

# Visual, Presaccadic, and Cognitive Activation of Single Neurons in Monkey Lateral Intraparietal Area

CAROL L. COLBY, JEAN-RENÉ DUHAMEL, AND MICHAEL E. GOLDBERG

*Laboratory of Sensorimotor Research, National Eye Institute, Bethesda, Maryland 20892; Department of Neuroscience and Center for the Neural Basis of Cognition, University of Pittsburgh, Pittsburgh, Pennsylvania 15260; and Department of Neurology, Georgetown University School of Medicine, Washington, DC 20007.*

## SUMMARY AND CONCLUSIONS

1. Posterior parietal cortex contains neurons that are visually responsive and active in relation to saccadic eye movements. We recorded from single neurons in a subregion of parietal cortex, the lateral intraparietal area (LIP), in alert rhesus monkeys. To characterize more completely the circumstances under which LIP neurons are responsive, we used five tasks designed to test the impact of sensory, motor, and cognitive factors. We obtained quantitative data in multiple tasks in 91 neurons. We measured neural activity during central fixation and in relation to stimulus onset and saccade onset.

2. LIP neurons have visual responses to the onset of a stationary stimulus in the receptive field. These visual responses occurred both in tasks that require a subsequent eye movement toward the stimulus and in tasks in which eye movements are not permitted, indicating that this activity is sensory rather than presaccadic.

3. Visual responses were enhanced when the monkey had to use information provided by the stimulus to guide its behavior. The amplitude of the sensory response to a given stimulus was increased in a task in which the monkey would subsequently make a saccade to the location signaled by the stimulus, as compared with the amplitude of the visual response in a simple fixation task.

4. The visual response was also enhanced when the monkey attended to the stimulus without looking at it. This result shows that enhancement does not reflect saccade preparation because the response is enhanced even when the monkey is not permitted to make a saccade. Instead, enhancement reflects the allocation of attention to the spatial locus of the receptive field.

5. Many LIP neurons had saccade-related activity in addition to their visual responses. The visual response for most neurons was stronger than the saccade-related activation.

6. Saccade-related activity was independent of visual activity. Similar presaccadic activity was observed in trials that included a recent visual stimulus (memory-guided saccade task) and in trials with no visual stimulus (learned saccade task).

7. We observed increases in activity during fixation in tasks in which the monkey could anticipate the onset of a behaviorally significant stimulus. LIP neurons usually showed low levels of background firing in the fixation task during the period before stimulus onset. This background activity was increased in the peripheral attention and memory-guided saccade tasks during the period when the monkey was waiting for a behaviorally relevant stimulus to appear.

8. The results from these several tasks indicate that LIP neurons are activated in a variety of circumstances and are not involved exclusively in sensory processing or motor planning. The modulation of sensory responses by attention and anticipation suggests that cognitive factors play a major role in parietal function.

as looking at or reaching for an object (Critchley 1953). A series of neurophysiological investigations have attempted to delineate the neural mechanisms that underlie these parietal functions. The initial single-unit studies of Hyvarinen and Poranen (1974) and of Mountcastle and his colleagues (Lynch et al. 1977; Mountcastle et al. 1975) demonstrated that parietal neurons discharge in association with visually guided saccades, suggesting a motor command function for these neurons. A different group of investigators found, however, that parietal neurons were also active during fixation when a visual stimulus appeared the receptive field, indicating a sensory role for these neurons (Robinson et al. 1978). These visual responses were enhanced when the stimulus was made behaviorally relevant, suggesting a specifically attentional role for parietal cortex (Bushnell et al. 1981; Robinson et al. 1978). These contrasting views of parietal cortex function arose in part from the use of different kinds of tasks. Also, these early investigations made use of tasks in which visual and motor events were temporally conjoined, making it difficult to isolate different sources of activation.

The introduction of the memory-guided saccade task by Hikosaka and Wurtz (1983) provided a way to separate visual and motor events in time and has led to a clearer understanding of parietal neuron activity. More recent studies using this task have shown that parietal neurons have distinct sensory, mnemonic, and motor activations (Andersen et al. 1987, 1990; Barash et al. 1991a,b; Gnadt and Andersen 1988; Goldberg et al. 1990). In the present experiments, we investigated the sources of neural activity in a particular area within parietal cortex, the lateral intraparietal area (LIP), a region with a high concentration of visuomotor neurons. We used multiple tasks in order to characterize more completely the activity of area LIP neurons. We found that LIP neurons are active under many different circumstances and that this activity is subject to modulation by cognitive factors such as anticipation and attention.

There are four main new results from this study. First, we found that the presaccadic enhancement originally described in area 7 (Bushnell et al. 1981; Robinson et al. 1978) is a specific enhancement of the visual response to stimulus onset. Second, this enhancement of the visual response in a saccade task is correlated with the degree of enhancement in a purely attentional task. Third, we found that LIP neurons have an independent presaccadic activation that is unrelated to the recent presentation of a visual stimulus. Fourth, baseline activity in LIP neurons is modulated by the monkey's anticipation that a behaviorally significant stimulus is about to appear.

## INTRODUCTION

Posterior parietal cortex is important for the appreciation of object location and for spatially oriented behaviors, such

The multiple sources of activation apparent in LIP neuron responses suggest that these neurons do not signal sensory or motor events exclusively. Instead, the common factor underlying activation for a given neuron appears to be the location of an event with respect to the receptive field. These results suggest that parietal neurons are involved in spatial representation and encode behaviorally significant spatial locations, that is, locations at which events have recently occurred or to which actions are about to be directed. Preliminary results from these experiments have been published previously (Colby et al. 1993; Goldberg et al. 1990).

## METHODS

### *Animal preparation*

Three rhesus monkeys (*Macaca mulatta*) were used in this study. Before surgery, they were trained to sit in a primate chair and fixate spots of light for a liquid reward (Wurtz 1969). They were then surgically prepared under general anesthesia (induced with ketamine and maintained with isoflurane) for chronic neurophysiological recording by the implantation of scleral search coils (Judge et al. 1980), headholding devices, and recording chambers through which electrodes could subsequently be introduced into the cerebral cortex. Recording chambers (1.8 cm diam) were centered over the intraparietal sulcus at stereotaxic coordinates AP - 5 and L 12 mm. Chambers were placed flat against the skull. The angle of the central portion of the intraparietal sulcus is approximately orthogonal to the skull, so this approach yielded long, tangential electrode penetrations through the lateral bank of the sulcus. Animals were watched closely after surgery and given analgesics as needed. During the recording period, animal weight and health status were carefully monitored. Fluid supplements were given as needed. Recording chambers were flushed with saline before and after each recording session and antibiotics applied as needed. When necessary, the exposed dura in the recording chamber was surgically debrided under ketamine anesthesia. All experimental protocols were approved by the National Eye Institute Animal Care and Use Committee and were certified to be in compliance with the guidelines set forth in the Public Health Service Guide for the Care and Use of Laboratory Animals.

### *Physiological methods*

Recordings were made with flexible tungsten microelectrodes (Frederick Haer) introduced through stainless steel guide tubes placed nearly but not quite through the dura, which in turn were stabilized by a nylon grid held rigidly in the recording cylinder (Crist et al. 1988). The grid system served as a guide to produce parallel penetrations with a resolution of 0.5 mm. The rigidity of the system and the atraumatic nature of the electrodes allowed us to perform a large number of penetrations at multiple recording sites within intraparietal sulcus. We found that electrode penetrations performed several months apart at the same grid location yielded neurons with similar response types at similar depths.

