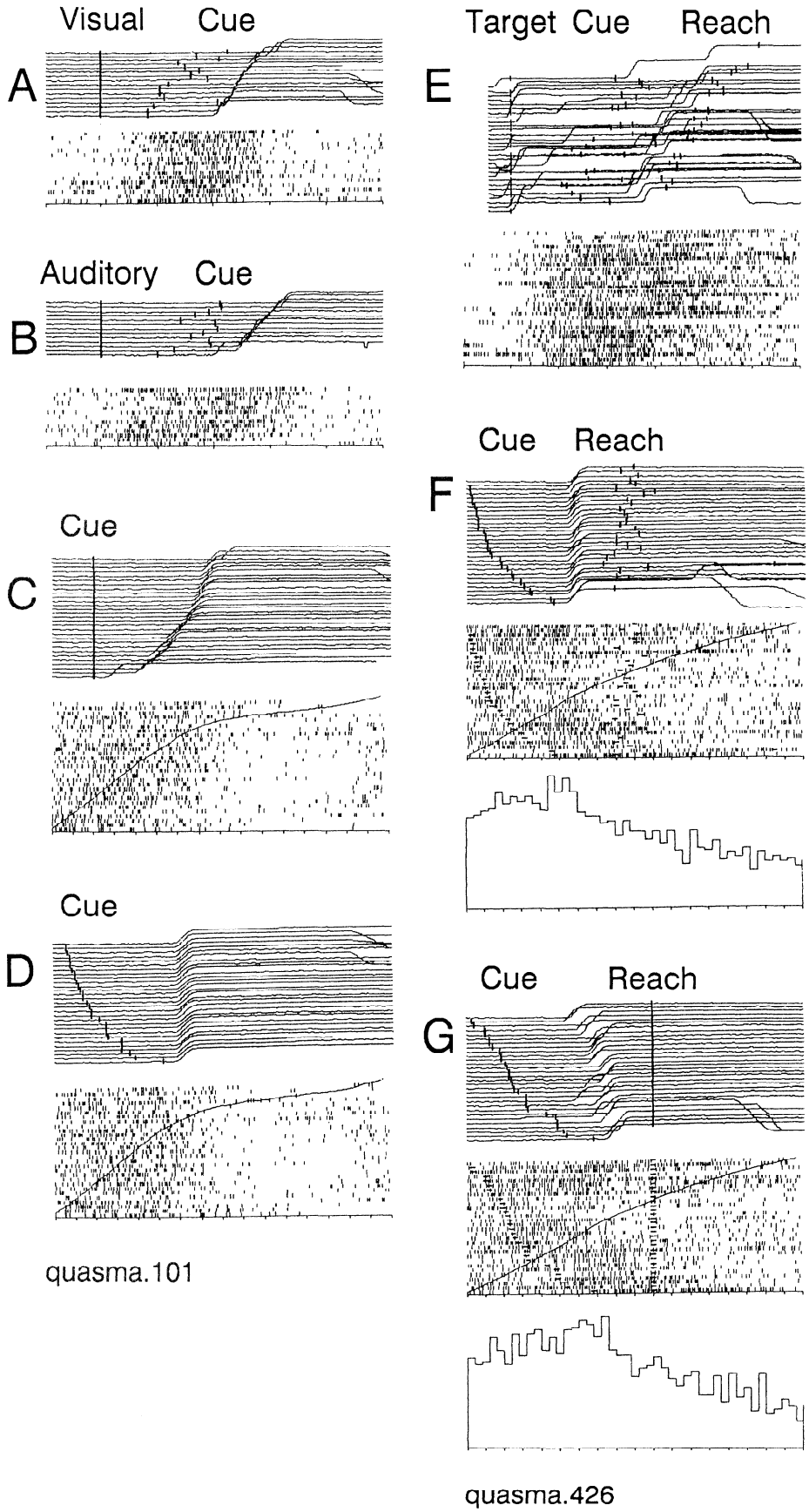

FIG. 10. Sensory-eye movement cell. Each panel illustrates the horizontal eye position traces and raster display of action potentials. Conventions as in Fig. 6. Time scale in *A*, *B*, and *E* represents 200 ms; time scale for the other panels is 50 ms. *Left*: activity of this unit collected during the eye movement task. *A*: response of the cell to the visual target; *B*: response to the spatially corresponding auditory target. *C* and *D*: this unit ceased to discharge once the saccade was initiated. *Right*: activity of another unit during the reaching task. Cumulative sum of spikes and histograms in *F* and *G* indicates that this unit has the most pronounced reduction of activity in relation to the eye movement as opposed to the reaching movement.

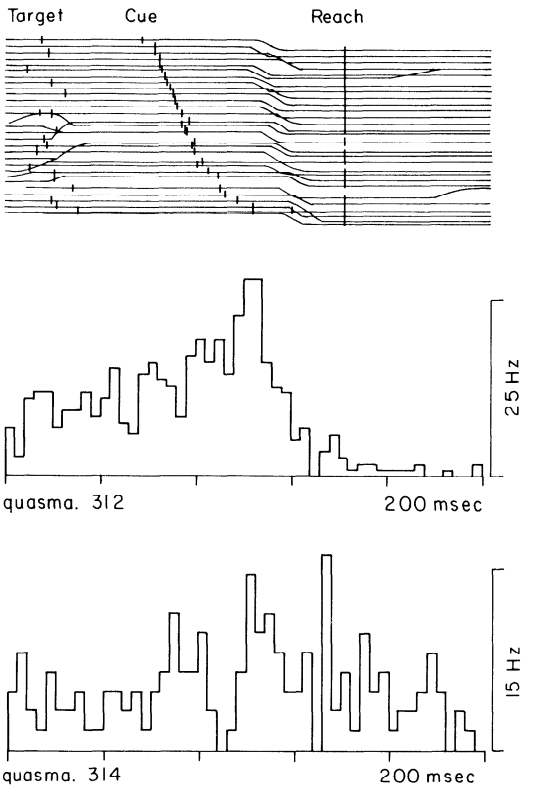

FIG. 11. Sensory-arm movement cell. Eye position trace and *top* histogram show the neural activity collected while the monkey was performing the forelimb movement task. *Bottom* histogram shows the activity of the same unit collected while the animal performed the eye movement task. Note the difference in the scales of the histograms.

in Fig. 10 had a visual/auditory response contrast ratio of 0.02.

The activity of a sensory–eye movement cell associated with goal-directed and spontaneous saccades is compared in Fig. 15. Most of the spontaneous saccades selected in this analysis were the first posttrial saccade; thus the elevation of activity that is evident at the beginning of the raster in Fig. 15*B* is the tail of the discharge associated with the goal-directed saccade. All of the sensory–eye movement cells discharged preferentially for task-related eye movements and were not as active in relation to spontaneous saccades made in the intertrial interval while the monkey was not performing the task.

Pause-rebound cells

Another population of neurons was identified by its unique, biphasic pattern of modulation (Fig. 16). These cells exhibited a moderate level of spontaneous activity in the intertrial interval; when the target appeared, the activity was suppressed until the initiation of the saccade, at which time there was a burst of activity followed by a decay to the baseline level. These groups will be referred to as pause-rebound cells to describe their modulation. Such a pattern of modulation has been reported before in the internal medullary lamina of the thalamus (Schlag-Rey and Schlag 1984) and in the pulvinar (Robinson et al. 1986).

In all, 18 pause-rebound cells were recorded in SMA. Most of the units were directional; the mean response direction bias was 0.20, and 46% had a response bias >0.2. Although the mean angle, 196°, was contralateral, there were not enough cells to demonstrate a significant tendency. The average time relative to target onset at which the activity was suppressed was 12 ± 16 ms. This exceedingly short average latency is a result of the fact that many pause-rebound cells exhibit a significant anticipatory capacity. This was possible because the time of presentation of the target stimulus was predictable within blocks of trials. The rebound burst occurred 38 ± 24 ms before the saccade. Finally, this cell class was not modulated before spontaneous saccades in the intertrial interval.

Presaccadic movement cells

Another population of neurons recorded in SMA was specifically active in relation to saccadic eye movements (Figs. 17 and 19). Presaccadic movement cells showed no measurable response to the visual or auditory stimuli, nor did they fire in no-go trials when no saccade was executed. These cells began to discharge shortly before the saccade was initiated and did not decay until well after the eye movement was completed. The units illustrated indicate the range of response magnitude observed in these cells; some presaccadic movement neurons exhibited a brisk response (Fig. 19), whereas others gave a no less consistent but less robust response (Fig. 17).

A total of 71 presaccadic movement cells was encountered. Although many presaccadic movement cells exhibited a significant degree of response directionality, several such units responded equally for all directions of movement (Fig. 18*A*). The average response direction bias was 0.23, and 46% of the presaccadic movement cells had a response direction bias >0.2. The distribution of the preferred directions of the significantly biased presaccadic movement neurons is illustrated in Fig. 18*B*. Although a percentage of the presaccadic movement cells responded best in association with ipsilateral saccades, there was a significant tendency for the population of cells to prefer contraversive movements (mean angle = 159°, df = 35, u = 1.82, $P < 0.05$).

The time of onset of activity before the visually triggered saccades is illustrated in Fig. 18*C* for 70 presaccadic movement neurons. Cells were found that were active >300 ms before the visually triggered saccades; the mean value was 144 ± 7 ms. Most presaccadic movement neurons stopped firing within 100 ms of the initiation of the saccade; the mean value was 103 ± 11 ms (Fig. 18*D*). The duration of the saccades in this data was very consistent at 50 ms. Accordingly, the inactivation of these units was not closely related to the termination of the eye movement.

The visual/auditory response contrast ratio is shown in Fig. 18*E*. The mean value, 0.18 ± 0.066, was marginally different from 0 (t = 2.71, df = 9, $P < 0.05$). So few cells contributed to this particular analysis, however, that a firm conclusion does not seem warranted. One would expect complete bimodality because, to a first approximation, the metrics of the saccades to the visual and auditory targets are the same (but see Zambarbieri et al. 1982).

Figure 19 shows the activity of a presaccadic movement

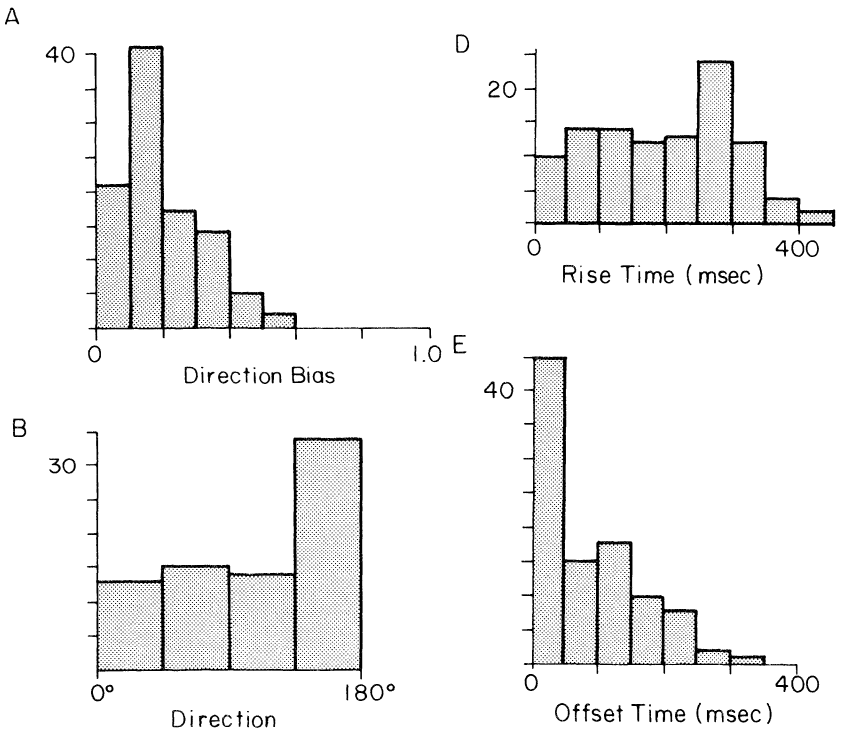

FIG. 12. Quantitative measures of sensory-eye movement cells. *A*: direction biases. *B*: preferred directions. *C*: onset times after target appearance. *D*: rise times. *E*: response termination times relative to saccade. *F*: visual/auditory response contrast ratio.

