Monkey Posterior Parietal Cortex Neurons Antidromically Activated From Superior Colliculus

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Paré, Martin and Robert H. Wurtz. Monkey posterior parietal cortex neurons antidromically activated from superior colliculus. *J. Neurophysiol.* 78: 3493–3497, 1997. The connection between the posterior parietal cortex (PPC) and the superior colliculus (SC) was investigated by antidromically activating neurons within the lateral intraparietal (LIP) area with single-pulse stimulation delivered to the intermediate layers of the SC. To dissociate visual and saccade-related responses, the discharge properties of the identified efferent neurons were studied in the delayed visually guided saccade task and the memory guided saccade task. We found that the great majority (74%) of the identified LIP efferent neurons have a peripheral visual receptive field, typically with a broad spatial tuning. About two-thirds (64%) exhibited sustained activity during the delay period of the behavioral tasks, during which the monkeys had to withhold eye movements, and 80% of these increased their activity just before the onset of saccades. Both delay and presaccadic discharges in the delayed visually guided saccade task were higher than in the memory guided saccade task. These results establish that the neuronal signal sent by LIP to the SC carries both visual and saccade-related information.

INTRODUCTION

Evidence accumulated in the last three decades from many different studies indicates that the intermediate layers of the superior colliculus (SC) are critical to the generation of saccadic eye movements (for review see Guitton 1991; Sparks and Hartwich-Young 1989; Wurtz 1996). Although these studies contributed to our understanding of the control of saccades, they focused mainly on the SC itself or its relationship with downstream elements. Less is known about the input signals to the SC from upstream structures.

Among the cortical areas that play a major role in saccade production, anatomic studies have identified two areas that project directly to the SC intermediate layers: the frontal eye field (FEF) in the anterior bank of the arcuate sulcus in frontal cortex (Fries 1984; Huerta et al. 1986; Leichnetz et al. 1981; Stanton et al. 1988) and the lateral intraparietal area (LIP) in the lateral bank of the intraparietal sulcus in posterior parietal cortex (PPC) (Andersen et al. 1990; Asanuma et al. 1985; Fries 1984; Lynch et al. 1985). Both areas contain neurons with saccade-related discharges (FEF: Bruce and Goldberg 1985; Schall 1991; LIP: Barash et al. 1991a,b; Colby et al. 1996; Gnadt and Andersen 1988), and saccades are evoked by electrical microstimulation delivered within each area (FEF: Bruce et al. 1985; Robinson and Fuchs 1969; LIP: Kurylo and Skavenski 1991; Shibutani et al. 1984; Thier and Andersen 1996).

With respect to these direct cortical projections to the SC, only those from the FEF have been physiologically studied (Segraves and Goldberg 1987); at the level of the basal ganglia, an indirect cortical input to the SC has also been investigated, namely from the substantia nigra pars reticulata (Hikosaka and Wurtz 1983). To explore the parietal output signal to the SC, we recorded the activity of antidromically activated LIP neurons in awake behaving monkeys. A brief report of some of the results appeared in abstract form (Paré and Wurtz 1997).

METHODS

Two male rhesus monkeys (*Macaca mulatta*, 6–11 kg) were trained to perform visuooculomotor tasks for a liquid reward and prepared for chronic recording of single neuron activity and eye position in a single surgical procedure described previously (Munoz and Wurtz 1993). All animal care and experimental procedures were approved by the Institute Animal Care and Use Committee and complied with Public Health Service Policy on the humane care and use of laboratory animals. Each monkey had two recording cylinders. One was centered on the midline with its top tilted 42° posterior of vertical and allowed recording and stimulation in the SC. The other was centered on the stereotaxic coordinates *P* 5.0 and *L* 12.0 mm and tilted 30° lateral of vertical and allowed recording from LIP neurons (Fig. 1*A*).