During a recording session the monkey sat in a primate chair in a darkened room facing a tangent screen 57 cm away. Visual stimuli were produced by red or white light-emitting diodes back-projected onto the screen. Stimulus position was set by servo-controlled mirror galvanometers (General Scanning). Behavioral monitoring, eye position and unit sampling, and on-line data analysis were performed by a PDP-11/73 computer (Goldberg 1983). Action potentials were detected by a window discriminator (Bak) with threshold and window adjusted to isolate spikes from an individual neuron. Spikes were sampled at 1 kHz. Horizontal and

vertical eye position signals were measured by a search coil system, also sampled at 1 kHz. The computer program displayed 16 rasters on-line, synchronized to one of several events such as achievement of fixation, stimulus onset or offset, fixation point offset, saccade beginning or end, reward, etc. Unit discharges, eye position traces, behavioral indicators, and six calculated rasters were saved on disk for off-line analysis.

In each electrode penetration we searched for neurons with the use of the memory-guided saccade task. Visual responses were enhanced in this task relative to the fixation task, which made neurons easier to locate. Also, we were specifically interested in recording from neurons with saccade-related activity, and this task allowed us to identify such cells. Neurons with only visual responses were intermingled with those that had both visual and saccade-related activity. We usually recorded complete data sets only from the latter. The saccade target position was controlled by a joy stick, allowing rapid intertrial changes in target position. After isolating a neuron, the receptive field was mapped with the use of the memory-guided saccade task, and the optimal stimulus location was determined. This stimulus location was then used for data collection in the five tasks described below.

### *Histological methods*

In each monkey, after having recorded from LIP in one or both hemispheres, we recorded again at several sites and placed a pattern of microlesions (10  $\mu$ A for 10 s) designed to identify specific electrode tracks and the depth at which specific types of activity were found. Animals were deeply anesthetized with pentobarbital sodium and perfused transcardially with heparinized saline followed by 10% formal saline. Marking pins were inserted through the recording grid to mark the extent of the recording zone. The brain was blocked in the plane of the grid in order to capture complete penetrations within single brain sections. Serial sections, cut at 50  $\mu$ m and thionine stained, were used to reconstruct the location of electrode penetrations. A one in five series was myelin stained by the use of the Gallyas method. We reconstructed the location of penetrations through LIP by identifying myeloarchitectonic boundaries and the locations of microlesions at known microdrive depths in recent penetrations.

### *Behavioral methods*

Monkeys were trained on a series of tasks designed to differentiate sensory, attentional, and motor correlates of neural activity. All tasks were run in blocks of 16 trials to reinforce the monkey's behavior, except for the learned saccade task, which was run in blocks long enough to ensure 16 trials each of the randomly intermixed visually triggered and learned saccade trials (Bruce and Goldberg 1985). Neurons were studied in a series of standard tasks, illustrated in Fig. 1.

1) *Visual fixation task.* The monkey gazed at a central fixation point while a second, behaviorally irrelevant stimulus was flashed elsewhere on the tangent screen. The monkey was rewarded either for holding eye position for a certain interval, or for releasing a lever to signal a slight dimming of the fixation point. This task was used to study the visual responsiveness of neurons in a situation where the stimulus had no behavioral significance.

2) *Peripheral attention task* (Wurtz and Mohler 1976). The fixation point and receptive-field stimulus appeared as in the fixation task, and the monkey had to maintain central fixation throughout the trial. The receptive-field stimulus dimmed slightly 400–1,600 ms after onset, and the monkey had to respond by immediately releasing a bar. Previous experiments used a version of this task in which either the fixation point or the receptive-field stimulus could be dimmed, requiring the monkey to attend to both (Bushnell

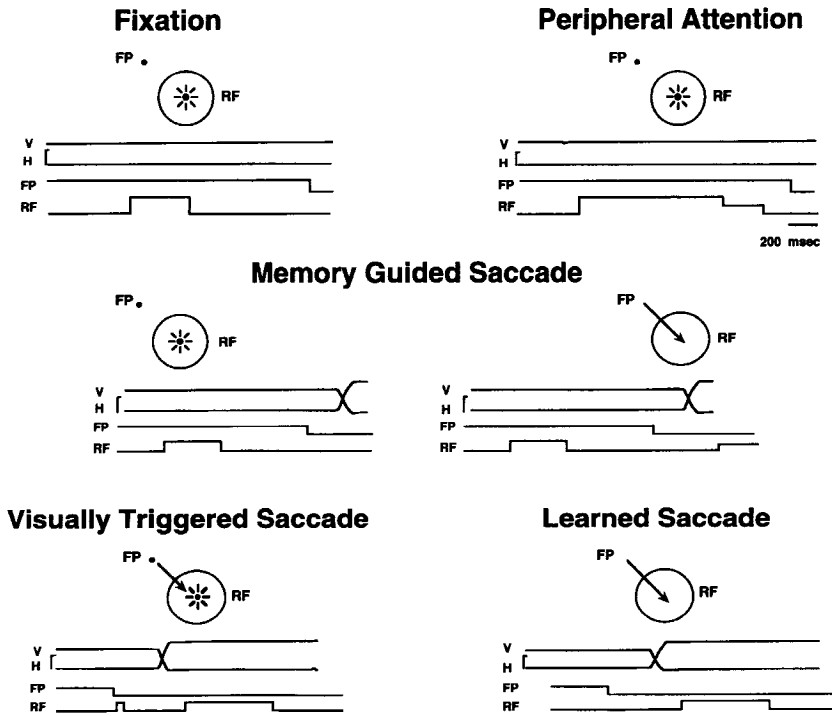


FIG. 1. Tasks used to characterize neural activity in the lateral intraparietal area (area LIP). For each task, a cartoon shows a sample trial with the location of the fixation point (FP), the receptive field (circle labeled RF) and visual stimulus (star). Saccade direction is indicated by an arrow, with the saccade goal at the arrowhead. Beneath each cartoon are time lines indicating horizontal (H) and vertical (V) eye position and the status of the lights at FP and RF (up is on, down is off). For the memory-guided saccade task, the 2 panels illustrate different time points with stimulus onset at left and saccade beginning at right. In the peripheral attention task, the monkey makes a manual response immediately after the target dims. In each of the saccade tasks, the target is absent at the time of the saccade but reappears at the fovea 50–200 ms after the end of the saccade.

et al. 1981). In the present experiment, only the receptive-field stimulus dimmed. The trial was aborted if the monkey made a saccade to the target. Monkeys maintained fixation during the intertrial interval and did not saccade to the target location after the light dimmed because this slowed down the onset of the next trial. This task was used to study the visual responsiveness of neurons when the monkey had to attend to a peripheral stimulus without generating an eye movement toward it.

3) *Memory-guided saccade task* (Hikosaka and Wurtz 1983). During the fixation period, the receptive-field stimulus appeared for  $\leq 200$  ms. The monkey had to continue to look at the fixation point for at least 500 and up to 1,500 ms after the stimulus had disappeared. If the monkey made a saccade at the appropriate time (fixation point offset) to the location where the target had been, the target reappeared 50–200 ms after the end of the saccade, and the monkey was rewarded for holding the new eye position. This task was used to dissociate activity related to the stimulus from activity related to the movement and to assess the impact of making the stimulus behaviorally relevant.