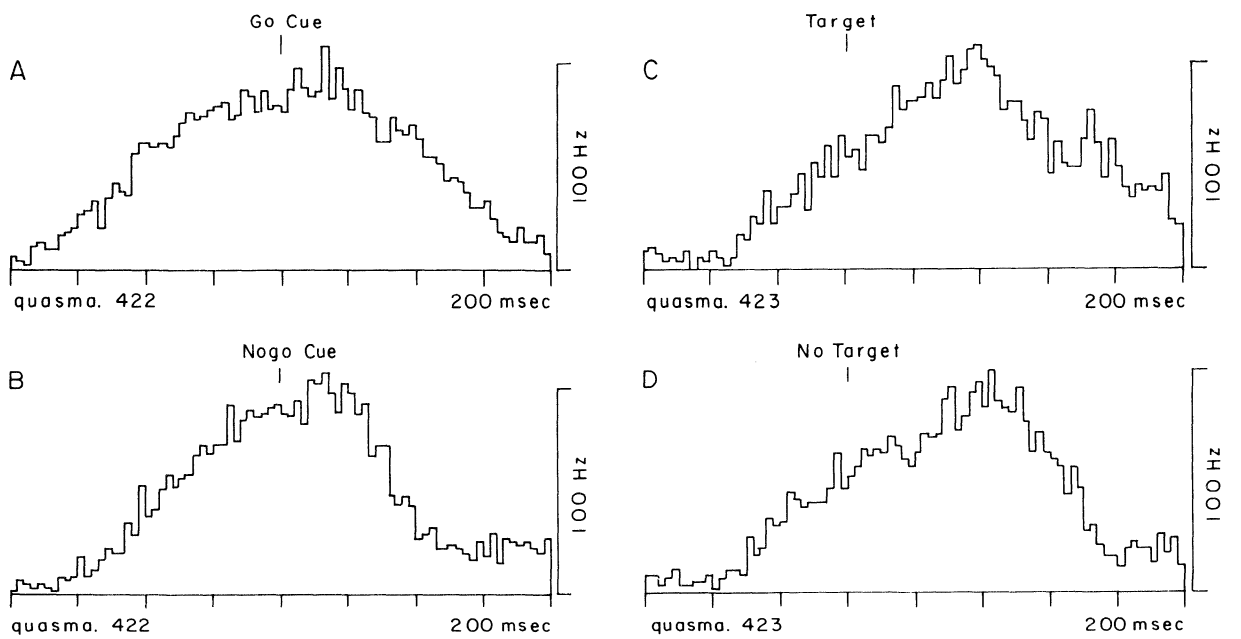

FIG. 13. Decay and onset of sensory-eye movement cell activity. *A* and *B*: histograms representing the activity collected during go and no-go trials, respectively, aligned on the cue. Notice the sharper cessation of activity after the no-go cue, which required the monkey to withhold a saccade. *C* and *D*: activity collected under the same conditions, except that during these no-go trials the target never appeared. Histograms are aligned on the presentation of the target. Notice the pronounced activity anticipating the onset of the target in both go and no-go trials. During the no-go trials, the cell's activity was elevated at the time the target would have appeared.

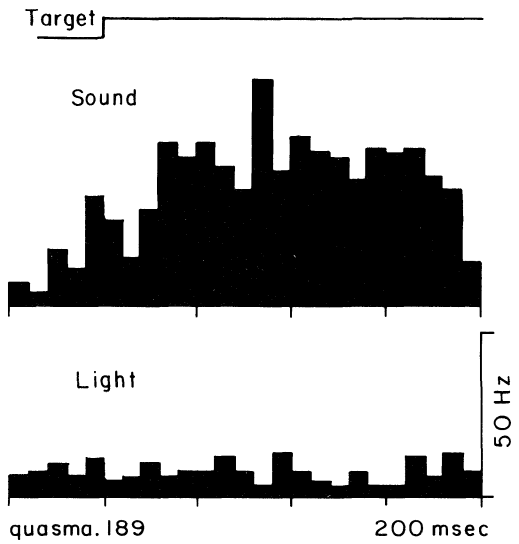

FIG. 14. Auditory-specific sensory-movement cell. Histograms are aligned on the presentation of the target. *Top*: activity recorded in response to the acoustic targets; *Bottom*: activity recorded in response to the visual target.

cell in relation to goal-directed and unrewarded, spontaneous saccades. This example is typical of the presaccadic movement cells in SMA, showing little if any activation in association with self-generated saccades that the monkey made when he was not performing the task or during the intertrial interval. Thus, for the presaccadic movement cells as well as for the sensory–eye movement and preparatory set cells described above, the report of Schlag and Schlag-Rey (1987) that presaccadic cells in SMA fire for "spontaneous" as well as goal-directed saccades is not verified. The reasons for this discrepancy, which is more apparent than real, are reviewed in the DISCUSSION.

Postsaccadic movement cells

Other eye movement–related cells discharged specifically after saccades; an example of such a postsaccadic cell is shown in Fig. 20. Just nine postsaccadic cells were encountered in SMA. They did not tend to be directional. The mean onset time was 17 ± 9 ms after the saccade was initiated, and they ceased firing, on average, after 213 ± 18 ms.

Eye position cells

Other neurons in SMA displayed activity that appeared to be modulated according to the position of the eye in the orbit. These units were unusual in that they discharged before and during both saccadic and pursuit eye movements. However, these neurons were active only in relation to gaze changes that brought the eyes to a particular orbital position. In addition, these units also discharged during fixation in a particular range of orbital positions. The behavior of one such cell is illustrated in Fig. 21. This cell was not very active while the monkey performed the task; a broader range of eye movements was required. Thus the investigator elicited a range of pursuit and saccadic eye movements by passing various objects before the monkey.

From the numerous eye movements that were collected while recording from this cell, a limited number were selected to illustrate the pattern of activity of this neuron. Figure 21, *A–D*, illustrates the activity of this cell in relation to saccades matched for amplitude and direction in different orbital positions. It is difficult if not impossible to reliably describe a movement field for this cell because of the marked orbital dependence of its activity. This unit discharged for saccades of widely varying directions and amplitudes that brought the eyes to the upper right quadrant. In other words, the activity of this neuron could be ac-

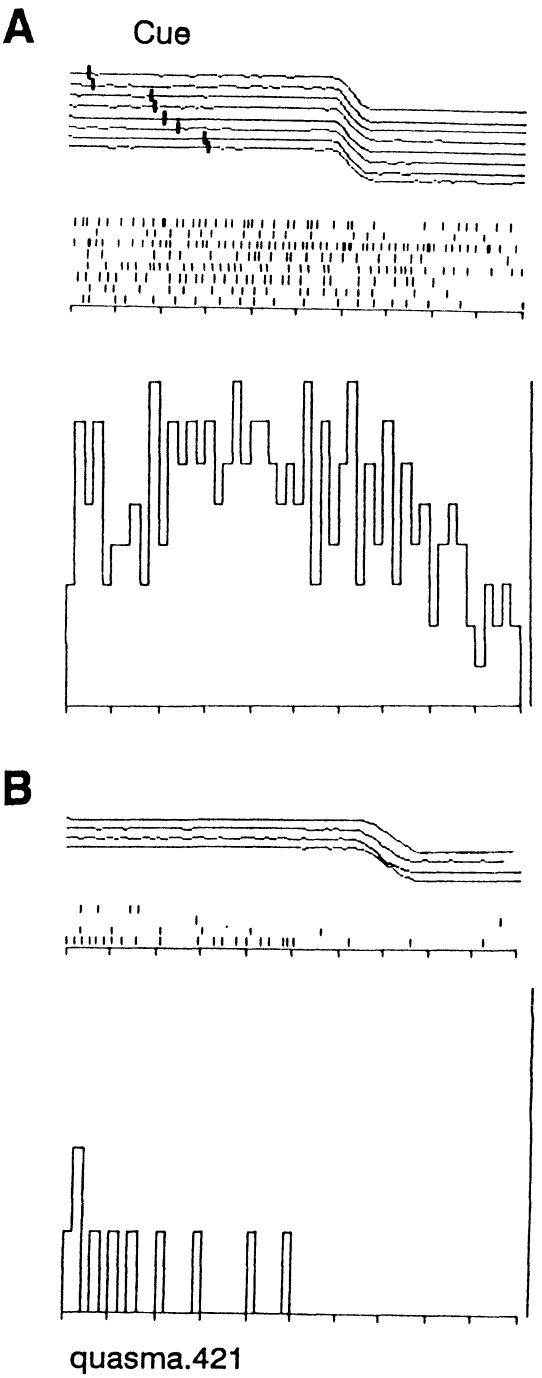

FIG. 15. Comparison of sensory–eye movement activity associated with matched goal-directed (*A*) and spontaneous (*B*) saccades. Rasters and histograms are aligned on the initiation of the saccade. Each tick mark on the time scale represents 50 ms, and the histogram scale signifies 100 Hz.

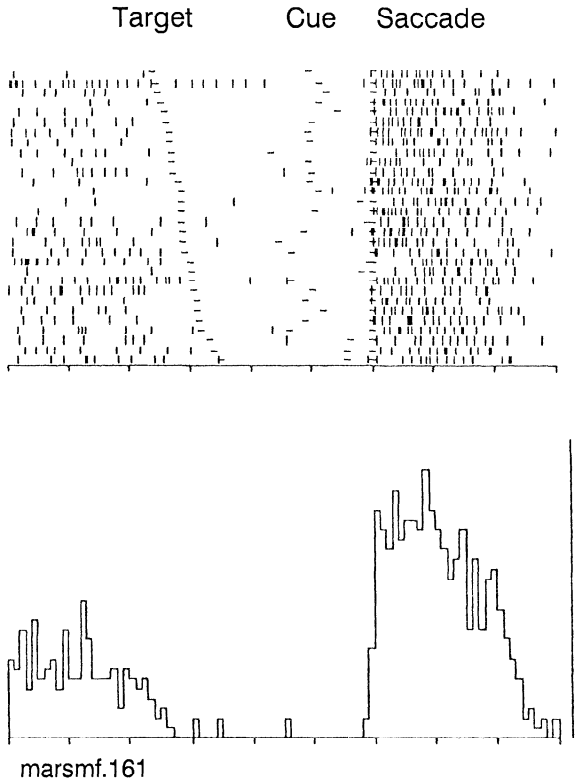

FIG. 16. Pause-rebound cell. Raster and histogram are aligned on the initiation of the saccade. Each tick mark on the time scale represents 200 ms, and the histogram scale signifies 50 Hz. Note the suppression of activity after the presentation of the target and the burst synchronized with the initiation of the saccade.

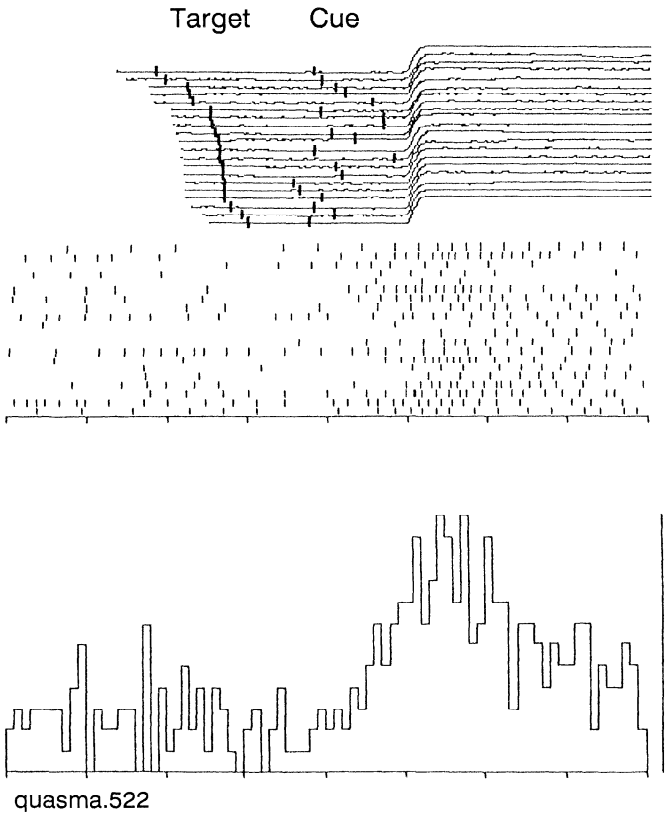

FIG. 17. Presaccadic eye movement cell. Eye position traces, raster, and histogram are aligned on the initiation of the saccade. Time scale is 200 ms, and histogram scale in 30 Hz. Note the absence of any modulation after the target presentation and the rise of activity before the saccade.

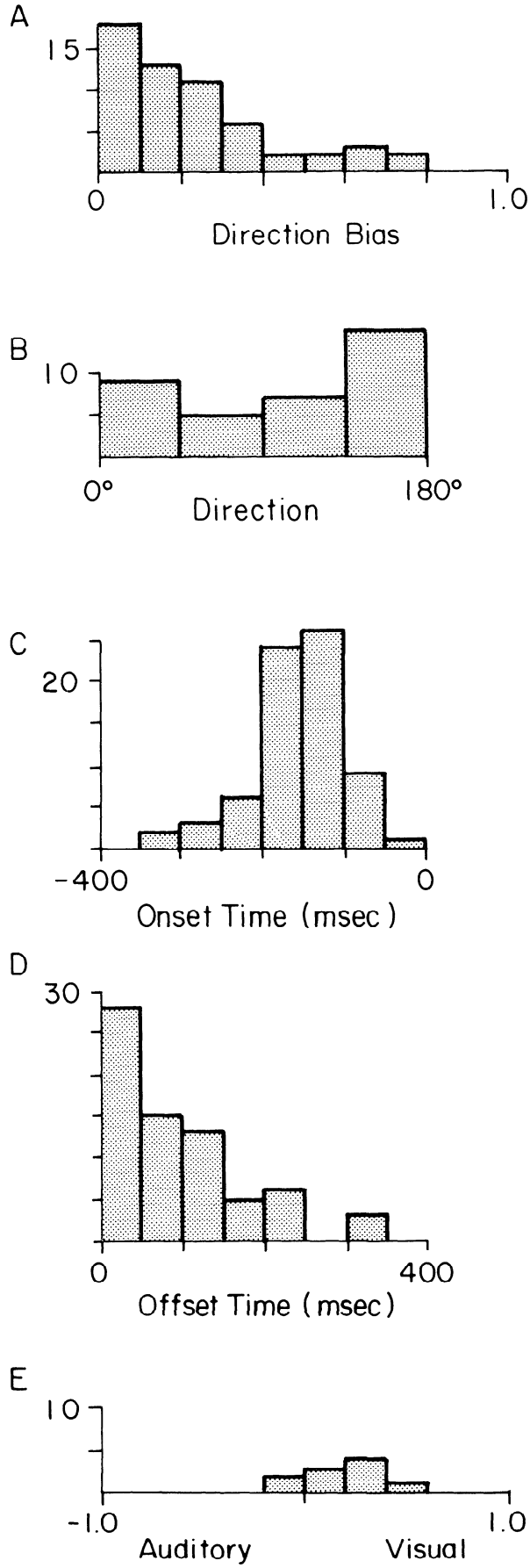

FIG. 18. Quantitative measures of presaccadic eye movement cells. *A*: direction biases. *B*: preferred directions. *C*: onset times after target appearance. *D*: response termination times relative to saccade. *E*: visual/auditory contrast ratio.