We first recorded in the SC to determine the layout of the motor map and the location of the intermediate layers containing saccade-related neurons, where stimulation trains evoked saccades at low-threshold intensities. Stimulating electrodes (1–4 monopolar tungsten microelectrodes with impedance of 70–120 kΩ at 1 kHZ) were either moved with a microdrive during each session or held fixed semichronically at low-threshold stimulation depths and predetermined locations within the SC map. The electrical stimulus used for antidromic activation was a single biphasic pulse (0.15 ms duration) (Fig. 1*A*).

Before the recordings, a magnetic resonance imaging (MRI) of the brain was obtained with at least one reference electrode fixed to a grid (Crist et al. 1988) in the PPC cylinder and directed near the intraparietal sulcus. This combined approach of a fixed grid and MRI-verified reference electrode provided the resolution necessary to correctly direct microelectrodes within the lateral bank of the intraparietal sulcus (Fig. 1*B*). The LIP area itself was identified physiologically by the concentration of neurons with significant visual and saccade-related activities. We studied the LIP neurons that were antidromically activated from the ipsilateral SC.

The threshold intensity to evoke antidromic responses by SC stimulation was defined as the intensity that evoked a response on ~50% of the stimulus presentations. Stimulus intensity was monitored on an oscilloscope and was measured by taking the voltage across a 10-kΩ resistor in series with the stimulating electrode. The latency of the antidromic responses was defined as the interval from the onset of the stimulus (at 1.2 times threshold intensity) to the onset of the evoked action potential. The antidromic nature of the responses was ascertained by the constant
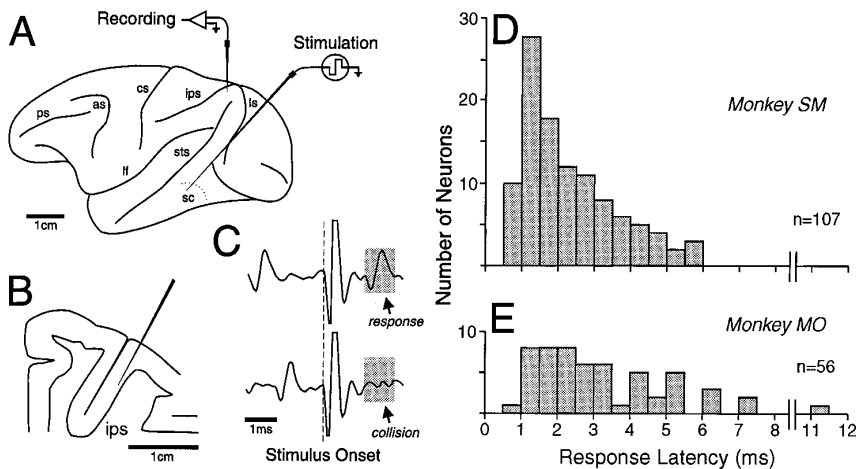
FIG. 1. Neurons recorded in the intraparietal sulcus were antidromically activated by stimulation of superior colliculus (SC). *A*: lateral view of a rhesus monkey brain illustrating stimulation and single-neuron recording configuration. *B*: coronal section based on magnetic resonance imaging (MRI) showing the 30° approach of recording electrode within the similarly oriented lateral bank of intraparietal sulcus (*monkey MO*). *C*: example of one antidromic response of a lateral intraparietal (LIP) neuron (*top*) and its collision (*bottom*) with a spontaneously generated action potential that triggered electrical stimulus (*monkey MO*). *D* and *E*: latencies of responses of LIP neurons to stimulation of SC in the two animals; histograms show only the shortest response latency observed for each neuron. as, arcuate sulcus; cs, central sulcus; ips, intraparietal sulcus; lf, lateral fissure; ls, lunate sulcus; ps, principal sulcus; sc, superior colliculus; sts, superior temporal sulcus.

latency of the responses and often further verified with the collision test by triggering the stimulus after variable delays relative to the appearance of a spontaneous action potential. The evoked response was then abolished (collision, shaded area in Fig. 1*C*) if the delay between the spontaneous action potential and the stimulus was equal or less than the neuron's response latency plus its refractory period (typically <0.5 ms), the collision interval (Fuller and Schlag 1976; Humphrey 1979; Lemon 1984). The occurrence of the collision was monitored routinely to confirm the isolation throughout the recording session.