4) *Visually triggered saccade task*. The monkey looked at a fixation point until it disappeared, at which time a peripheral light appeared briefly ( $< 50$  ms). A 5-ms pause intervened between extinguishing the fixation point and illuminating the saccade target so that the two lights did not appear simultaneously. The monkey immediately made a saccade to the position of the new target, and the target then reappeared. The animal was rewarded for holding the new eye position. The target reappeared at the fovea 50–200 ms after the end of the saccade.

5) *Learned saccade task* (Bruce and Goldberg 1985). Two trial types were interleaved in this task. The monkey first made visually triggered saccades to a briefly flashed target that always appeared in the receptive field. After a few of these trials, to establish the correct location for the saccade, visually triggered saccade trials were interleaved with learned saccade trials. In learned saccade trials, the fixation point was extinguished, but no peripheral target appeared. The monkey was rewarded for making a saccade to the location at which the target had appeared on previous trials. The

target reappeared at the fovea 50–200 ms after the end of the saccade. This task was used to determine whether the neuron had movement-related activity that was independent of the recent presence of a visual target.

The order of the tasks varied. Typically, the memory-guided saccade task was run first, followed by the fixation task, the peripheral attention task, and then the learned saccade/visually triggered saccade task. Tasks were repeated as time permitted.

*Data analysis*

For each neuron in each task, responses were measured off-line for 16 successive correctly performed trials. To measure the response to visual stimuli, we calculated a cumulative histogram and smoothed and differentiated it with the use of a finite impulse response filter. The computer program automatically defined the beginning of the response as the point after the appearance of the visual stimulus at which the instantaneous first derivative exceeded an arbitrary number, usually 125 spikes/s. Each histogram was checked visually to ensure that the cursor position was at a plausible location, near the first inflection point of the cumulative histogram. The response was then calculated as mean spike frequency for the 100 ms after the beginning of the burst. To measure the presaccadic activity of neurons, the mean spike frequency during the 100 ms before the beginning of the saccade was calculated. This measure does not include activity occurring during or after the saccade. The saccade beginning was determined on-line with the use of a digital filtering algorithm, and markers for the beginning and end of saccades were stored with the analog record. For each trial the computed saccade beginning was verified off-line. Background activity was measured as the mean spike discharge in the 100 ms before the presentation of visual stimulus or saccade target, at a time well after the monkey had achieved fixation. We did not subtract background activity from our response values because, as will be described later, background activity varied as a function of task.

Neural responses across the population were compared with the

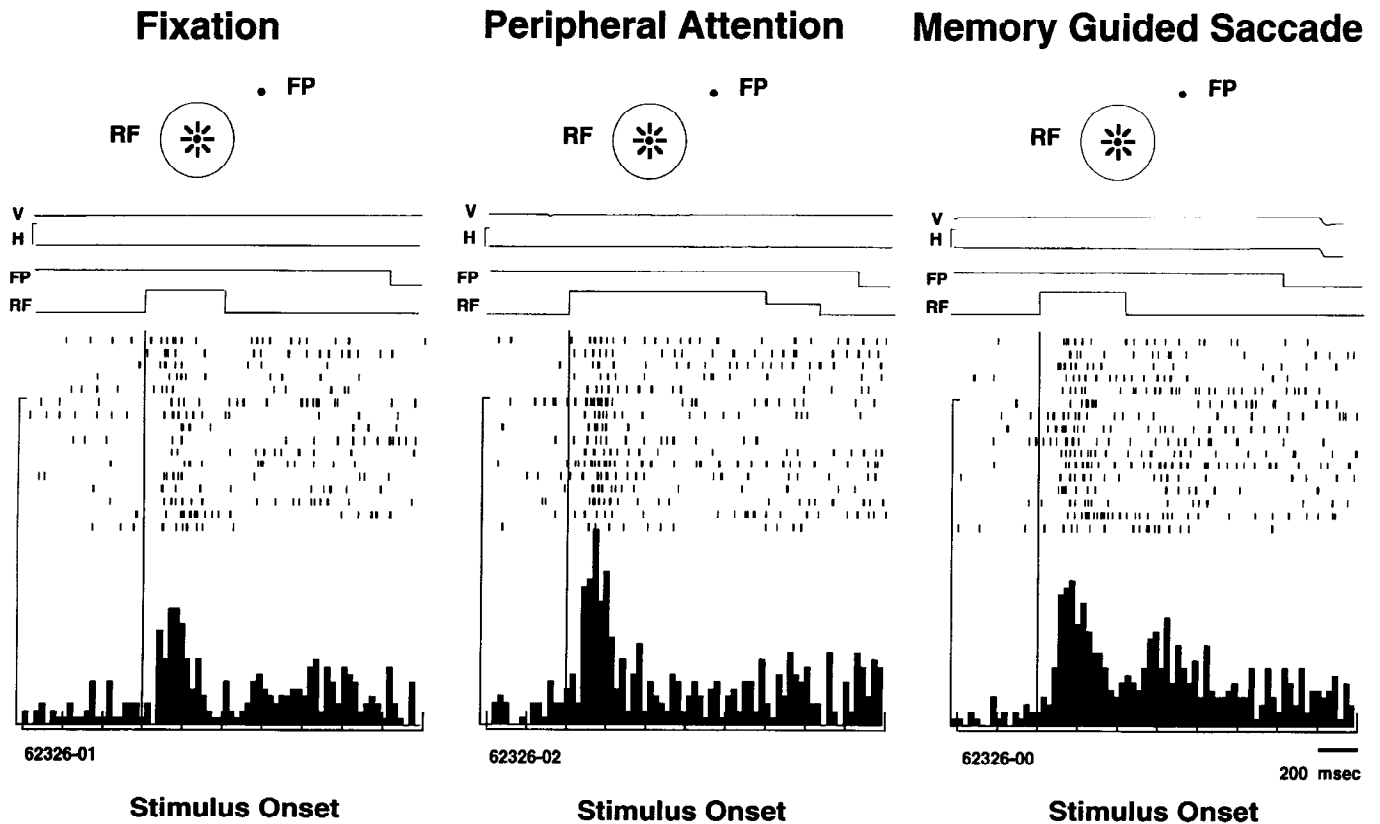


FIG. 2. Enhancement of visual responses to behaviorally significant stimuli in a single LIP neuron. Each panel shows a raster and histogram synchronized on stimulus onset. In the raster display, each vertical tic mark indicates the time of occurrence of an action potential, and each horizontal line shows activity during a single trial. Successive trials are aligned on the vertical trigger line. The histogram calibration bar at far left signifies a firing rate of 100 spikes/s. The amplitude of the visual response to stimulus onset is enhanced in both the peripheral attention and memory-guided saccade tasks as compared with that in the fixation task.

use of the Wilcoxon paired rank test as implemented in the SuperAnova statistical package. This statistic allowed us to ask whether neural activity in pairs of tasks differed across the sample without requiring an assumption of a normal distribution.

We quantified the degree of response modulation in the memory-guided saccade task by calculating for each neuron an enhancement index: the ratio between the visual response in that task and the response in the fixation task. We then used a *t*-test to determine whether there was a significant change in the neuron's response between the two conditions. An enhancement index was also calculated for visual responses in the peripheral attention task as compared with the fixation task. We correlated the two enhancement indices to test whether neurons with enhanced responses in one task were also enhanced in the other.

## RESULTS

Neurons were studied in five main tasks, designed to assess sensory, motor, and cognitive modulation of neural activity. Quantitative data in multiple tasks were obtained from 91 LIP neurons in 5 hemispheres of 3 monkeys.