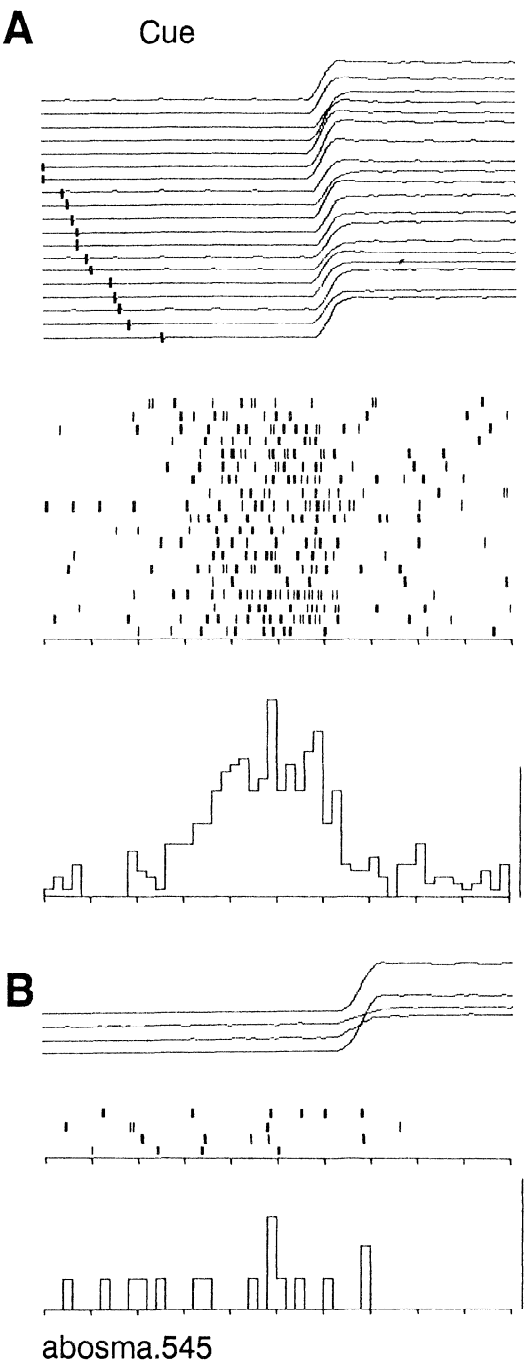

FIG. 19. Comparison of presaccadic eye movement activity associated with goal-directed (*A*) and spontaneous (*B*) saccades. Time scale is 50 ms, and histogram scale is 100 Hz. Activity illustrated in this figure is from a different cell from that shown in Fig. 17. Activity is significantly modulated in relation to goal-directed but not spontaneous saccades.

counted for more clearly by the endpoint of the eye movement than by its vector. Moreover, as illustrated in Fig. 21*G*, the unit begins to fire before saccades with the appropriate endpoint in a manner reminiscent of the presaccadic movement neurons. In addition, it can be seen in Fig. 21, *G* and *I*, that the unit also ceases to discharge before saccades taking the eyes away from the appropriate quadrant.

This unit was also active in relation to pursuit eye movements, as shown in Fig. 21, *E* and *H*, although, as with the saccades, the discharge was accounted for by the endpoint of the eye movement rather than by the trajectory. Also, the change in discharge rate for this cell occurs as early as the change in eye position.

Figure 21, *F* and *I*, shows data indicating that this unit seems to also signal fixation eye position. Figure 21*F* depicts the maintained discharge rate during fixation at different positions. It is evident that this unit exhibited a higher level of activity when the monkey's gaze was directed toward the upper right quadrant. Figure 21*I* shows that, as long as the monkey's gaze is directed in the appropriate quadrant (up to 4,000 ms), this unit discharges.

These data were analyzed using a multiple linear regression. According to this analysis, 58% of the variation in spike rate can be accounted for by eye position. As indicated by this unit's response in relation to saccadic and pursuit eye movements, another source of variation in the firing rate was the direction and amplitude of the subsequent eye movement. Nevertheless, the average discharge frequency during fixation was significantly related to eye position ($F(2,223) = 154.22$, $P < 0.001$). The spike rate at the fixation point was 6.1 Hz; the slope of discharge rate parallel to the horizontal meridian was 0.42 Hz/deg, and the slope parallel to the vertical meridian was 0.18 Hz/deg. These values are in good agreement with corresponding values published for cells recorded in the inferior parietal lobule (Andersen et al. 1990a,b).

Several qualifications must be placed on this description. First, the relation of the activity of this cell to orbital position would have been better demonstrated had a wider range of trajectories been tested; unfortunately the experimental paradigm did not afford this. The eye movements that comprise this data were evoked by the experimenter moving various objects before the monkey. Moreover, the orbital position for which the cell was most active was fairly eccentric and broadly defined. Second, these data were not collected in darkness, so it is possible that there was a sen-

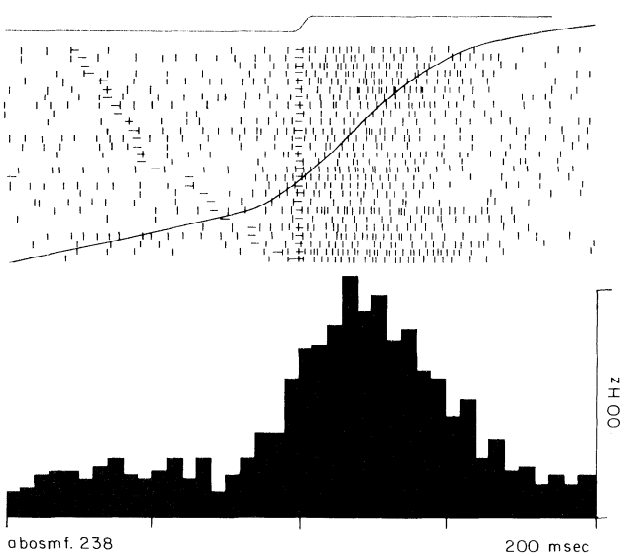

FIG. 20. Postsaccadic cell. The 1st tick mark in the raster indicates the time of the go-cue. Raster and histogram are aligned on the saccade. This neuron's activity follows saccade initiation.

sory component to the activity. Third, because the task used in this study was not designed to study these cells, only two other eye position cells of this type could be reliably identified in these recordings from SMA. The other task-related presaccadic cells that were analyzed for this study were tested for orbital dependence, but either their activity did not vary with gaze angle or the range of eye movements was not broad enough to show any relation. Fourth, in contrast to the previous classes of eye movement–related cells, the present data do not indicate whether or not the activity of these eye position units is contingent on the performance of a task—although it should be noted that the experimenter was eliciting gaze changes directly to obtain data from these units, so it seems possible that the eye movements may have been derived from a more motivated state. Finally, because the head was restrained, it is not possible to state whether this activity is related directly to orbital position or the true angle of gaze in space.

Forelimb movement cells

Another population of neurons in SMA was related to forelimb movements. Such a neuron is illustrated in Fig. 22; it became active after the saccade but before the arm movement was detected and remained active while the monkey touched the target. It is interesting to note the temporal correlation between the saccade and the forelimb movement, which has been observed previously (Biguer et al. 1982; Fischer and Rogal 1986; Fisk and Goodale 1985; Gielen et al. 1984; Herman et al. 1981). Forty-two cells related to forelimb movements were recorded. Some of the cells seemed to be related to proximal movements and others to distal. These differences, however, could be distinguished only informally, because EMG was not recorded.

As shown in Fig. 23*A*, most forelimb movement cells exhibited a significant degree of response directionality. The mean bias was 0.25; 53% had a direction bias >0.2. Each of the three monkeys spontaneously used his right arm to perform the task. Neurons that were active in association with forelimb movements were recorded in SMA in both hemispheres. As illustrated in Fig. 23*B*, there was a difference in the distributions of preferred response directions of cells recorded in the two hemispheres. Cells in the right hemisphere responded for either ipsilateral or contralateral movements of the right arm, but there was no significant bias in the distribution. In contrast, cells in the left hemisphere tended to prefer ipsilateral movements, i.e., leftward movements of the right forelimb (mean angle = 342°, $u = 4.75$, df = 12, $P < 0.0001$). A larger sample of units, however, is required to verify this curious difference.

Figure 23*C* illustrates the distribution of onset times for the population of forelimb movement cells. There was no difference between the cells recorded in the two hemispheres. Neurons could be active as much as 400 ms before the visually triggered arm movements; the mean onset time was 174 ± 13 ms before the movement was detected. Finally, Fig. 23*D* shows the visual/auditory contrast ratio response for 18 forelimb movement cells. Overall, the arm movement cells were as active for reaches to targets of either modality. It was not possible to test task contingency of the arm movement cells because the monkeys did not make spontaneous reaching movements.

Other movement cells

Other cells were recorded that were active in relation to movements of the mouth. They were particularly active when the monkey received the juice reward but could be not further characterized. I also had the impression that another population of neurons was active in association with trunk or hindlimb movements. These cells were active in the intertrial interval when the monkeys made postural adjustments, but when the trial began and the monkey became still, attending to the task, the activity of this group of cells was reduced. These cells are classified as suppressed through trial in Table 1. Because EMG was not recorded and the task did not require or control trunk or hindlimb movements, these neurons could not be further studied.

The spatial distribution of cells responding in relation to eye, mouth, and forelimb movements in two of the monkeys is illustrated in Fig. 24. This figure was compiled from both sensory-movement and premovement cells. The few postsaccadic cells were not included. Although there is intermingling, somatotopy is evident. Eye movement cells tended to be found rostrally; forelimb movement cells were found caudally, and oral cells were recorded in between.

No-go–specific cells

Neurons in SMA were encountered that were modulated specifically after the no-go cue, which required the monkeys to withhold movement. An example of a no-go–specific cell is shown in Fig. 25. This cell gave a burst after the no-go cue, but only when the saccade would have been directed to the contralateral targets. It gave no response after the go cue, which resulted in a movement.

Seven cells were encountered that exhibited specific modulation after the no-go cue. Four showed elevated activity, and three showed suppression. The average response latency was 121 ± 16 ms, which is slightly longer than the latency of sensory cells. This no-go–specific modulation is transient; the time of cessation averaged 382 ± 48 ms, which was also slightly longer than that of sensory cells. It is conceivable that this modulation is actually a sensory response to the changing color of the central spot. This interpretation does not seem plausible, however, because these no-go–specific neurons do not respond to the color change that represented the go cue and there is no evidence for color-selective cells in SMA. Furthermore, the fact that they respond preferentially in association with targets in different directions is not consistent with a simple sensory response.

Unmodulated cells

Other units were clearly modulated but in a less straightforward manner that could not be characterized, or they were not recorded for a sufficiently long period. These are listed as modulated but unclear in Table 1. Many neurons were encountered in SMA that were unmodulated or inactive. They constituted 26% of the total population of cells in

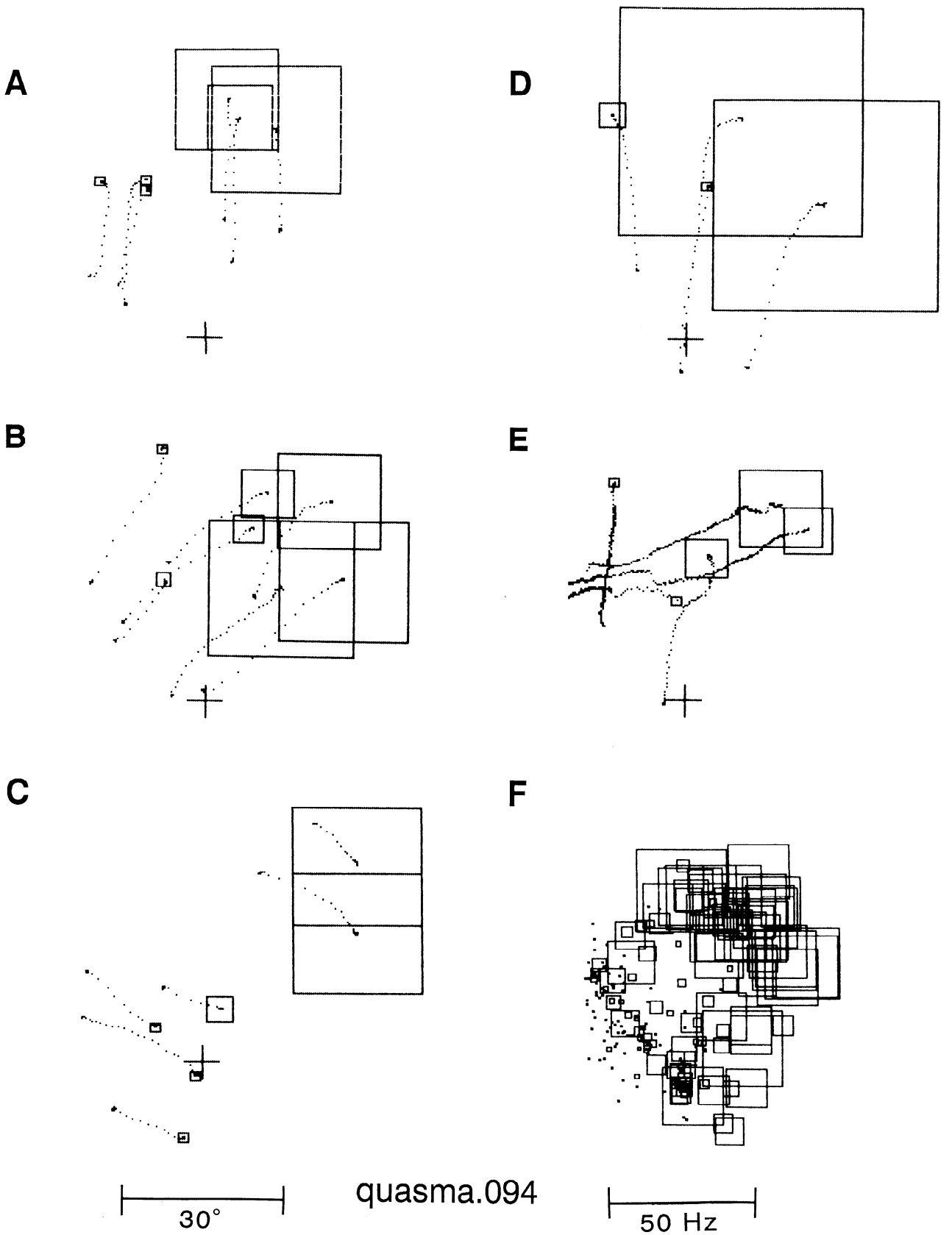

FIG. 21.