Several visuooculomotor tasks were used to characterize the discharges of the identified LIP efferent neurons. The data reported here were obtained in the delayed visually guided saccade task (overlap saccade task in Munoz and Wurtz 1993) and the memory guided saccade task. Both tasks were performed in dim ambient light with visual stimuli (0.25° diam) generated by a television projector and back-projected onto a translucent tangent screen. At the start of each trial, a visual fixation point appeared on the screen and the monkey was required to maintain its visual axis within a computer-defined window (±1°) centered on the fixation point. After 500–800 ms of fixation, an eccentric visual target appeared and remained present either for 100 ms in the memory guided saccade task or throughout the trial in the delayed visually guided saccade task. After a 500- to 1,000-ms delay period, the fixation point disappeared signaling the monkey to make a saccade within 500 ms to either the remembered location of the target or the still visible target.

RESULTS

Antidromic responses

A total of 163 LIP neurons were found to be driven by single-pulse stimuli delivered to the SC. All responses had a near-constant latency (variability < 0.1 ms) at threshold stimulus intensity and this latency was decreased negligibly for higher stimulus intensities. Because of these two criteria, we believe that all 163 neurons were antidromically activated. In addition, for 127 of these neurons, we used the collision test and the occurrence of a collision was always observed (Fig. 1*C*).

The distribution of the antidromic response latencies was unimodal and comparable in both monkeys (Figs. 1*D, E*). In *monkey SM*, the latencies varied between 0.8 and 5.6 ms, with a mean of 2.3 ± 1.3 (SD) ms (Fig. 1*D*). In *monkey MO*, it ranged from 0.9 to 11.0 ms, with a mean of 3.2 ±

1.9 ms (Fig. 1*E*). The mean threshold intensities were 196 ± 206 μA (range 5–1,200) and 304 ± 286 μA (range 2–1,200) in *monkey SM* and *MO*, respectively. The great majority (150/163, 96%) of the neurons were activated with intensities <600 μA.

Several different stimulating electrodes frequently were able to evoke antidromic responses in LIP neurons, but with different latencies and threshold intensities at each electrode. The electrode with the lowest threshold intensity either was in a SC site that contained neurons that had visual receptive fields and movement fields similar to those of the LIP neurons or located in the rostral SC where the corticotectal axons enter the SC. For 13 neurons, we studied carefully the change in threshold intensity for antidromic activation as a function of the depth of the stimulating electrode within the SC. As exemplified in Fig. 2, high-threshold stimulus intensities were required in the superficial layers of the SC where neurons had only visual activity. The threshold intensities attained a minimum value at a depth where neurons showed saccade-related activity and then increased for deeper locations. The minima were 1.0–3.0 mm below the dorsal surface of the SC.

LIP neuronal activity

Of the 163 antidromically activated neurons, 111 were adequately isolated for a period long enough to characterize their activity in relation to visual stimulation and saccadic eye movements. The great majority (82/111, 74%) responded to visual stimulation with a latency ≤100 ms of the appearance of the spot of light in their receptive field. Most neurons (67/82, 82%) had a large receptive field centered in the contralateral visual field. The other neurons (15/82, 18%) had a receptive field centered near the vertical meridian.