### Visual responses and attentional enhancement

Neurons gave brisk visual responses to the onset of a small spot in the receptive field (Fig. 2). In the fixation task, the onset of a light in the receptive field was not relevant

for the animal's behavior: the task required only that the monkey keep its eyes on the fixation point. We found that the amplitude of this visual response could be modulated by using tasks in which the stimulus was made behaviorally significant.

Two tasks were used to test the impact of requiring the monkey to use the information provided by the stimulus. The first was the memory-guided saccade task, in which the receptive-field stimulus marks the location to which a saccadic eye movement must subsequently be directed. In this task, a delay is introduced between the offset of the target and the offset of the fixation point, which is the signal to perform a saccade. At the time of the saccade, both the target and the fixation point have been turned off, so that the monkey makes a saccade in the dark to the remembered location of the target. Because visual and motor events are separated in time, modulation of visual activity can be measured independently of motor-related activity. The *right panel* in Fig. 2 shows that the visual response to the identical receptive-field stimulus was stronger in the memory-guided saccade task than in the central fixation task. This enhancement of the visual response was common for LIP neurons. The graph in Fig. 3A plots the mean discharge rate during the first 100 ms of the visual response in the memory-guided saccade task against that in the fixation task. Each point represents the responses of a single neuron in the two tasks

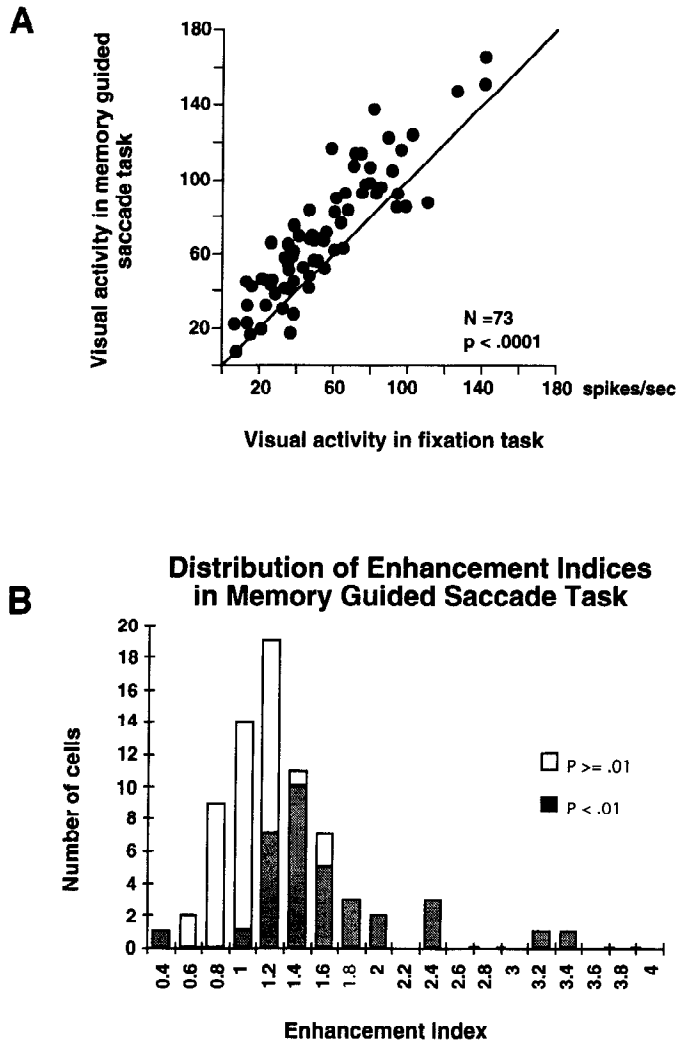


FIG. 3. *A*: enhancement of visual responses in the memory-guided saccade task for a population of LIP neurons. Each dot represents the activity of a single neuron in the memory task plotted against activity in the fixation task. Activity is measured as the average firing frequency across 16 successive trials in the 100-ms epoch following the beginning of the response burst. The diagonal line has a slope of 1. Every neuron above the line had a stronger visual response in the memory-guided saccade task. *B*: enhancement index. For each neuron, the ratio of the visual response in the memory-guided saccade task vs. the fixation task is shown. Shaded bars indicate neurons whose responses were significantly enhanced (or, for 1 neuron, suppressed) in the saccade task.

( $n = 73$ ). The diagonal line has a slope of 1. If there were no systematic difference between visual responses in the fixation and memory-guided saccade tasks, an equal number of points would be expected to fall above and below the line. The graph shows that for most LIP neurons the visual response was enhanced in the memory-guided saccade task compared with the response in the fixation task. The tendency for LIP visual responses to be enhanced in the saccade task was highly significant (Wilcoxon,  $P < 0.0001$ ). The degree of enhancement was measured by calculating an enhancement index for each neuron (Fig. 3*B*). The ratio of visual responses in the memory-guided saccade task compared with visual responses in the fixation task ranged from 0.4 to 3.4. A  $t$ -test analysis of response strength in the two

conditions showed that 47 of 73 neurons (64%) had a significant increase in response in the saccade task ( $P < 0.05$ ).

Visual responses to behaviorally significant stimuli were still enhanced even when the monkey was not planning a saccade as shown in the peripheral attention task. In this task, the monkey maintained central fixation throughout the trial but had to attend to a peripheral stimulus placed in the receptive field and release a bar when that stimulus dimmed slightly. The stimulus was behaviorally relevant in this condition and evoked a larger amplitude response than the same stimulus in the fixation task (Fig. 2, *middle*). This attentional enhancement was a general characteristic of neurons in LIP, as shown in Fig. 4*A*. For a sample of 35 neurons, there was a significant tendency for visual responses to be larger in the attention task (Wilcoxon,  $P < 0.002$ ). A  $t$ -test analysis showed that 16 of 35 neurons (46%) had significantly enhanced responses in the peripheral attention task ( $P < 0.05$ ).

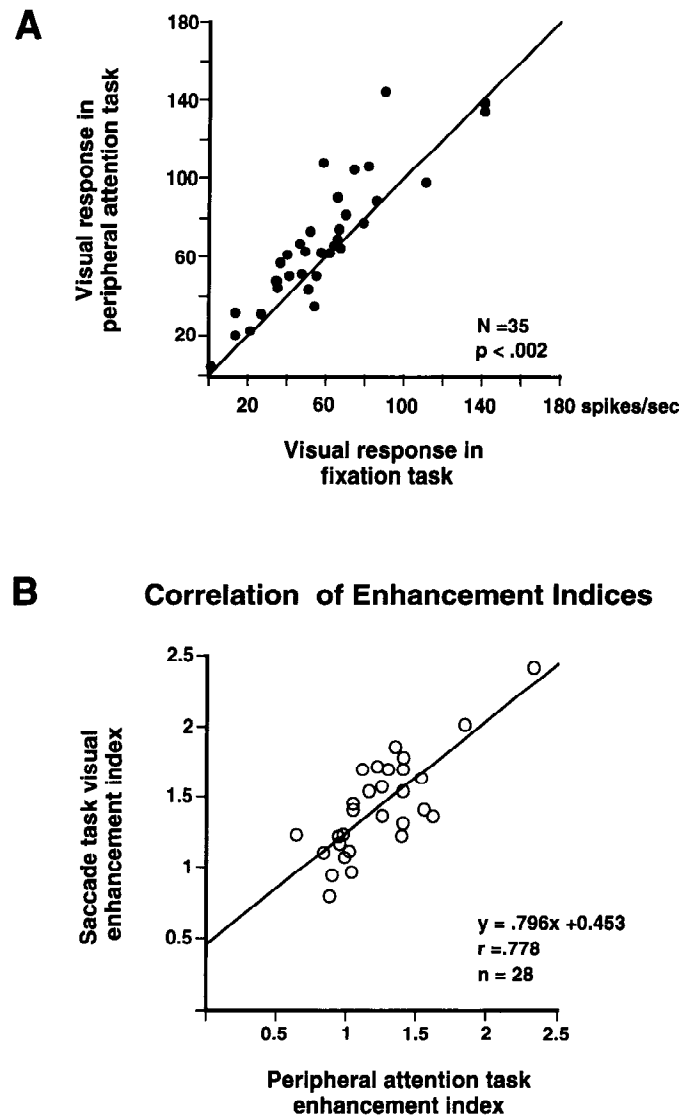


FIG. 4. *A*: enhancement of visual responses in the peripheral attention task compared with the fixation task. The diagonal has a slope of 1. *B*: correlation between enhancement of visual responses in the memory-guided and the peripheral attention tasks. The diagonal is the regression line.