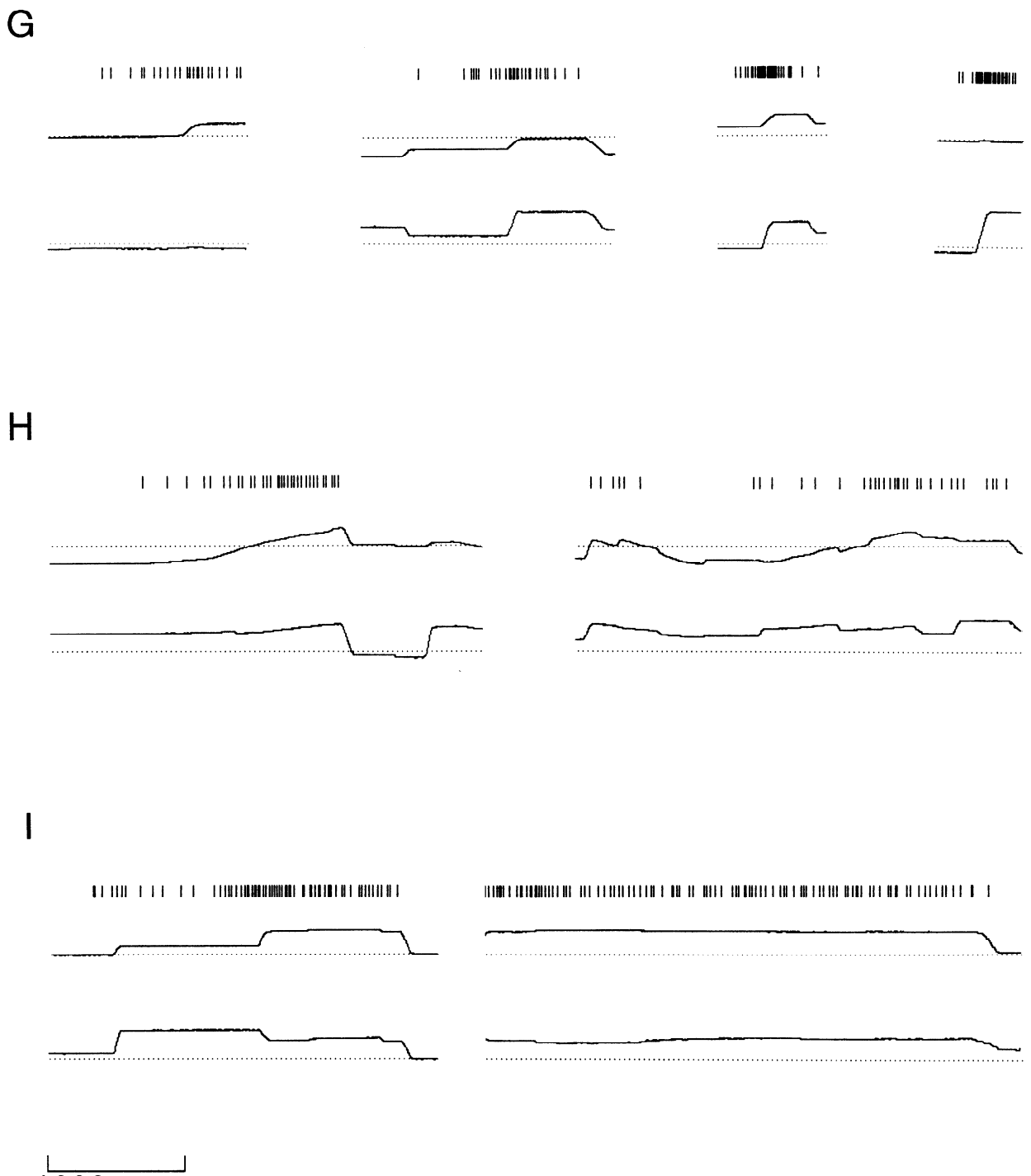

FIG. 21. Eye position cell. *A–E*: eye movements with a box centered on the endpoint of the movement; the size of the box is proportional to the discharge rate associated with the eye movement, according to the scale shown at the bottom. The cross in each panel indicates the central position of gaze. *G–I*: selected examples of unit discharge associated with different eye positions and movements. Horizontal eye position is shown above and vertical below. *A*: 6 upward saccades of the same amplitude; significantly more activity was associated with the 3 saccades that brought the eyes to the upper right quadrant than with the other 3 that ended in the left quadrant. *B–D*: similar data for saccades of different amplitudes and directions. In each case the level of neuronal activation is accounted for better by the endpoint of the saccade than by its vector. *G*: individual horizontal, oblique, and vertical saccades with which this unit was active. Saccades with which this unit was not active can be seen in each of *G–I*. *E*: 5 pursuit eye movements; the 3 movements that ended in the upper right quadrant were associated with much more activity than the 2 that ended in the left quadrant. *H*: temporal relationship of this neuron's discharge and the pursuit eye movements; the activity gradually builds as the eyes move into the appropriate quadrant. *F*: variation in maintained discharge rate as a function of orbital position for 226 fixation periods ranging in duration from 200 to 4,000 ms, with an average of 751 ms. Location of each square corresponds to actual fixation position, and the size of each square is proportional to the average discharge rate during that fixation period. Mean discharge rate across all fixation periods was 7.4 Hz. Although there was variation, this unit was most active when the monkey's gaze was directed in the upper right quadrant. *I*: fixation periods during which this unit was active; as long as the monkey looked up and to the right, this cell fired.

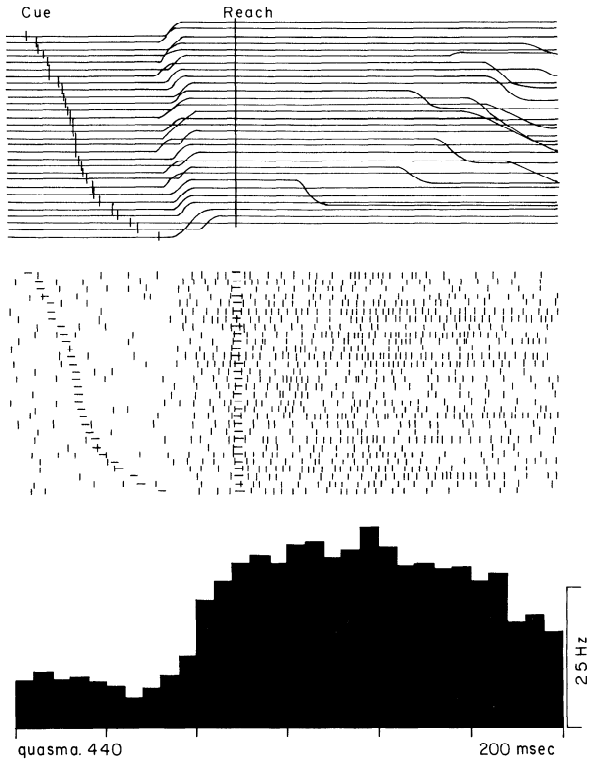

FIG. 22. Forelimb movement cell. Conventions as in Fig. 6. Eye position traces, rasters, and histogram are aligned on the time that the monkey began reaching for the target, and the trials have been sorted in order of increasing reaction time.

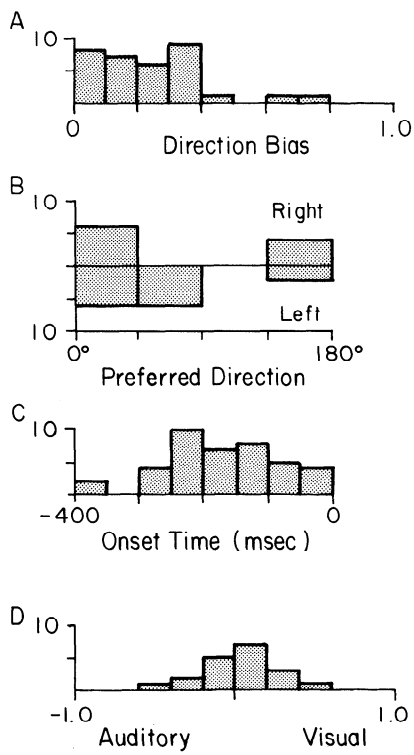

FIG. 23. Quantitative measures of forelimb movement cells. *A*: direction bias. *B*: preferred direction for cells recorded in the right hemisphere (*top histogram*) and for cells recorded in the left hemisphere (*bottom*). Each monkey spontaneously used his right arm to perform the task. *C*: onset times. *D*: visual/auditory response contrast ratio.

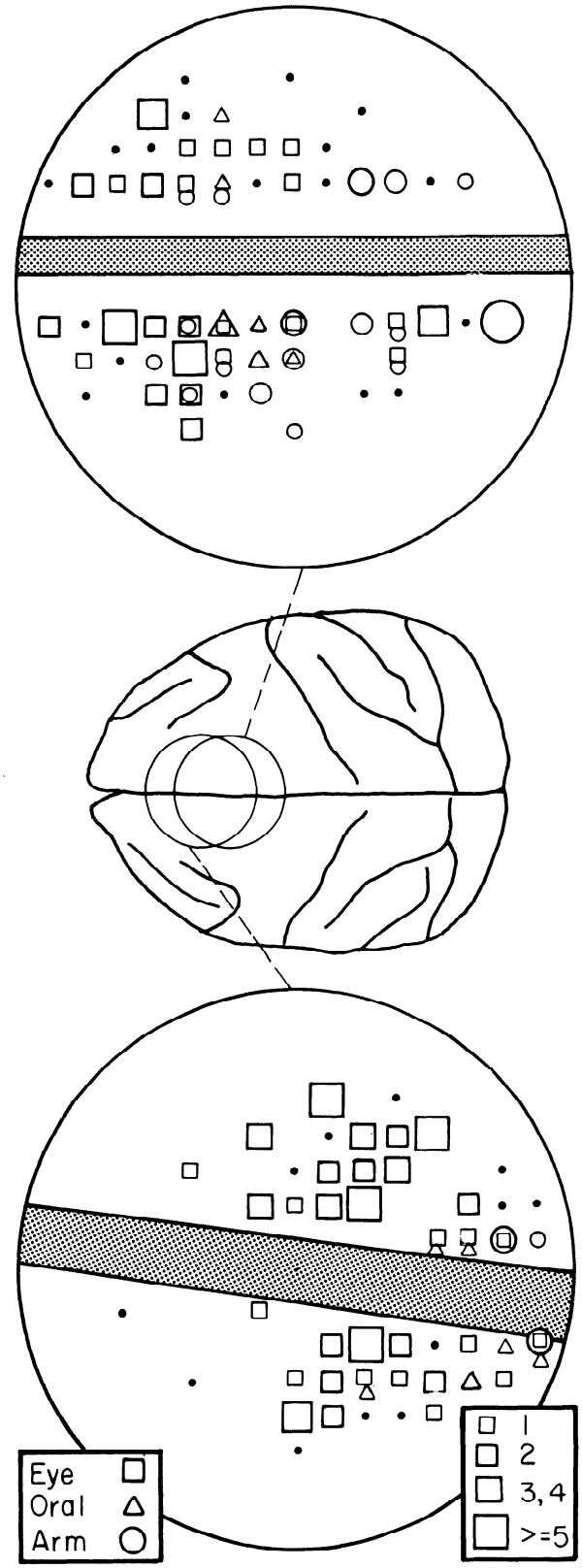

FIG. 24. Location of penetrations in *monkeys M* and *Q* encountering sensory-movement and movement cells related to eye, mouth, and forelimb movements. Conventions as in Fig. 5. It is evident that, although there is much intermingling, eye movement cells tend to be found rostrally and forelimb movement cells caudally. Mouth movement cells are found in between.