When tested in the delayed visually guided and/or memory guided saccade tasks, many visually responsive neurons (71/111, 64%) maintained their activity during the delay period and until the saccade was executed (Fig. 3). They ceased discharging either near the start of the saccade or shortly after the end of the saccade. Several neurons also exhibited a saccade-related increase in activity, but we did not encounter neurons with only saccade-related activity.
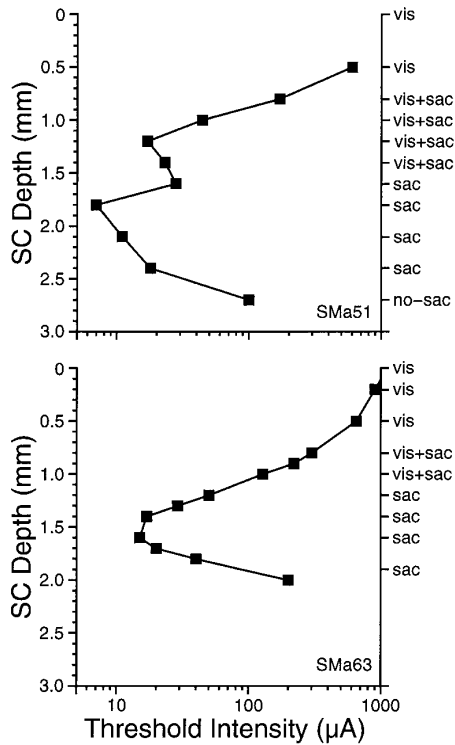
FIG. 2. Relationship between the depth of the stimulating electrode within the SC and threshold intensity required to evoke an antidromic response from 2 LIP neurons (*monkey SM*). *Right*: type of SC activity recorded with the same electrode at each depth; activity time-locked to visual target (vis), saccade-related activity (sac), and a combination of both (vis+sac).
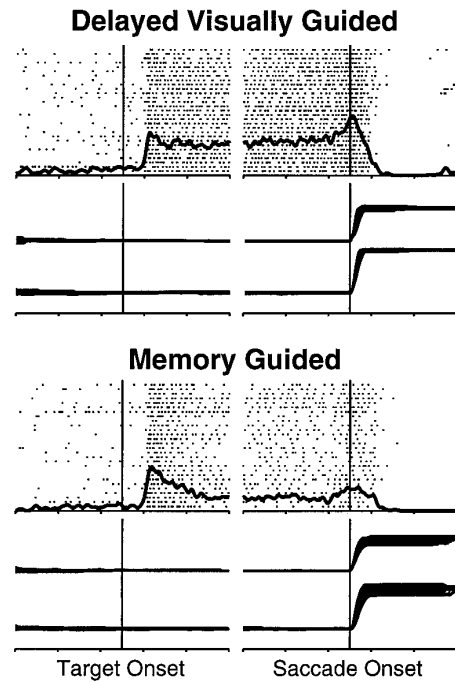

FIG. 3. Discharge properties of one antidromically activated LIP neuron (*monkey SM*). Rasters and spike densities along with horizontal and vertical eye position traces are illustrated for delayed visually guided saccade task (*top*) and memory guided saccade task (*bottom*). Activity is aligned on either target onset (*left*) or saccade onset (*right*). These data were collected with the tasks interleaved randomly and the target positioned in the center of the neuron's receptive field. To generate spike-density function, a Gaussian pulse of 10-ms width was substituted for each spike and then all Gaussians were summed together to produce a continuous function in time (MacPherson and Aldridge 1979; Richmond et al. 1987). Calibrations are 100 spikes/s and 30°; each time mark indicates 200 ms.

Unlike the initial target-related responses, the level of both the delay and presaccadic activities generally was lower in the memory guided saccade task than in the delayed visually guided saccade task. To quantify the different types of activity, we measured the discharge rate during *1*) a 100-ms epoch from 75 to 175 ms after target appearance (visual period); *2*) the last 300 ms before the fixation point was extinguished (delay period); and *3*) the last 100 ms before saccade onset (presaccadic period). The analysis was performed on neurons ($n = 50$) that showed significant delay activity and for which the two tasks were randomly interleaved and the target positioned in the center of the neuron's receptive field. Table 1 shows the results of this analysis for the sample of neurons. Statistically significant differences within and between the two tasks were found in the delay and presaccadic periods [Kruskal-Wallis analysis of variance (ANOVA) on ranks, $P < 0.01$; Student-Newman-Keuls method, $P < 0.05$]. Both the delay and presaccadic activities in the delayed visually guided saccade task were significantly higher than those in the memory guided saccade task. Among individual neurons, the delay and presaccadic activities were significantly higher in the delayed visually guided saccade task than in the memory guided saccade task for 44/50 (88%) and 41/50 (82%) neurons, respectively. Only one neuron had significantly lower activity. In both tasks, the presaccadic activity of the sample was significantly higher than that of the delay period. Among individual neurons, the presaccadic activity of 40/50 neurons (80%) was significantly higher than the delay activity in either the de-

layed visually guided or memory guided saccade task, or both.