## Memory Guided Saccade

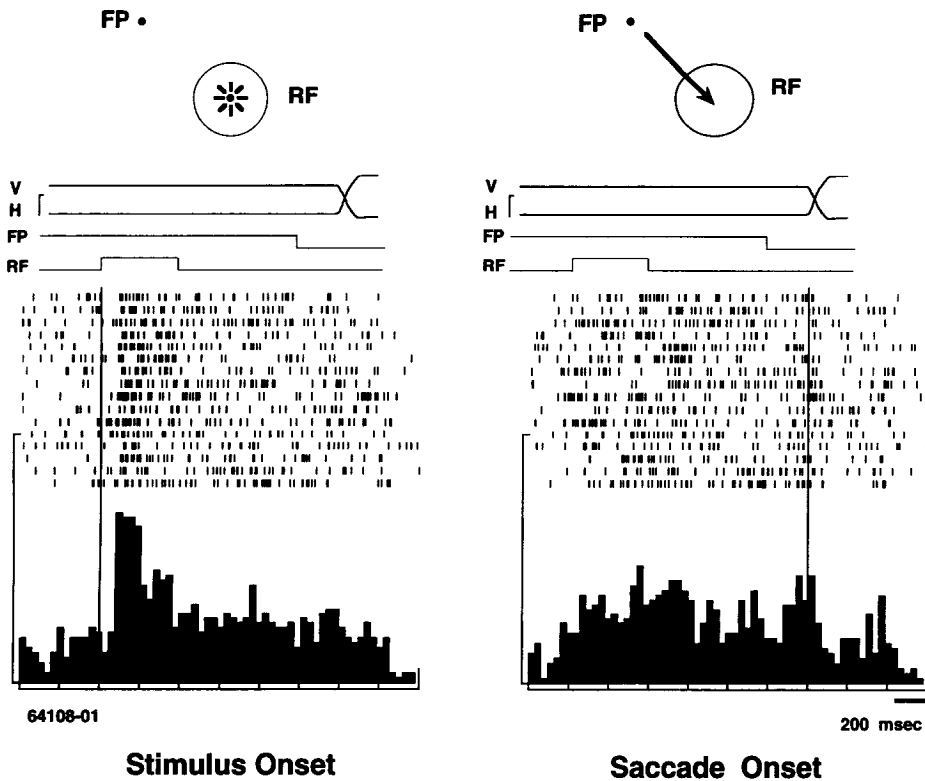


FIG. 5. Visual and presaccadic activity in the memory-guided saccade task. The delay between stimulus onset and fixation point offset (go signal for saccade) varies across trials. *Left*: trials are synchronized on stimulus onset showing visual response. *Right*: trials are synchronized on saccade onset and show activity before and during the saccade to the receptive-field location.

We compared the degree of enhancement in the peripheral attention with that in the memory-guided saccade task for each neuron by correlating the enhancement indices in the two tasks (Fig. 4B). There was a strong tendency for neural responses to be enhanced in both tasks and to a similar degree. These results show that LIP neurons have enhanced visual responses both in the memory-guided saccade task, in which a saccade is required, and in the peripheral attention task, in which saccades are forbidden. Enhancement is thus independent of the kind of motor response the animal will make.

### Saccade-related activity

Many LIP neurons have saccade-related activity in addition to their visual responses. In selecting neurons for study, we focused on those with saccade-related activity and tended to exclude those with only visual responses. An example of a neuron with both visual and saccade-related activity is shown in Fig. 5. On the *left*, the rasters are aligned on stimulus onset, and the histogram shows a strong visual response to the appearance of the stimulus in the receptive field. On the *right*, the rasters are aligned on the beginning of the saccade and show that the neuron was active immediately before and during a saccade directed toward the receptive field.

A comparison of the strength of visual and motor activations in LIP neurons shows that visual activity was typically stronger. The graph in Fig. 6 compares the mean spike frequency during the first 100 ms of the visual response for a given cell in the peripheral attention task to the mean

spike frequency of the presaccadic burst in the memory-guided saccade task. Most LIP neurons have larger sensory responses (points above the equal response line). For a sample of 31 neurons, there was a significant tendency for neurons to be more strongly activated by vision than by movement (Wilcoxon,  $P < 0.0001$ ). A *t*-test analysis revealed that 29 of 31 neurons (94%) had stronger visual activity ( $P < 0.05$ ).

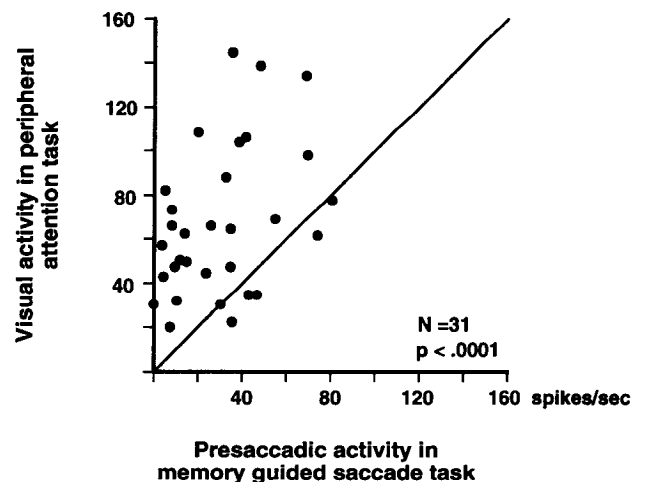


FIG. 6. Visual responses in the peripheral attention task plotted against movement activity in the memory-guided saccade task. Visual responses are significantly larger than saccadic activity.