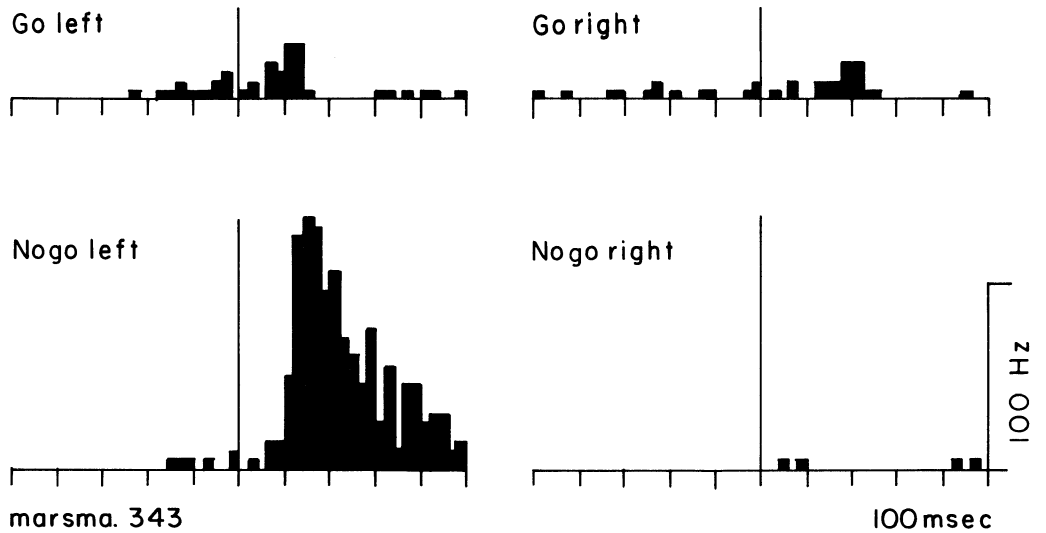

FIG. 25. No-go–specific cell. Perievent time histograms are shown for go trials and no-go trials to the left and right. Histograms are aligned on the onset of the cue. This cell was specifically active when the no-go cue prohibited saccades to the left but not to the right. This cell was recorded in the right hemisphere.

the three monkeys. The proportion of unmodulated or inactive cells is apparently higher in *monkey Q* because a special effort was made to identify such units as well as the task-related neurons.

Figure 26 shows the spatial distribution of the unmodulated cells in the SMA of *monkey Q*. Two results are evident. First, unmodulated cells were encountered in most penetrations. Second, the most lateral penetrations tended to encounter only unmodulated or inactive cells. In *monkey M*, in which the recording chamber was positioned more rostrally, the most rostral penetrations also encountered only unmodulated neurons. This result is consistent with the cytoarchitecture, which suggests that these rostral penetrations were in the frontal granular cortex, beyond the border of SMA. Further, it appears that the region of cortex lateral to SMA, which is in the frontal agranular region, does not participate in the task that these monkeys were performing.

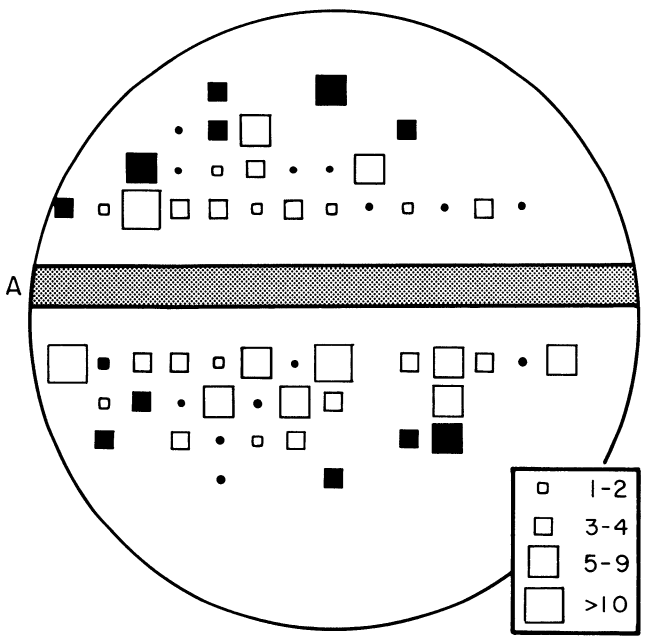

FIG. 26. Spatial distribution of penetrations encountering unmodulated cells in *monkey Q*. Rostral (A-anterior) is to the left. Small spots represent penetrations in which only task-related units were isolated. Open squares represent the number of unmodulated or inactive cells encountered in penetrations that also encountered task-related units. Solid squares represent penetrations in which no task-related modulated cells were recorded.

DISCUSSION

A summary of the results provided by this study is illustrated in Fig. 27. A number of response profiles were observed in the SMA of monkeys performing visually guided movements. Sensory cells responding to either visual or auditory stimuli were recorded. Preparatory set cells were active from the appearance of the target until the monkeys were given the go/no-go cue to either move or not move. Sensory-movement cells were active from the appearance of the target until the saccade was executed. Pause-rebound cells were suppressed at the appearance of the target and burst at the saccade. Presaccadic eye movement cells burst before the saccade; other cells were postsaccadic. Other eye movement–related cells were modulated by the position of the eye in the orbit. Neurons with activity associated with eye movements tended to be found rostrally; cells with activity related to forelimb movements were found caudally. Neurons related to oral movements were interspersed between the eye and forelimb regions. Certain cells exhibited specific activity in relation to withholding the movement in no-go trials. Finally, many neurons were not modulated while the monkey performed the task.

Relation to previous work

The SMA has received much attention because of its apparent role in the preparation and execution of intentional, goal-directed movements. One line of evidence is based on the observation that, before the execution of a limb movement, a "readiness potential" is observed in the electroencephalogram recorded over SMA (Deecke and Kornhuber

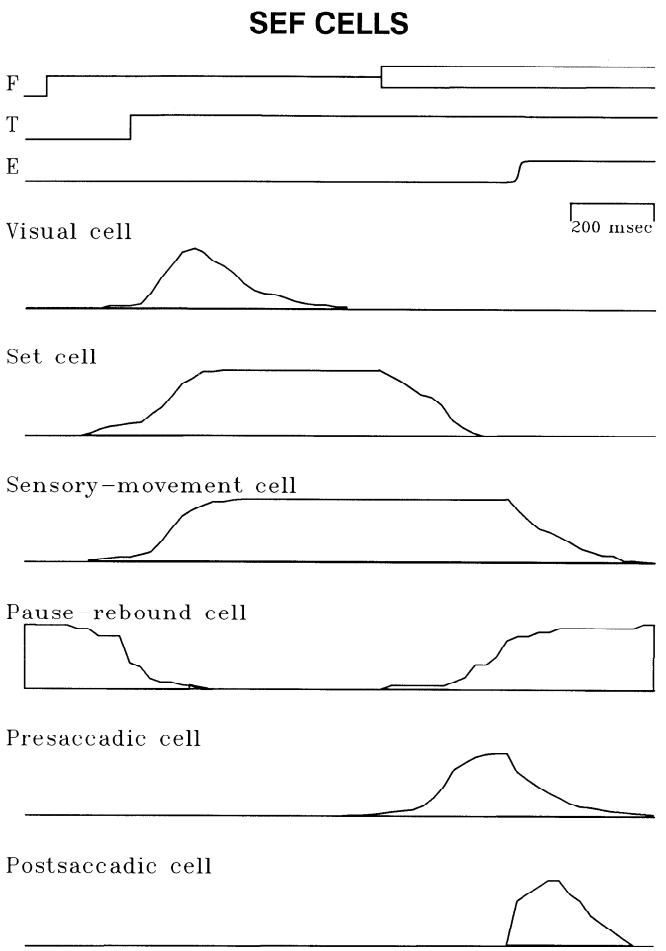

FIG. 27. Summary of the different cell types recorded in SMA. Timing of the task is shown on the *top*. Cumulative distributions of response activation and inactivation for each cell type is illustrated; the magnitude of activity is not reflected in this figure.

1978; Deecke et al. 1985). This readiness potential also appears when a human subject plans a limb movement that is subsequently withheld (Libet et al. 1983b). Further, the readiness potential recorded before preplanned, externally cued movements is different from that recorded before self-generated movements (Libet et al. 1982); and, finally, the readiness potential begins before the subject reports being aware of the intention to act (Libet et al. 1983a). A readiness potential is also observed over SMA before voluntary saccadic eye movements (Deecke et al. 1985; Kurtzberg and Vaughan 1982; Moster and Goldberg 1990).

Another line of evidence is provided by regional cerebral blood flow studies in human subjects performing a variety of movement tasks. These have demonstrated that SMA is activated during complex, intentional movements and not during sustained muscular contraction or simple, repetitive movements (Orgogozo and Larsen 1979; Roland et al. 1980; but see Fox et al. 1985). Moreover, blood flow in SMA is also elevated when subjects only imagine a complex movement sequence without actually executing it (Roland et al. 1980).

Yet another line of evidence is provided by single-unit recordings in SMA of alert, behaving monkeys that have demonstrated a variety of response properties. The remainder of the DISCUSSION will focus on the new information that the present single-unit recording study provides.

SENSORY CELLS. Neurons responding to visual (Brinkman and Porter 1979; Schlag and Schlag-Rey 1987; Tanji and Kurata 1982), auditory (Tanji and Kurata 1982; Wise and Tanji 1981), and tactile stimuli (Tanji and Kurata 1982) have been reported in SMA. In this study new information about the visual receptive field arrangement was presented. It was demonstrated that some sensory cells include the fovea in their receptive fields, whereas others do not. Although they extend into the ipsilateral hemifield, receptive fields that exclude the fovea tend to emphasize the contralateral hemifield. Cells with foveal receptive fields tended to respond equally to visual and auditory stimuli, whereas cells with peripheral receptive fields tended to respond preferentially to visual or auditory stimuli.

The response of these units after the presentation of the stimuli could be quite variable from trial to trial. At least two sources for this variation can be imagined: first, the stimuli may not have been situated in the most sensitive part of the receptive field; second, the attentional state of the monkey may have wavered. Because just four fixed LEDs were used as the stimuli, it was not possible to map the receptive field as has been done in the FEF (Bruce and Goldberg 1985). Thus the contribution of the first factor is not known at this time, and further experimental work is therefore required to describe more clearly the receptive-field organization of SMA visual cells. Nevertheless, extraretinal input to these units also should not be ignored in future studies.

In this study, the temporal parameters of the sensory responses were reported. The latency of response observed corresponds to what has been described in the aforementioned reports. However, the values of response rise and cessation times have not been previously reported. These data are necessary to provide a complete description of the sequence and pattern of activation of this area in the preparation of a visually guided saccade. Although it seems self-evident that the sensory responses must be involved in specifying the target of an eye movement, further work is required to elucidate the nature of their involvement.

Recent anatomic studies indicate possible sources for the visual and auditory input to the SEF (Huerta and Kaas 1990; Jürgens 1984). The eye movement representation in rostral SMA appears to receive intracortical afferents from the medial superior temporal (MST) and superior temporal polysensory (STP) extrastriate visual areas, as well as from the ventral intraparietal area (VIP) of the inferior parietal lobule and the frontal eye fields. Rostral SMA also gets input from thalamic regions in which visually evoked activity has been recorded (Schlag and Schlag-Rey 1984) including certain intralaminar nuclei, the lateral portion of the mediodorsal nucleus, and the medial portion of the ventroanterior nucleus.

PREPARATORY SET CELLS. After the target appeared, the monkeys could prepare the movement, i.e., the amplitude and direction of the saccade or forelimb movement could be programmed. This preparatory process or motor set has been the focus of many studies (reviewed in Evarts et al. 1984; Kornblum and Requin 1984). Neurons that are spe-

cifically active during this preparatory period have been observed in primary motor cortex (Tanji and Evarts 1976), the postarcuate premotor region (Godschalk and Lemon 1983; Weinrich and Wise 1982; Weinrich et al. 1984; Wise and Mauritz 1985), and prefrontal cortex (Kubota and Funahashi 1982). A similar pattern of modulation associated with forelimb movements has been observed before in SMA (Tanji et al. 1980; Tanji and Kurata 1985).

In the present investigation, a key defining feature of the preparatory set cell class was the cessation of activity before the movement, usually after the go/no-go cue. This time course of activation distinguishes this population of neurons from the sensory-movement neurons that continue to fire until the eye has moved. The termination of activity of the set neurons appears to be related more closely to initiation of the saccade rather than to presentation of the cue. This relationship has been observed previously in the postarcuate premotor cortex (e.g., Weinrich et al. 1984) and is being analyzed in more detail for the SMA cells (see Schall 1988).

Several results indicate that the activity of set cells is not stimulus bound, that these neurons receive a potent extraretinal input. First, a significant number of these units became active in anticipation of the target presentation. Second, the response latency and rise time of preparatory set cells were longer and more variable than those of sensory cells. Third, set cells in SMA ceased firing with essentially the same time course after the no-go cue, which instructs the monkey to withhold a movement, as after the go cue. In no-go trials these units quit discharging even though the target stimulus was still present. Moreover, set neurons cease discharging before the target is removed from the receptive field by an eye movement. Fourth, this population displayed equivalent responsiveness to visual and auditory stimuli. Finally, a number of preparatory set neurons displayed elevated activity synchronized on the expected time of presentation of a target that was not actually turned on.

Set cell activity was associated with goal-directed and not spontaneous saccades. This result indicates that these neurons are involved in generating only particular kinds of saccades (discussed below). It has been proposed that set cells play a key role in the preparation of a movement. The precise nature of this function, however, requires investigation. For example, the level of activity of a set cell on any trial does not predict saccade latency (Schall 1988). Analyses are currently underway to determine whether temporal parameters of set cell activity predict eye movement latency.