In a minority of neurons, responses other than those presented above were observed. Seven neurons (6%) were responsive mainly or only when visual stimuli were presented near the face of the animal, six neurons (5%) had fixation-related activity modulated by eye position (see Lynch et

TABLE 1. *Activity of LIP efferent neurons in the delayed visually guided and memory guided saccade tasks*

Activity Period	Delayed Visually Guided Saccade Task	Memory Guided Saccade Task
Visual	61 ± 4	59 ± 4
	(16–126)	(15–129)
Delay	48 ± 3	29 ± 3*
	(14–104)	(3–100)
Presaccadic	59 ± 4†	38 ± 4*·†
	(15–130)	(3–152)

Activity periods are defined in text and activity levels are presented as discharge rates in spikes/s. Values are mean ± SE ($n = 50$) with range in parentheses. There was a statistically significant difference between the median values among the groups [Kruskal-Wallis analysis of variance (ANOVA) on ranks, $P < 0.01$]. An all pairwise multiple comparison (Student-Newman-Keuls method, $P < 0.05$) revealed that the delayed and presaccadic discharges were significantly different between the 2 tasks (*) and the presaccadic activity in both tasks was significantly different than that of the delay period (†).

al. 1977; Sakata et al. 1980), and 16 neurons (14%) were unresponsive during any of the behavioral tasks used.

DISCUSSION

We have now identified physiologically the LIP efferent neurons that send an axon to the SC. The majority (64%) displayed visual responses to target onset that were followed by sustained discharges during the delay period in the delayed visually guided and memory guided saccade tasks, and 80% of these showed significant presaccadic activity. The activity of these neurons was modulated by the presence of the visual stimulus, for their delay and presaccadic discharges were higher in the delayed visually guided saccade task than in the memory guided saccade task. No LIP efferent neurons discharged only for saccades. The visual and saccade-related discharge properties of these antidromically identified LIP efferent neurons are consistent with the characteristics of the neurons studied most extensively in LIP (Barash et al. 1991a,b; Colby et al. 1996; Gnadt and Andersen 1988).

In the FEF, Segraves and Goldberg (1987) demonstrated that saccade-related neurons predominantly project to the SC. However, few of these SC projection neurons had visual and/or delay activity during the memory guided saccade task. This is in striking contrast with the responses of LIP neurons and it appears to be the major difference between the signals carried by the two populations of cortical efferent neurons. When compared with their putative target neurons in the intermediate layers of the SC, the LIP and FEF efferent neurons share attributes with two classes of saccade-related neurons (Munoz and Wurtz 1995). The SC *buildup* neurons exhibit delay activity, as do the LIP neurons. The SC *burst* neurons lack delay activity and often have no target-related responses, as is the case for nearly all FEF neurons. Although the projection from the FEF appears to contact both burst and buildup neurons (Helminski and Segraves 1996), the SC delay activity would seem likely to be derived more from LIP than FEF inputs. However, unlike the LIP neurons, the level of SC delay activity in the delayed visually guided saccade task is not consistently higher than in the memory guided saccade task (Kojima et al. 1996), thereby indicating additional processing performed in the SC.

The combination of visual and saccade-related signals observed in LIP efferent neurons suggests that only a partial sensory-motor transformation occurs before PPC projection to the SC. In contrast, the FEF signal reaching the SC appears more related to the encoding of movement characteristics (Segraves and Goldberg 1987) and thus may represent the output of a distinct sensory-motor transformation taking place in the frontal cortex. We conclude that the outputs of these two cortical areas carry complementary rather than similar information, which can be further processed by SC neurons to generate commands for goal-directed saccadic eye movements.

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