**Visually Triggered Saccade**

**Learned Saccade**

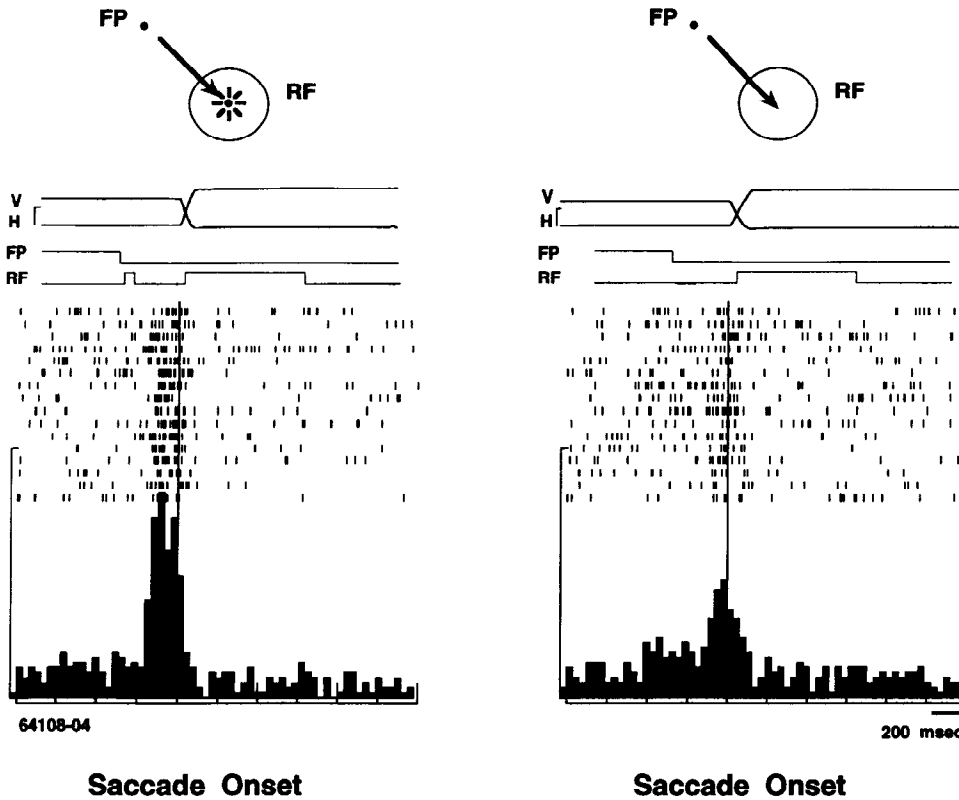


FIG. 7. Presaccadic activity in visually triggered and learned saccade trials. In visually triggered trials, the visual response is added on to the saccade-related activation. In the learned saccade trials, which do not have any visual stimulus, the presaccadic activity is comparable with that for the same neuron in the delayed saccade task (Fig. 5).

To determine whether the motor activation was truly independent of the visual activation, we used a learned saccade task in which the monkey makes a saccade without a visual target. We found that LIP neurons have saccade-related activity even when no visual stimulus appeared during a given trial. Learned saccade trials were interleaved with visually triggered saccade trials, in which the monkey saccades to a visual target in the receptive field as soon as it appears. In the trials with no target, the learned saccade trials, the monkey made a saccade to the same location as soon as the fixation point was extinguished. An example of presaccadic responses in these two conditions is shown in Fig. 7. In the visually triggered condition, on the left, the presaccadic burst reflects both visual and saccade-related activity. In the learned saccade condition, on the right, the remaining activity reflects a purely motor activation. The activity in the learned saccade trials shows that the presaccadic burst is not a reactivation of the visual response, that is, it does not depend on the occurrence of an immediately preceding visual stimulus.

To confirm that the saccade burst is independent of the visual response, we compared the amplitude of saccade-related activity in learned saccade trials with that in memory-guided saccade trials (Fig. 8). In both conditions, the visual stimulus is absent at the time of the saccade, but in the memory-guided task a stimulus has appeared within the same trial. For a sample of 29 neurons, there was no consistent difference between response levels in the 2 conditions ( $P > 0.08$ ). The ratio between activity in the learned saccade

and memory-guided saccade tasks varied on either side of 1, indicating that the type of task did not matter. The conclusion from both tasks is that LIP neurons have an independent saccade burst. This saccade-related activity does not depend on current or recent visual stimulation.

*Modulation of background activity by anticipation*

We observed modulations in baseline activity level that reflect anticipation of a behaviorally relevant sensory event.

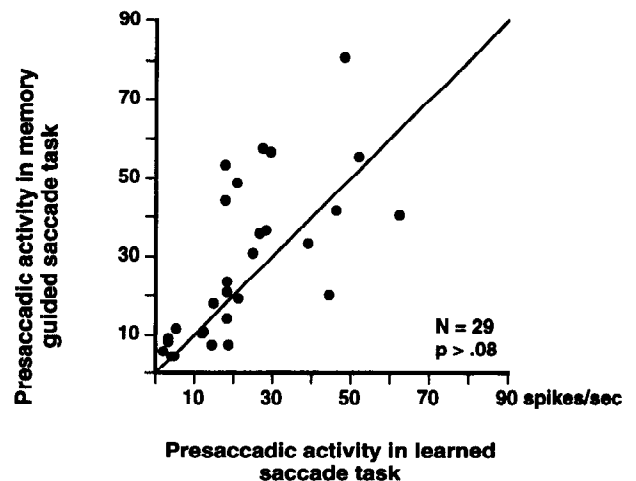


FIG. 8. Presaccadic activity in the memory-guided saccade task plotted against presaccadic activity in the learned saccade task.

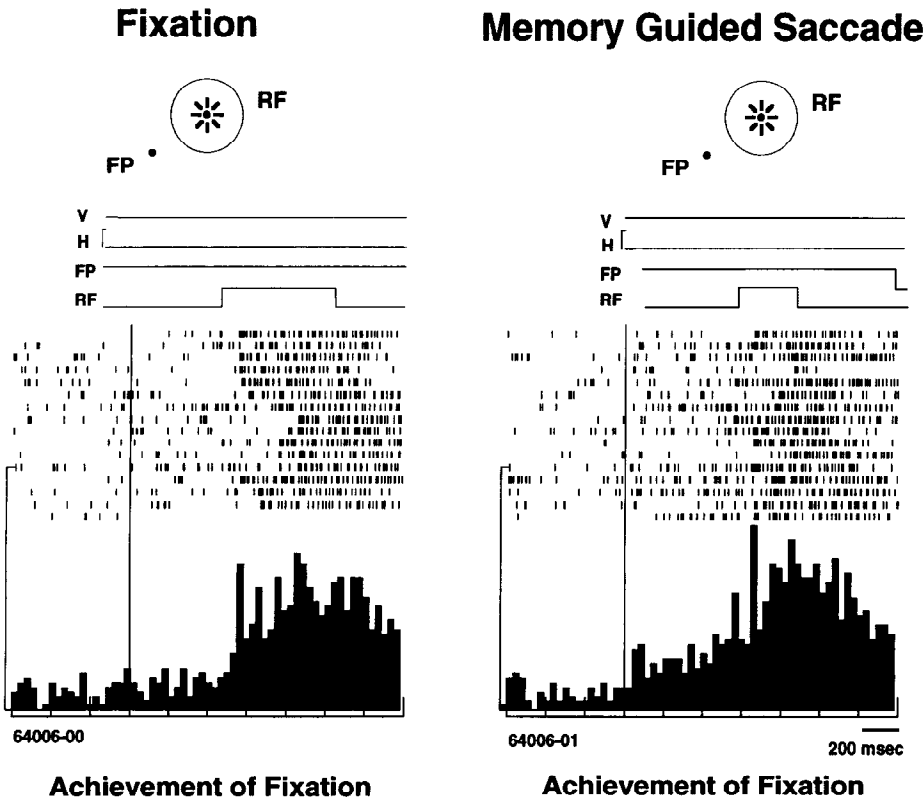


FIG. 9. Background activity in the fixation task compared with the memory-guided saccade task. Histograms are aligned on the time at which the monkey began to fixate the central fixation point. Time of stimulus onset varies from trial to trial. The sample trial illustrated by the RF time line shows the earliest time at which the stimulus appeared. In the fixation trials, the neuron does not fire until the stimulus appears. In the memory-guided saccade trials, neural activity builds up before stimulus onset.