SENSORY-MOVEMENT CELLS. Sensory-movement cells have also been observed in FEF (Bruce and Goldberg 1985), prefrontal cortex (Boch and Goldberg 1989; Joseph and Barone 1987), and the inferior parietal lobule (Andersen et al. 1987, 1990b; Colby et al. 1988) in relation to visually guided saccades. A corresponding pattern of neuronal modulation has also been recorded in relation to visually guided forelimb movements in the postarcuate premotor region (Godschalk and Lemon 1983; Godschalk et al. 1985; Weinrich and Wise 1982). This pattern of modulation has also been observed in a number of subcortical structures, including the caudate nucleus (Hikosaka et al. 1989a,b), the substantia nigra pars reticulata (Hikosaka and Wurtz 1983a), the superior colliculus (Mays and Sparks 1980; Mohler and Wurtz 1976), and the nucleus reticularis tegmenti pontis (Crandall and Keller 1985). It will be of interest to determine whether any of these sensory-movement cells in SMA are active for memory-guided saccades, as are cells in prefrontal cortex and FEF (Funahashi et al. 1989), the inferior parietal lobule (Gnadt and Andersen 1988), caudate nucleus (Hikosaka et al. 1989a), and substantia nigra (Hikosaka and Wurtz 1983b) or whether they respond in a double-step task like the quasivisual cells of the superior colliculus (Mays and Sparks 1980).

Separate populations of sensory–eye movement and sensory–arm movement cells were distinguished in SMA; this has not been emphasized in earlier investigations. Because no clear changes in activity were observed in the activity of these two subpopulations during the eye movement task versus the forelimb movement task, it is not possible to implicate these neurons directly in eye-hand coordination. But it seems that recording from these units in monkeys performing more demanding eye and limb movement tasks is necessary (e.g., Baedeker and Wolf 1987; Fischer and Rogal 1986; Georgopoulos and Massey 1987; Gielen et al. 1984; Herman et al. 1981).

The behavior of these units under a variety of circumstances indicates that they are neither purely sensory nor purely motor, but instead signal higher level elements of sensorimotor integration. First, sensory-movements cells in SMA became active during the period that a target normally was presented even when that target was not turned on. Second, some sensory-movement neurons exhibited anticipatory activity. Third, the sensory-movement cells tended to respond equally to visual and auditory targets. Thus this population of cells receives an extraretinal input that can signal that a target will or ought to be present. Indeed, it might be more appropriate to describe the activation of these neurons as preparatory rather than sensory. Moreover, sensory-movement cells were not modulated in relation to spontaneous saccades; their activation was conditional. These properties of the sensory-movement cells in SMA may arise through input from areas of prefrontal cortex (Huerta and Kaas 1990) where corresponding neuronal response patterns are observed (reviewed by Fuster 1985; Goldman-Rakic 1987).

PAUSE-REBOUND CELLS. In an earlier report from this laboratory, Mann et al. (1988) noted that many units in SMA exhibited reductions in firing rate during visually guided movements. In subsequent recordings and in further analysis of their data, the pause-rebound class was identified in the present study. Pause-rebound cells have also been observed in the thalamic internal medullary lamina (Schlag-Rey and Schlag 1984) and the inferior and medial pulvinar (Robinson et al. 1986), which are reciprocally connected to SMA (Huerta and Kaas 1990; Jürgens 1984; Schell and Strick 1984; Schlag-Rey et al. 1987; Wiesendanger and Wiesendanger 1985). The pause-rebound units recorded in the central thalamus exhibited a pause at different times relative to the saccade, whereas in the present study the pause was observed from the appearance of the target until the saccade. Because the study by Schlag-Rey and Schlag (1984) did not use a delayed response paradigm, it is diffi-

cult to compare these populations of cells more directly. It is possible that this population of cells is in some sense the inverse of sensory–eye movement cells, although the additional burst associated with the saccade has no counterpart suppression in sensory-movement cells.

Centers involved in visual processing need to be informed of the execution of a saccade so that their processing can be halted or modified while the rapid eye movement degrades the image (e.g., Matin 1974). It has been proposed that this might be one function of the pause-rebound cells in the intralaminar nuclei (Schlag and Schlag-Rey 1983) and thus, by extension, in SEF. If the pause-rebound cells provided inhibitory input to visual processing neurons, then such cells would be disinhibited when a potential target was asserted until the subsequent saccade. For SEF, however, the potential extrinsic cortical targets for this signal appear to be limited to FEF and VIP (Huerta and Kaas 1990).

EYE MOVEMENT CELLS. Presaccadic bursting neurons have been observed in SMA previously by Brinkman and Porter (1979) and Schlag and Schlag-Rey (1987). However, these investigators did not make the distinction between sensory–eye movement and purely eye movement cells because they did not use a task that temporally separated the sensory and the motor components of the response. A fundamental difference in the results of Schlag and Schlag-Rey (1987) and the present investigation concerns the activity of SMA neurons associated with spontaneous, self-generated saccades. Schlag and Schlag-Rey demonstrated that units in rostral SMA discharged before self-generated saccades with no visual target. The onset of activity occurred earlier and was more gradual than that observed with visually triggered saccades. In the present study, however, it was found that preparatory set, sensory–eye movement, pause-rebound, and presaccadic burst cells were not modulated in relation to spontaneous saccades.

The report by Schlag and Schlag-Rey (1987) of presaccadic activity in SEF associated with spontaneous saccades was especially interesting in comparison with FEF. In the initial observations of FEF (Bizzi 1968; Bizzi and Schiller 1970), presaccadic activity was not recorded in alert but untrained monkeys making unrewarded, spontaneous eye movements. This result was a puzzle because stimulation of the FEF elicited saccades (Ferrier 1875; Robinson and Fuchs 1969) and a presaccadic EEG shift could be recorded over FEF (Kurtzberg and Vaughan 1973). The apparent inconsistency was clarified by training monkeys to make saccades to visual targets (Bruce and Goldberg 1985; Goldberg and Bushnell 1981; Wurtz and Mohler 1976). Many cells exhibit an enhanced response to visual stimuli that were targets for saccades. After such training, other cells have been recorded in FEF that were active specifically before purposive, goal-directed saccades, even in the dark (Bruce and Goldberg 1985). The apparent functional differences revealed between the different studies of FEF reflected differences in experimental paradigm and reward contingency.

A similar interpretation may explain the apparent inconsistency between the results of Schlag and Schlag-Rey (1987) and those of this investigation. It is critical to understand the nature of the tasks that were used by Schlag and Schlag-Rey and in the present study. Schlag and Schlag-Rey trained monkeys to fixate spots of light that appeared at unpredictable locations and times. In their paradigm the monkeys were required to be vigilant constantly; each successful saccade to a target was rewarded. Under these circumstances "spontaneous," i.e., self-generated, saccades would seem to be generated in a more motivated state. In the task used for the present investigation, each trial required a specific pattern of eye movements to be successfully completed, and each trial was separated by a defined intertrial interval. Saccades during the intertrial interval or when the task was not being run were considered spontaneous. These self-generated saccades were unrewarded and had no relation to the task; thus, it can be argued that they are derived from a less motivated state. Hence, the results presented by Schlag and Schlag-Rey and by the present report provide alternative views of the same neuronal system and should be seen as complementary rather than conflicting.

Before leaving this point, it is interesting to note that the activity of cells in SMA associated with visually triggered and self-generated forelimb movements has been described recently (Kurata and Wise 1988; Okano and Tanji 1987; Romo and Schultz 1987). These studies demonstrate that the activity of single units in SMA before visually triggered movements begins at the appearance of the target, whereas the onset of activity before self-generated movements is earlier and more gradual. This pattern of modulation appears to be the same as Schlag and Schlag-Rey (1987) have observed associated with saccades. Again, in each of these studies the monkeys were rewarded for making self-generated as well as visually triggered movements.

Although it seems self-evident that presaccadic movement cells probably participate in triggering a saccade, the route of access to the saccade-generating network in the brain stem has yet to be worked out. Because low-intensity (<50 μA) microstimulation elicits saccades with a relatively short latency (30 ms) (Gould et al. 1986; Mann et al. 1988; Mitz and Godschalk 1989; Schall 1991b; Schlag and Schlag-Rey 1987), it seems that these units must have rather direct access to the brain stem saccade generator. In fact, as mentioned above, projections from SEF to brain stem oculomotor regions have been described (Huerta and Kaas 1990; Shook et al. 1990).

EYE POSITION CELLS. Another population of cells recorded in the present study were modulated by the position of the eye in the orbit. These units discharged in association with both saccadic and pursuit eye movements that brought the eyes to the particular orbital position; they also fired during fixation in the particular direction. Schlag and Schlag-Rey (1985, 1986) have also reported neurons in SMA that were active during fixation both with and without orbital dependence. The properties of the few units of this type observed in the present survey corresponded precisely to those described by Schlag and Schlag-Rey.

The present data, although admittedly limited both in quantity and quality, are relevant to the current attempts to understand the precise nature of the supranuclear saccade command signals. On the one hand, a number of investiga-

tors have argued that an eye position signal of some sort is required to generate accurate saccades under a variety of circumstances (e.g., Andersen et al. 1990b; Mays and Sparks 1980); on the other hand, others assert that saccades can be programmed without such information (e.g., Goldberg and Bruce 1990). If substantiated, the existence of an explicit eye position signal in SMA would be an important contribution to this debate. Furthermore, the properties of the eye position units identified in SMA are distinct from their counterparts in other brain regions.

Various neurons recorded in posterior parietal cortex show an orbital dependence (Andersen et al. 1985, 1987, 1990a,b; Lynch et al. 1977; Robinson et al. 1978; Sakata et al. 1980). Some units are activated during attentive fixation in limited directions of gaze; others are active during tracking eye movements (e.g., Lynch et al. 1977; Robinson 1978). However, in contrast to the units observed in SEF, these neurons in posterior parietal cortex do not also discharge before saccades; instead their activity is interrupted by saccadic eye movements. On the other hand, orbital position has also been shown to affect the magnitude of the visual and saccade-related responses of posterior parietal neurons (Andersen et al. 1990b). It is difficult to compare the present results directly with those obtained in the parietal lobe because the experimental paradigms were so different. Nevertheless, the multiple linear regression analysis of the variation of neuronal activity with fixation position for the units in SEF yielded values for the slope of discharge rate as a function of eye position that were comparable with what has been described in parietal cortex.

Neurons with activity modulated by eye position have also been described in FEF; these are all related to tracking and fixation in particular directions (Bizzi 1968; Bizzi and Schiller 1979; Bruce and Goldberg 1985). These units appear to differ, however, from what was observed in SEF by the lack of presaccadic modulation [compare Fig. 3 of Bizzi (1968) or Fig. 4 of Bizzi and Schiller (1970) with Fig. 21 of the present paper]. The time course of modulation of the eye position cells in SEF relative to saccadic and pursuit eye movements indicates that their signal may be more of a command than a correlate. In the first place, these cells display a burst that begins before saccades that have the appropriate endpoint. In the second place, during fixation of the appropriate point, the sustained activation is interrupted well before the eye movement that carries gaze from that point.

FORELIMB MOVEMENT CELLS. Other cells in SMA were associated with reaching movements of the forelimb. Neurons related to movements of the forelimb (Brinkman and Porter 1979; Okano and Tanji 1987; Romo and Schultz 1987; Sakai 1978; Smith 1979; Tanji and Kurata 1979, 1982; Tanji and Tanaguchi 1978; Tanji et al. 1980, 1988; Wise and Tanji 1981) and hindlimb (Tanji and Kurata 1981, 1982) have been observed previously in SMA. In the present study each monkey spontaneously used his right arm to perform the task; this was not imposed on them. As observed in another recent study (Tanji et al. 1988), single units in both hemispheres of SMA are related to movements of the right arm. Moreover, the data obtained in the present investigation showed that these neurons tended to respond best for movements in a particular direction. Cells in primary motor cortex are also tuned for the direction of forelimb movements (Georgopoulos et al. 1982, 1986). These authors found a tendency for cells in the hemisphere contralateral to the moving arm to respond best for contralateral movements. Although this was not observed in the present data, the sample was too small to determine this issue reliably for SMA. The results of the present investigation also suggest that the population of forelimb movement cells in the two hemispheres tended to be tuned for different directions of movement of the same limb, which has not

An earlier report from this laboratory (Mann et al. 1988) proposed that there were neurons in SMA that were active in association with both eye and forelimb movements. These cells were called motor equivalent because they were thought to be involved in generating either eye or forelimb movements. The results of the present investigation do not support this conclusion. The earlier investigation did not use a delayed-response forelimb movement task; instead, the monkeys were allowed to initiate a reaching movement as soon as the target appeared. As shown in the present results and by other studies (Biguer et al. 1982; Fischer and Rogal 1986; Fisk and Goodale 1985; Gielen et al. 1984; Herman et al. 1981), saccades are temporally correlated with these reaching movements, so it is likely that saccade-related activity may appear to be associated with the forelimb movements. In the recordings from *monkey Q*, a delayed response reaching task was used. No units were recorded that were truly motor equivalent; instead, units that were active before saccades could appear to be active in relation to forelimb movements if the response delay were very short. Moreover, a reexamination of the data used in that previous study revealed that the cells classified as motor equivalent actually were sensory–eye movement or presaccadic movement cells.

NO-GO CELLS. A few neurons were recorded in SMA that were specifically active only after the no-go cue to withhold movement (see also Mann et al. 1988). Using more sophisticated tasks, other investigators have demonstrated neurons in SMA that were specifically active for a cue for movement (Kurata and Tanji 1985; Sakai 1978) or for a particular instruction stimulus during the task (Tanji et al. 1980; Tanji and Kurata 1985). In fact, cells have been recorded in SMA that were specifically active after stimuli that instructed a monkey not to trigger a movement (Tanji and Kurata 1985). No-go–specific activity has been recorded in the periarcuate prefrontal cortex (Sasaki and Gemba 1986; Watanabe 1986); the latency of a field potential response in prefrontal cortex was 110–150 ms, and the latency of the single-unit responses was 200–400 ms. The latency of the no-go response in SMA was also ~100 ms. These time relationships do not allow one to conclude that the no-go–specific activity in SMA is derived from prefrontal cortex. The nature of the specific suppression these cells might exert requires further investigation.