LIP neurons typically had a low level of baseline activity, as measured during the intertrial interval. In the fixation task, this low level was maintained during the interval between achievement of fixation and the onset of a visual stimulus in the receptive field, at which time there was a sharp onset of visual responsiveness. In both the memory-guided saccade task and the peripheral attention task, where the stimulus was behaviorally significant, the rate of firing began to increase even before the stimulus appeared. These tasks were done in blocks of trials so that the monkey could anticipate that a behaviorally significant stimulus was about to appear. This anticipation was reflected in an increased firing rate. In Fig. 9, the histograms are aligned on the time at which the monkey began to fixate the central fixation point. The time of stimulus onset varied from trial to trial in both tasks so that the monkey could not predict the exact time of onset. Even so, the level of background activity during fixation increased when the monkey expected a behaviorally significant stimulus to appear (Fig. 9, right). In contrast, the level of baseline activity in the fixation task, in which the monkey expected an irrelevant stimulus to appear, remained constant (Fig. 9, left). The graph in Fig. 10 shows that this anticipatory activity was common in the memory-guided saccade task. For a sample of 68 neurons, there was a significant tendency for background activity to be higher in the memory-guided saccade task than in the fixation task (Wilcoxon,  $P < 0.002$ ). A  $t$ -test analysis indicated that 31 of 68 neurons (45%) had significantly higher background activity in the saccade task ( $P < 0.05$ ).

Anticipatory changes in baseline activity also occurred in the peripheral attention task. For a sample of 35 neurons, there

was a significant tendency across the population (Wilcoxon,  $P < 0.005$ ) for background activity to be stronger when the monkey expected the onset of a stimulus to which it would have to attend (Fig. 11). A  $t$ -test analysis showed that this effect was significant for 11 of 35 neurons (31%) tested ( $P < 0.05$ ). Anticipatory activity thus occurs even in a task in which the monkey is not permitted to make a saccade.

DISCUSSION

*Attention modulates visual responses in LIP*

Sensory responses of LIP neurons were modulated in tasks that required the animal to attend to a stimulus in the re-

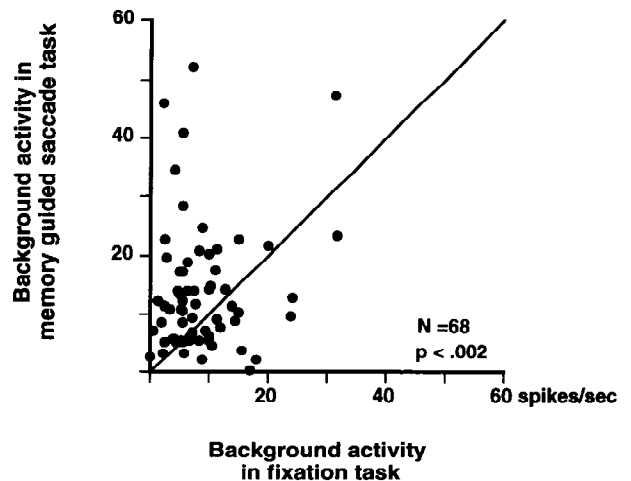


FIG. 10. Background activity in the memory-guided saccade task plotted against background activity in the fixation task.



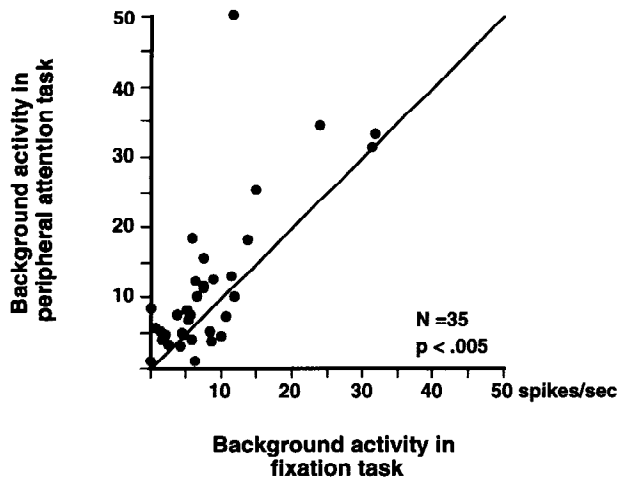


FIG. 11. Background activity in the peripheral attention task plotted against background activity in the fixation task.

ceptive field. The amplitude of the visual response was enhanced when the stimulus was made relevant for the animal's behavior. In two different tasks, we have shown that the same sensory input produced a larger response when the monkey had to make use of the information provided by the stimulus. In agreement with previous results (Bushnell et al. 1981), we have shown that enhancement is independent of the type of motor response the animal will make: it occurs both when the monkey is about to make a saccade to the target location as well as when the animal must respond by releasing a bar without making a saccade. The present results, by using the memory-guided saccade task to separate sensory and motor activations, demonstrate that it is specifically the sensory response that is enhanced by attention.

The onset of a light on a dark screen must always attract the monkey's attention to some degree. Psychophysical investigations of attention mechanisms in humans have shown that the abrupt onset of a visual stimulus captures attention (Jonides and Irwin 1981; Posner 1980; Yantis and Jonides 1984) and reduces saccadic reaction times (Todd and Van Gelder 1979). These psychophysical results suggest that the monkey's attention must be reflexively drawn to the sudden onset of the visual stimulus in the receptive field even in the fixation task. In contrast, the enhancement of the visual response in the two tasks that explicitly require the monkey to attend to the stimulus reflects voluntary control of attentional resources. In other words, when the stimulus is behaviorally significant, the monkey actively directs its attention to the location of the receptive field. When there is neither a voluntary shift of attention, produced by task demands, nor an involuntary shift, produced by the sudden onset of a stimulus, there may be little response to a new stimulus. Recent physiological work indicates that when a constantly present stimulus is brought into the receptive field of a neuron by means of an eye movement there may be a reduced visual response (in V1 and V2) (Gallant et al. 1994) or, in LIP, none at all (Kusunoki and Goldberg 1995). In these experiments, the stimulus is both irrelevant for the animal's behavior, and there is no sudden onset to attract attention. In a task where the stimulus is made relevant, however, a normal visual response is observed (Kusunoki and Goldberg

1995). These findings suggest that all visual responses in LIP reflect the degree to which attention is allocated to the stimulus. Even in the fixation task, where the stimulus is irrelevant for the animal's behavior, some attention is allocated to the stimulus simply because its onset is a new event in the receptive field. In the two tasks in which the animal must act on information provided by the stimulus, a greater degree of attention is allocated, and this is reflected in larger amplitude sensory responses.

A very different sort of attentional modulation, resulting in reduced visual responsiveness, has been described for neurons in extrastriate cortex. Moran and Desimone (1985) showed that if two stimuli are presented in the receptive field of a visual neuron in V4, one for which the neuron is selective and one for which it is not, the response of the neuron to the optimal stimulus is reduced when the monkey attends to the other stimulus. The response is not reduced when the monkey attends to a stimulus outside the receptive field. This is unlike posterior parietal cortex, where attention to a location outside the receptive field of the neuron neither enhances nor suppresses the visual response (Bushnell et al. 1981; Robinson et al. 1978).

Suppression of visual responsiveness has also been observed in parietal cortex in certain attention tasks. Robinson et al. (1995) showed that neurons in an area of parietal cortex including area LIP and 7a had a reduced response to an attended stimulus if the monkey had shifted its attention to the spatial location of that stimulus by a cue that appeared 100 ms but not 400 ms before the stimulus. We would not have seen such a phenomenon because we performed our experiments in blocks of trials in which the monkey always had to respond to the same location, and presumably did not shift its attention away from the location when the stimulus was present.

In parietal area 7a, Steinmetz and colleagues (1994) observed reduced visual responsiveness in a delayed match to sample task. They studied a class of neurons with large bilateral receptive fields and showed that when the stimulus matched the cue location the response was significantly attenuated even if the cue had appeared several seconds previously. In our sample of neurons in adjacent area LIP, few (12/73) showed reduced visual responsiveness in the memory-guided saccade task, and only one neuron was significantly suppressed. This very different task, and the different nature of the cells studied, may explain the differences in results between these two experiments.

#### *Visual and saccade-related activity are independent*

In the present study we have demonstrated that LIP neurons are independently activated in relation to both sensory and motor events. Previous studies of LIP have used the memory-guided saccade task to show the existence of sensory and motor activity (Barash et al. 1991a,b; Gnadt and Andersen 1988). In the present study we used a battery of tests to demonstrate that these activities are independent. Visual responses were measured in the fixation task, the peripheral attention task, and the memory-guided saccade task. LIP neurons responded to the onset of a visual stimulus in the receptive field and did so regardless of whether or not

the information provided by that stimulus was behaviorally relevant. Conversely, we found that these same neurons were active when the monkey made a saccade to the receptive-field location, regardless of whether or not a stimulus had been presented at that location. This independent motor activation was observed by comparing presaccadic activation in the memory-guided saccade task and the learned saccade task. Because a visual stimulus is presented in the memory-guided saccade task, it is possible that the presaccadic burst represents a reactivation of the visual response rather than an independent saccade-related activation (Boch and Goldberg 1989; Fischer and Boch 1980). To distinguish between these alternatives, we used a learned saccade task, in which no target appears during the trial. We found a definite, if weak, stimulus-independent presaccadic burst. This burst was not significantly different in amplitude from the presaccadic burst in the memory-guided saccade task (Fig. 8). Presaccadic activity was, however, significantly weaker than the visual response in a task that did not permit performance of a saccade (Fig. 6). Although it has been suggested that LIP is primarily involved in the generation of saccades (Andersen et al. 1992; Gnadt and Andersen 1988), the relative weakness of the nonvisual presaccadic signal (learned saccade and memory-guided saccade tasks) compared with the more robust visual signal in a task in which saccades were not permitted (peripheral attention task) suggests that LIP has a more general role in visuospatial behavior. Further, we failed to find in LIP a population of neurons with presaccadic but not visual responses, such as has been demonstrated in the frontal eye fields (Bruce and Goldberg 1985; Segraves and Goldberg 1987).

#### *Anticipation modulates baseline activity*

We found that the rate of background activity during fixation is modulated by the animal's anticipation of the onset of a behaviorally relevant stimulus. This modulation occurs regardless of whether a saccade will ultimately be generated to the stimulus location. We observed an increase in baseline activity in two conditions, the memory-guided saccade task and the peripheral attention task. In both these tasks, the monkey can anticipate that a visual stimulus will appear in the receptive field and that this stimulus will require a particular response (saccade or bar release). In these tasks there was an increase in activity before the onset of the stimulus, as compared with the same period in the fixation task. In the fixation task, the monkey could equally well anticipate that a stimulus was about to appear in the receptive field. There was no increase in baseline activity, however, because the stimulus in the fixation task was irrelevant for the monkey's behavior. The buildup of activity preceding stimulus onset may reflect the voluntary direction of attention to the location where the monkey expects a behaviorally significant stimulus to appear.

#### *Area LIP and visuospatial attention*

The present results show that LIP neuron activity is multifaceted and subject to modulation by cognitive factors such as attention and anticipation. LIP neurons have independent

sensory responses and saccade-related bursts. Further, attention to a spatial location modulates the sensory response to stimulus onset, and anticipation of a behaviorally significant sensory event affects the level of baseline neural activity. Previous studies have shown that visual responses are modulated by the position of the eye in the orbit (Andersen and Mountcastle 1983) and by the presence or absence of attentive fixation (Mountcastle et al. 1981). It is difficult to claim that these neurons are subserving any single one of these functions. They cannot be regarded exclusively as analyzing visual stimuli because they discharge before saccades even when there has been no recent visual stimulus. They cannot be regarded exclusively as planning saccades because they are strongly responsive in a task in which saccades are expressly forbidden. One way of understanding the significance of this varied collection of activations is to consider their point of intersection: the spatial location defined by the preferred stimulus location and the preferred saccade for a given neuron. We suggest that LIP neuron activity encodes events related to a particular spatial location.

#### *Spatial representation in area LIP*

This idea about the meaning of neural activity in LIP raises the issue of how spatial locations are represented. LIP neurons have retinotopic receptive fields, representing spatial locations relative to the fovea, and are active before matching directions of saccades (Andersen et al. 1990). We suggest that the attentional signal borne by these neurons is also in a gaze-centered coordinate system: an attended spatial location will not excite a neuron unless the location lies a certain distance and direction from the center of gaze. Because some LIP neurons modulate the excitability of their visual responses as a function of the position of the eye in the orbit, Zipser and Andersen (1988) argued that an ensemble of such neurons could code the spatial position of saccadic targets in a head- or body-centered reference frame. They devised a three-layered neural network whose inputs were eye position and retinal location of the stimulus, and whose output was saccade target position in space. The hidden layer neurons had planar gain fields resembling those described in LIP (Andersen et al. 1990). The most important variable in this model is firing frequency. The intensity of activation of each neuron would be critical for determining target position in space. We have demonstrated that response frequency is affected by many factors other than orbital position, e.g., attention, anticipation, and the presence or absence of a visual stimulus. A distributed system that uses orbital position modulation as a primary input for calculating space must control for all these other sources of frequency modulation in order to be accurate. For example, the same spatial location when acquired by a visually guided saccade evokes a much more intense response than when it is acquired by a learned saccade. If spatial information were conveyed by a frequency code, a given neuron would represent different spatial locations in different situations unless the decoding network were able to compensate for the many other constantly changing sources of frequency modulation.

A simpler alternative to using a frequency code to represent space is to use a place code. In this scheme, the ensemble

ble of active neurons would signal the relevant spatial location, and the intensity of activation could signal the behavioral significance or degree of attention allocated to that location. A place code can unambiguously signal a spatial location in a way that is independent of sensory or cognitive modulation. The parietal place code would signal a displacement from the current center of gaze, a spatial vector, and not an absolute spatial position. This kind of place code has been found in the superior colliculus (SC), where the location of electrical stimulation, and not the frequency, determines the direction and size of saccadic eye movements (Lee et al. 1988). The strong output from area LIP to the intermediate layers of the SC (Lynch et al. 1985) makes it reasonable to suppose that both structures use a similar representation for encoding space. We have shown elsewhere that neurons in both LIP and SC have a gaze-centered spatial representation that is updated in conjunction with saccadic eye movements (Duhamel et al. 1992; Walker et al. 1995). This updating provides a mechanism for maintaining spatial accuracy in the control of eye movements without necessitating an explicit representation of target position in head-centered or absolute space. The combination of an unambiguous place code and a mechanism for updating target position information yields a gaze-centered spatial representation. This kind of representation is appropriate for the oculomotor system that generates eye movements relative to the current center of gaze.

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Address for reprint requests: M. E. Goldberg, Laboratory of Sensorimotor Research, National Eye Institute, Bldg. 49, Rm. 2A50, Bethesda, MD 20892.

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