Topography of SMA

It has taken some time to acquire data to show the somatotopy in SMA (compare Macpherson et al. 1982 with

Gould et al. 1986 and Mitz and Wise 1987; and compare Orgogozo and Larsen 1979 with Fox et al. 1985). In the present investigation, monkeys performed eye movements and forelimb movements as well as oral movements so that the topography of the region of SMA representing the forelimb, mouth, and eyes could be studied. Histological reconstructions of the penetration sites indicated that the recordings were made in the agranular frontal cortex, rostral to the giant layer 5 pyramidal cells and caudal to the prefrontal granular layer. Neuronal activity related to eye movements tended to be found rostrally and cells related to forelimb movements tended to be found caudally. This result confirms the reports of somatotopy in SMA based on microstimulation (Mitz and Wise 1987), regional cerebral blood flow (Fox et al. 1985), and single-unit recordings (Brinkman and Porter 1979; Tanji and Kurata 1982).

Evidence has recently been presented showing that saccades can be elicited from cortical regions extending laterally from SMA/SEF to FEF (Mitz and Godschalk 1989). The present single-unit recordings appear to be inconsistent with this stimulation data. The most laterally placed penetrations encountered only cells that were not modulated in relation to saccadic eye movements. Evidently, more work is needed to resolve this discrepancy.

Conclusion

The results of this investigation provide new information about the functional cell classes in SMA and show that a portion of SMA is involved in gaze control. This region has been referred to as the SEF (Schlag and Schlag-Rey 1987) or dorsomedial frontal cortex (Mann et al. 1988) to distinguish it from the FEF. It appears that this area of cerebral cortex plays a role in generating goal-directed, intentional but not unmotivated spontaneous movements. A comparison of SEF with FEF is presented in the companion article.

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REFERENCES

ANDERSEN, R. A., ASANUMA, C., ESSICK, G., AND SIEGEL, R. M. Corticocortical connections of anatomically and physiologically defined subdivisions within the inferior parietal lobule. *J. Comp. Neurol.* 296: 65–113, 1990a.

ANDERSEN, R. A., BRACEWELL, R. M., BARASH, S., GNADT, J. W., AND FOGASSI, L. Eye position effects on visual, memory and saccade-related activity in areas LIP and 7a of macaque. *J. Neurosci.* 10: 1176–1196, 1990b.

ANDERSEN, R. A., ESSICK, G. K., AND SIEGEL, R. M. Encoding of spatial location by posterior parietal neurons. *Science Wash. DC* 230: 456–458, 1985.

ANDERSEN, R., ESSICK, G. K., AND SIEGEL, R. M. Neurons of area 7 activated by both visual stimuli and oculomotor behavior. *Exp. Brain Res.* 67: 316–322, 1987.

BAEDEKER, L. AND WOLF, W. Influence of saccades on manual reactions: a reaction time and VEP study. *Vision Res.* 27: 609–619, 1987.

BATSCHELET, E. *Circular Statistics in Biology.* New York: Academic, 1981.

BIGUER, B., JEANNEROD, M., AND PRABLANC, C. The coordination of eye, head and arm movements during reaching at a single visual target. *Exp. Brain Res.* 46: 301–304, 1982.

BIZZI, E. Discharge of frontal eye field neurons during saccadic and following eye movements in unanesthetized monkeys. *Exp. Brian Res.* 6: 69–80, 1968.

BIZZI, E. AND SCHILLER, P. H. Neuronal activity in the frontal eye fields of unanesthetized monkeys during head and eye movement. *Exp. Brain Res.* 10: 151–158, 1970.

BIZZI, E., KALIL, R. E., AND TAGLIASCO, V. Eye-head coordination in monkeys: evidence for centrally patterned organization. *Science Wash. DC* 173: 453–454, 1971.

BOCH, R. A. AND GOLDBERG, M. E. Participation of prefrontal neurons in the preparation of visually guided eye movements in rhesus monkey. *J. Neurophysiol.* 61: 1064–1084, 1989.

BRINKMAN, C. AND PORTER, R. Supplementary motor area in the monkey: activity of neurons during performance of a learned motor task. *J. Neurophysiol.* 42: 681–709, 1979.

BRUCE, C. J. Integration of sensory and motor signals for saccadic eye movements in the primate frontal eye fields. In: *Signals and Sense in Cerebral Cortex.* New York: Wiley, 1990, p. 261–314.

BRUCE, C. J. AND GOLDBERG, M. E. Primate frontal eye fields. I. Single neurons discharging before saccades. *J. Neurophysiol.* 53: 603–635, 1985.

BRUCE, C. J., GOLDBERG, M. E., BUSHNELL, C., AND STANTON, G. B. Primate frontal eye fields. II. Physiological and anatomical correlates of electrically evoked eye movements. *J. Neurophysiol.* 54: 714–734, 1985.

CARPENTER, R. H. S. Oculomotor procrastination. In: *Eye Movements: Cognition and Visual Perception.* Hillsdale, NJ: Erlbaum, 1984, p. 237–246.

COLBY, C. L., DUHAMEL, J-R., AND GOLDBERG, M. E. Response properties of neurons in macaque intraparietal sulcus. *Soc. Neurosci. Abstr.* 14: 11, 1988.

CRANDALL, W. F. AND KELLER, E. L. Visual and oculomotor signals in nucleus reticularis tegmenti pontis in alert monkey. *J. Neurophysiol.* 54: 1326–1345, 1985.

DEECKE, L. AND KORNHUBER, H. H. An electrical sign of participation of the mesial "supplementary" motor cortex in human voluntary finger movements. *Brain Res.* 159: 473–476, 1978.

DEECKE, L., KORNHUBER, H. H., LANG, W., LANG, M., AND SCHREIBER, H. Timing function of the frontal cortex in sequential motor and learning tasks. *Hum. Neurobiol.* 4: 143–154, 1985.

EVARTS, E. V., SHINODA, Y., AND WISE, S. P. *Neurophysiological Approaches to Higher Brain Functions.* New York: Wiley, 1984.

FALZETT, M., MOORE, R. K., PETRY, H. M., AND POWERS, M. K. A method for determining threshold from single-unit neural activity. *Brain Res.* 347: 127–131, 1985.

FERRIER, D. Experiments on the brains of monkeys. *Proc. R. Soc. Lond. B Biol. Sci.* 23: 409–430, 1875.

FISCHER, B. AND ROGAL, L. Eye-hand-coordination in man: a reaction time study. *Biol. Cybern.* 55: 253–261, 1986.

FISK, J. D. AND GOODALE, M. A. The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. *Exp. Brain Res.* 60: 159–178, 1985.

FOX, P. T., FOX, J. M., RAICHLE, M. E., AND BURDE, R. M. The role of cerebral cortex in the generation of voluntary saccades: a positron emission tomographic study. *J. Neurophysiol.* 54: 348–369, 1985.

FUNAHASHI, S., BRUCE, C. J., AND GOLDMAN-RAKIC, P. S. Mnemonic coding of visual space in the monkey's dorsolateral prefrontal cortex. *J. Neurophysiol.* 61: 331–349, 1989.

FUSTER, J. M. The prefrontal cortex and temporal integration. In: *Cerebral Cortex: Association and Auditory Cortices,* edited by A. Peters and E. G. Jones. New York: Plenum, 1985, vol. 4, p. 151–177.

GEORGOPOULOS, A. P., KALASKA, J. F., CAMINITI, R., AND MASSEY, J. T.

On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *J. Neurosci.* 2: 1527–1537, 1982.

GEORGOPOULOS, A. P. AND MASSEY, J. T. Cognitive spatial-motor processes. I. The making of movements at various angles from a stimulus direction. *Exp. Brain Res.* 65: 361–370, 1987.

GEORGOPOULOS, A. P., SCHWARTZ, A. B., AND KETTNER, R. E. Neuronal population coding of movement direction. *Science Wash. DC* 233: 1416–1419, 1986.

GIELEN, C. C. A. M., VAN DEN HEUVEL, P. J. M., AND VAN GISBERGEN, J. A. M. Coordination of fast eye and arm movements in a tracking task. *Exp. Brain Res.* 56: 154–161, 1984.

GNADT, J. W. AND ANDERSEN, R. A. Memory related motor planning activity in posterior parietal cortex of macaque. *Exp. Brain Res.* 70: 216–220, 1988.

GODSCHALK, M. AND LEMON, R. N. Involvement of monkey premotor cortex in the preparation of arm movements. *Exp. Brain Res. Suppl.* 7: 114–119, 1983.

GODSCHALK, M., LEMON, R. N., KUYPERS, H. G. J. M., AND VAN DER STEEN, J. The involvement of monkey premotor cortex neurones in preparation of visually cued arm movements. *Behav. Brain Res.* 18: 143–157, 1985.

GOLDBERG, M. E. AND BRUCE, C. J. Primate frontal eye fields. III. Maintenance of a spatially accurate saccade signal. *J. Neurophysiol.* 64: 489–508, 1990.

GOLDBERG, M. E. AND BUSHNELL, M. C. Behavioral enhancement of visual responses in monkey cerebral cortex. II. Modulation in frontal eye fields specifically related to saccades. *J. Neurophysiol.* 46: 773–787, 1981.

GOLDBERG, M. E. AND SEGRAVES, M. A. Visual and frontal cortices. In: *The Neurobiology of Saccadic Eye Movements.* New York: Elsevier, 1989, p. 283–313.

GOLDMAN-RAKIC, P. S. Circuitry of prefrontal cortex and regulation of behavior by representation memory. In: *Handbook of Physiology. The Nervous System. Higher Functions of the Brain.* Bethesda, MD: Am. Physiol. Soc., 1987, sect. 1, vol. I, p. 373–417.

GOULD, J. H., CUSICK, C. G., PONS, T. P., AND KAAS, J. H. The relationship of corpus callosum connections to electrical stimulation maps of motor, supplementary motor and frontal eye fields in owl monkeys. *J. Comp. Neurol.* 247: 297–325, 1986.

HERMAN, R., HERMAN, R., AND MAULUCCI, R. Visually triggered eye-arm movements in man. *Exp. Brain Res.* 42: 392–398, 1981.

HIKOSAKA, O., SAKAMOTO, M., AND USUI, S. Functional properties of monkey caudate neurons. I. Activities related to saccadic eye movements. *J. Neurophysiol.* 61: 780–798, 1989a.

HIKOSAKA, O., SAKAMOTO, M., AND USUI, S. Functional properties of monkey caudate neurons. II. Visual and auditory responses. *J. Neurophysiol.* 61: 799–813, 1989b.

HIKOSAKA, O. AND WURTZ, R. H. Visual and oculomotor functions of monkey substantia nigra pars reticulata. I. Relation of visual and auditory responses to saccades. *J. Neurophysiol.* 49: 1230–1253, 1983a.

HIKOSAKA, O. AND WURTZ, R. H. Visual and oculomotor functions of monkey substantia nigra pars reticulata. III. Memory-contingent visual and saccade responses. *J. Neurophysiol.* 49: 1268–1284, 1983b.

HUERTA, M. F. AND KAAS, J. H. Supplementary eye field as defined by intracortical microstimulation: connections in macaques. *J. Comp. Neurol.* 293: 299–330, 1990.

JOSEPH, J. P. AND BARONE, P. Prefrontal unit activity during a delayed oculomotor task in the monkey. *Exp. Brain Res.* 67: 460–468, 1987.

JÜRGENS, U. The efferent and afferent connections of the supplementary motor area. *Brain Res.* 300: 63–81, 1984.

KORNBLUM, S. AND REQUIN, J. *Preparatory States and Processes.* Hillsdale, NJ: Erlbaum, 1984.

KUBOTA, K. AND FUNAHASHI, S. Direction-specific activities of dorsolateral prefrontal and motor cortex pyramidal tract neurons during visual tracking. *J. Neurophysiol.* 47: 362–376, 1982.

KURATA, K. AND TANJI, J. Contrasting neuronal activity in supplementary and precentral motor cortex of monkeys. II. Responses to movement triggering vs. nontriggering sensory signals. *J. Neurophysiol.* 53: 142–152, 1985.

KURATA, K. AND WISE, S. P. Premotor and supplementary motor cortex in rhesus monkeys: neuronal activity during externally- and internally-instructed motor tasks. *Exp. Brain Res.* 72: 237–248, 1988.

KURTZBERG, D. AND VAUGHAN, H. G. Electrocortical potentials associated with eye movements. In: *The Oculomotor System and Brain Functions,* edited by V. Zikmund, London: Butterworths, 1973, p. 137–145.

KURTZBERG, D. AND VAUGHAN, H. G. Topographic analysis of human cortical potentials preceding self-initiated and visually triggered saccades. *Brain Res.* 243: 1–9, 1982.

LEICHNETZ, G. R., SMITH, D. J., AND SPENCER, R. F. Cortical projections to the paramedian tegmental and basilar pons in the monkey. *J. Comp. Neurol.* 228: 388–408, 1984a.

LEICHNETZ, G. R., SPENCER, R. F., AND SMITH, D. J. Cortical projections to nuclei adjacent to the oculomotor complex in the medial dien-mesencephalic tegmentum in the monkey. *J. Comp. Neurol.* 228: 359–387, 1984b.

LIBET, B., GLEASON, C. A., WRIGHT, E. W., AND PEARL, D. K. Time of conscious intention to act in relation to onset of cerebral activity (readiness potential): the unconscious initiation of a freely voluntary act. *Brain* 106: 623–642, 1983a.

LIBET, B., WRIGHT, E. W., AND GLEASON, C. A. Readiness potentials preceding unrestricted "spontaneous" vs. pre-planned voluntary acts. *Electroencephalogr. Clin. Neurophysiol.* 54: 322–335, 1982.

LIBET, B., WRIGHT, E. W., AND GLEASON, C. A. Preparation or intention-to-act in relation to pre-event potentials recorded at the vertex. *Electroencephalogr. Clin. Neurophysiol.* 56: 367–372, 1983b.

LYNCH, J. C., MOUNTCASTLE, V. B., TALBOT, W. H., AND YIN, T. C. T. Parietal lobe mechanisms for directed visual attention. *J. Neurophysiol.* 40: 362–389, 1977.

MACPHERSON, J. M., MARANGOZ, C., MILES, T. S., AND WIESENDANGER, M. Microstimulation of the supplementary motor area (SMA) in the awake monkey. *Exp. Brain Res.* 45: 410–416, 1982.

MANN, S. E., THAU, R., AND SCHILLER, P. H. Conditional task-related responses in monkey dorsomedial frontal cortex. *Exp. Brain Res.* 69: 460–468, 1988.

MARROCCO, R. T. Saccades induced by stimulation of the frontal eye fields: interaction with voluntary and reflexive eye movements. *Brain Res.* 146: 23–34, 1978.

MATIN, E. Saccadic suppression: a review and an analysis. *Psychol. Bull.* 81: 899–917, 1974.

MAYS, L. E. AND SPARKS, D. L. Dissociation of visual and saccade-related responses in superior colliculus neurons. *J. Neurophysiol.* 43: 207–232, 1980.

MELAMED, E. AND LARSEN, B. Cortical activation pattern during saccadic eye movements in humans: localization by focal cerebral blood flow increases. *Ann. Neurol.* 5: 79–88, 1979.

MITZ, A. R. AND GODSCHALK, M. Eye movement representation in the frontal lobe of rhesus monkeys. *Neurosci. Lett.* 106: 157–162, 1989.

MITZ, A. R. AND WISE, S. P. The somatotopic organization of the supplementary motor area: intracortical microstimulation mapping. *J. Neurosci.* 7: 1010–1021, 1987.

MOHLER, C. W. AND WURTZ, R. H. Organization of monkey superior colliculus: intermediate layer cells discharging before eye movements. *J. Neurophysiol.* 39: 722–744, 1976.

MOSTER, M. L. AND GOLDBERG, G. Topography of scalp potentials preceding self-initiated saccades. *Neurology* 40: 644–648, 1990.

OKANO, K. AND TANJI, J. Neuronal activities in the primate motor fields of the agranular frontal cortex preceding visually triggered and self-paced movement. *Exp. Brain Res.* 66: 155–166, 1987.

ORGOGOZO, J. M. AND LARSEN, B. Activation of the supplementary motor area during voluntary movement in man suggests it works as a supramotor area. *Science Wash. DC* 206: 847–850, 1979.

PARTHASARATHY, H. B., SCHALL, J. D., AND GRAYBIEL, A. M. Dual-tracer comparison of the corticostriatal projections of the frontal eye field and the supplementary eye field in the primate. *Soc. Neurosci. Abstr.* 16: 1231, 1990.

PENFIELD, W. AND WELCH, K. The supplementary motor area in the cerebral cortex of man. *Trans. Am. Neurol. Assoc.* 74: 179–184, 1949.

PENFIELD, W. AND WELCH, K. The supplementary motor area of the cerebral cortex: a clinical and experimental study. *Arch. Neurol. Psychiatry* 66: 289–317, 1951.

REULEN, J. P. H. Latency of visually evoked saccadic eye movements. I. Saccadic latency and the facilitation model. *Biol. Cybern.* 50: 251–262, 1984.

ROBINSON, D. A. A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Trans. Biomed. Eng.* 10: 137–145, 1963.

ROBINSON, D. A. AND FUCHS, A. F. Eye movements evoked by stimulation of frontal eye fields. *J. Neurophysiol.* 32: 637–648, 1969.

ROBINSON, D. L., GOLDBERG, M. E., AND STANTON, G. B. Parietal association cortex in the primate: sensory mechanisms and behavioral modulations. *J. Neurophysiol.* 41: 910–932, 1978.

ROBINSON, D. L., PETERSON, S. E., AND KEYS, W. Saccade-related and visual activities in the pulvinar nuclei of the behaving rhesus monkey. *Exp. Brain Res.* 62: 625–634, 1986.

ROLAND, P. E., LARSEN, B., LASSEN, N. A., AND SKINHJ, E. Supplementary motor area and other cortical areas in organization of voluntary movements in man. *J. Neurophysiol.* 43: 118–136, 1980.

ROMO, R. AND SCHULTZ, W. Neuronal activity preceding self-initiated or externally timed arm movements in area 6 of monkey cortex. *Exp. Brain Res.* 67: 656–662, 1987.

SAKAI, M. Single unit activity in a border area between the dorsal prefrontal and premotor regions in the visually conditioned motor task of monkeys. *Brain Res.* 147: 377–383, 1978.

SAKATA, H., SHIBUTANI, H., AND KAWANO, K. Spatial properties of visual fixation neurons in posterior parietal association cortex of the monkey. *J. Neurophysiol.* 43: 1654–1672, 1980.

SASAKI, K. AND GEMBA, H. Electrical activity in the prefrontal cortex specific to no-go reaction of conditioned hand movement with color discrimination in the monkey. *Exp. Brain Res.* 64: 603–606, 1986.

SCHALL, J. D. Saccade latency and preparatory neuronal activity in the supplementary and frontal eye fields. *Soc. Neurosci. Abstr.* 14: 159, 1988.

SCHALL, J. D. Neural basis of saccadic eye movements in primates. In: *Vision and Visual Dysfunction. The Neural Basis of Visual Function,* edited by A. G. Leventhal. London: MacMillan, 1991, p. 388–442.

SCHALL, J. D. Neuronal activity related to visually guided saccades in the frontal eye fields of rhesus monkeys: comparison with supplementary eye fields. *J. Neurophysiol.* 66: 559–579, 1991b.

SCHALL, J. D., MANN, S. E., AND SCHILLER, P. H. Investigation of the roles of dorsomedial and ventrolateral premotor regions and the frontal eye fields in visually guided movements. *Soc. Neurosci. Abstr.* 13: 1095, 1987.

SCHELL, G. R. AND STRICK, P. L. The origin of thalamic inputs to the arcuate premotor and supplementary motor areas. *J. Neurosci.* 4: 539–560, 1984.

SCHILLER, P. H. The effect of superior colliculus ablation on saccades elicited by cortical stimulation. *Brain Res.* 122: 154–156, 1977.

SCHILLER, P. H., TRUE, S. D., AND CONWAY, J. L. Paired stimulation of the frontal eye fields and the superior colliculus of the rhesus monkey. *Brain Res.* 179: 162–164, 1979.

SCHILLER, P. H., TRUE, S. D., AND CONWAY, J. L. Deficits in eye movements following frontal eye field and superior colliculus ablations. *J. Neurophysiol.* 44: 1175–1189, 1980.

SCHLAG, J. AND SCHLAG-REY, M. Thalamic units firing upon refixation may be responsible for plasticity in visual cortex. *Exp. Brain Res.* 50: 146–148, 1983.

SCHLAG, J. AND SCHLAG-REY, M. Visuomotor functions of central thalamus in monkey. II. Unit activity related to visual events, targeting and fixation. *J. Neurophysiol.* 51: 1175–1195, 1984.

SCHLAG, J. AND SCHLAG-REY, M. Eye fixation units in the supplementary eye field of monkey. *Soc. Neurosci. Abstr.* 11: 82, 1985.

SCHLAG, J. AND SCHLAG-REY, M. Role of central thalamus and supplementary eye field in voluntary control of gaze in space. *Bull. Tokyo Metrop. Inst. Neurosci. Suppl.* 17–31, 1986.

SCHLAG, J. AND SCHLAG-REY, M. Evidence for a supplementary eye field. *J. Neurophysiol.* 57: 179–200, 1987.

SCHLAG-REY, M., JEFFERS, I., AND SCHLAG, J. Central thalamus and supplementary eye field sites for goal-directed saccades have reciprocal connections (Abstract). *Invest. Ophthalmol. Visual Sci.* 28, *Suppl.*: 333, 1987.

SCHLAG-REY, M. AND SCHLAG, J. Visuomotor functions of central thalamus in monkey. I. Unit activity related to spontaneous eye movements. *J. Neurophysiol.* 51: 1149–1174, 1984.

SCHNYDER, H., REISINE, H., HEPP, K., AND HENN, V. Frontal eye field projection to the paramedian pontine reticular formation traced with wheatgerm agglutinin in the monkey. *Brain Res.* 329: 151–160, 1985.

SHOOK, B. L., SCHLAG-REY, M., AND SCHLAG, J. Primate supplementary eye field. I. Comparative aspects of mesencephalic and pontine connections. *J. Comp. Neurol.* 301: 618–642, 1990.

SMITH, A. M. The activity of supplementary motor area neurons during a maintained precision grip. *Brain Res.* 172: 315–327, 1979.

SUZUKI, H. AND AZUMA, M. Topographic studies on visual neurons in the dorsolateral prefrontal cortex of the monkey. *Exp. Brain Res.* 53: 47–58, 1983.

TANJI, J. AND EVARTS, E. V. Anticipatory activity of motor cortex neurons in relation to direction of an intended movement. *J. Neurophysiol.* 39: 1062–1068, 1976.

TANJI, J. AND KURATA, K. Neuronal activity in the cortical supplementary motor area related with distal and proximal forelimb movements. *Neurosci. Lett.* 12: 201–206, 1979.

TANJI, J. AND KURATA, K. Contrasting neuronal activity in the ipsilateral and contralateral supplementary motor areas in relation to a movement of monkey's distal hindlimb. *Brain Res.* 222: 155–158, 1981.

TANJI, J. AND KURATA, K. Comparison of movement-related activity in two cortical motor areas of primates. *J. Neurophysiol.* 48: 633–653, 1982.

TANJI, J. AND KURATA, K. Contrasting neuronal activity in supplementary and precentral motor cortex of monkeys. I. Responses to instructions determining motor responses to forthcoming signals of different modalities. *J. Neurophysiol.* 53: 129–141, 1985.

TANJI, J., OKANO, K., AND SATO, K. C. Neuronal activity in cortical motor areas related to ipsilateral, contralateral and bilateral digit movements of the monkey. *J. Neurophysiol.* 60: 325–343, 1988.

TANJI, J. AND TANIGUCHI, K. Does the supplementary motor area play a role in modifying motor cortex reflexes? *J. Physiol. Paris* 74: 317–318, 1978.

TANJI, J., TANIGUCHI, K., AND SAGA, T. Supplementary motor area: neuronal response to motor instructions. *J. Neurophysiol.* 43: 60–68, 1980.

VAN GISBERGEN, J. A. M. AND VAN OPSTAL, A. J. Models. In: *The Neurobiology of Saccadic Eye Movements,* edited by R. H. Wurtz and M. E. Goldberg. New York: Elsevier, 1989, p. 69–101.

WALKER, A. E. A cytoarchitectural study of the prefrontal area of the macaque monkey. *J. Comp. Neurol.* 73: 59–86, 1940.

WATANABE, M. Prefrontal unit activity during delayed conditional go/no-go discrimination in the monkey. II. Relation to go and no-go responses. *Brain Res.* 382: 15–27, 1986.

WEINRICH, M. AND WISE, S. P. The premotor cortex of the monkey. *J. Neurosci.* 2: 1329–1345, 1982.

WEINRICH, M., WISE, S. P., AND MAURITZ, K-H. A neurophysiological analysis of the premotor cortex of the monkey. *Brain* 107: 385–414, 1984.

WIESENDANGER, R. AND WIESENDANGER, M. The thalamic connections with medial area 6 (supplementary motor cortex) in the monkey (*Macaca fascicularis*). *Exp. Brain Res.* 59: 91–104, 1985.

WIESENDANGER, R., WIESENDANGER, M., AND RUEGG, D. G. An anatomical investigation of the corticopontine projection in the primate (*Macaca fascicularis* and *Saimiri sciureus*). II. The projection from frontal and parietal association areas. *Neuroscience* 4: 747–765, 1979.

WISE, S. P. AND MAURITZ, K-H. Set-related neuronal activity in the premotor cortex of rhesus monkeys: effects of changes in motor set. *Proc. R. Soc. Lond. B Biol. Sci.* 223: 331–354, 1985.

WISE, S. P. AND TANJI, J. Supplementary and precentral motor cortex: contrast in responsiveness to peripheral input in the hindlimb area of the unanesthetized monkey. *J. Comp. Neurol.* 195: 433–451, 1981.

WOOLSEY, C. N., SETTLAGE, P. H., MEYER, D. R., SPENCER, W., HAMEY, T. P., AND TRAVIS, A. M. Patterns of localization in precentral and "supplementary" motor areas and their relation to the concept of a premotor area. *Res. Publ. Assoc. Res. Nerv. Ment. Dis.* 30: 238–264, 1952.

WURTZ, R. H. AND MOHLER, C. W. Enhancement of visual response in monkey striate cortex and frontal eye fields. *J. Neurophysiol.* 39: 666–722, 1976.

ZAMBARBIERI, D., SCHMID, R., MAGENES, G., AND PRABLANC, C. Saccadic responses evoked by presentation of visual and auditory targets. *Exp. Brain Res.* 47: 417–427, 1982.