JOURNAL OF NEUROPHYSIOLOGY
Vol. 67, No. 4, April 1992. *Printed in U.S.A.*

RAPID PUBLICATION

Role of the Rostral Superior Colliculus in Active Visual Fixation and Execution of Express Saccades

DOUGLAS P. MUNOZ AND ROBERT H. WURTZ
Laboratory of Sensorimotor Research, National Eye Institute, National Institutes of Health, Bethesda, Maryland 20892

SUMMARY AND CONCLUSIONS

1. In the rostral pole of the monkey superior colliculus (SC) a subset of neurons (fixation cells) discharge tonically when a monkey actively fixates a target spot and pause during the execution of saccadic eye movements.

2. To test whether these fixation cells are necessary for the control of visual fixation and saccade suppression, we artificially inhibited them with a local injection of muscimol, an agonist of the inhibitory neurotransmitter γ-aminobutyric acid (GABA). After injection of muscimol into the rostral pole of one SC, the monkey was less able to suppress the initiation of saccades. Many unwanted visually guided saccades were initiated <100 ms after onset of a peripheral visual stimulus and therefore fell into the range of express saccades.

3. We propose that fixation cells in the rostral SC form part of a fixation system that facilitates active visual fixation and suppresses the initiation of unwanted saccadic eye movements. Express saccades can only occur when activity in this fixation system is reduced.

INTRODUCTION

Saccades are high-velocity eye movements that rapidly change the line of sight. Between saccades, the eyes remain stationary with the fovea centered on a selected target. This active visual fixation must be disengaged before a new saccadic eye movement can be initiated (Fischer 1987). Release from fixation is a prerequisite for the generation of express saccades—those saccades with latencies <100 ms in the monkey (Fischer and Boch 1983).

It was recently proposed that cells located in the rostral SC of the cat may be specifically involved in controlling fixation and suppressing the initiation of saccades because these neurons discharge maximally when a cat attentively fixates a visual target and pause during saccades (Munoz and Guitton 1989, 1991; Munoz et al. 1991; Peck 1989). We now report that a subset of neurons in the rostral pole of the monkey SC also discharges during active fixation and pauses during saccades, and we show that fixation is disrupted when these cells are artificially inhibited with a reversible chemical lesion. Some of these observations have been reported in abstract form (Munoz et al. 1990; Munoz and Wurtz 1991).

METHODS

We recorded single-cell activity from the rostral SC of two monkeys. Procedures employed to record eye movements and single cell activity in awake monkeys (*Macaca mulatta*) with their heads immobilized have been described previously (Komatsu and Wurtz 1988). We injected muscimol (Sigma) into the physiologically defined fixation zone in one monkey using previously described procedures (Crist et al. 1988). We made three separate injections (2–4 μg muscimol in 2 μg/μl saline solution) into the rostral left SC of one monkey and obtained similar results in all three cases. After each injection we allowed the monkey ≥48 h to recover. Postrecovery testing revealed no lasting deficits. Postmortem histology verified that the cell recordings and muscimol injections were in the rostral pole of the SC. The procedures reported here were approved by the NEI Animal Care and Use Committee and complied with USPHS guidelines for animal care and use.

The monkeys were trained to perform a behavioral task (Fig. 1) that required them to look at a fixation point (FP) that appeared at the center of a screen in front of them. They were rewarded if they delayed the initiation of a saccade to a visual target (T) that momentarily appeared (80-ms flash) during fixation in the peripheral visual field until after the FP was turned off. If the monkey performed the task correctly, then the resultant saccade occurred after the FP was extinguished (correct saccade, —— in Fig. 1). If the monkey could not delay saccade initiation, however, the saccade would occur after T onset but before FP offset (incorrect saccade, – – – in Fig. 1). In this task, the periods from FP onset to T onset and T offset to FP offset were randomized between 500 and 1,000 ms. We presented the target in random order 20° to the right or left of the FP.

RESULTS

We recorded fixation-related activity from a subset of cells (fixation cells) in the rostrolateral pole of the monkey SC, where the foveal visual field is represented. The discharge properties described here were characteristic of 40 fixation cells recorded in two monkeys. Fixation cells were located 1–2 mm beneath the dorsal surface of the SC and had the following discharge properties: *1*) they were tonically active while the monkey fixated on a visible target spot even when this target was momentarily removed (300–600 ms), and the monkey had to maintain the same eye position; *2*) their level of tonic activity always dropped when the monkey made saccades and fixated spontaneously in a darkened room; *3*) their level of tonic discharge was not influenced by the position of the eye in the orbit; and *4*) they paused for saccades in all directions. Figure 2 shows the activity recorded from a fixation cell located in the rostral right SC when the monkey performed the memory-guided saccade task illustrated in Fig. 1. The rasters, spike density profile, and horizontal eye position traces are aligned on the onset of the saccade to the remembered target location. This neuron discharged tonically when the monkey fixated the FP and paused for the saccade to the remembered location of the T. Some fixation cells, like the one illustrated in Fig. 2, had an elevated discharge rate for a brief period after a saccade. This increased discharge rate

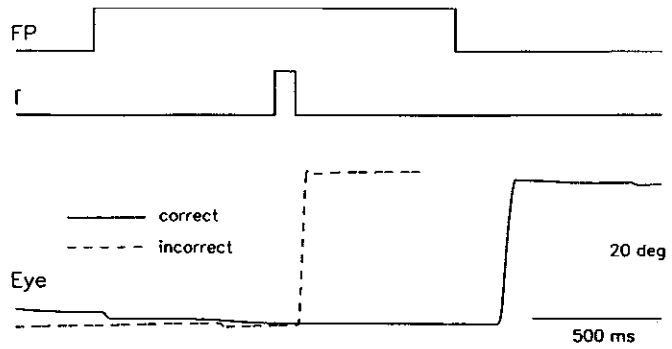

FIG. 1. Memory guided saccade paradigm. The monkey looked at a fixation point (FP) while a peripheral target (T) momentarily appeared in the peripheral visual field. The monkey received a reward for making the rightward saccade to the remembered location of T only after FP was extinguished. Shown are the target traces (FP and T) and two eye position traces (E), a correct saccade initiated after offset of FP (——), and an incorrect saccade initiated after the onset of T (– – –).

was independent of saccade direction or final orbital position.

If fixation cells are involved in facilitating fixation and suppressing unwanted saccades, then deactivation of these neurons should make it harder for the monkey to maintain fixation and easier to generate saccades. To test this hypothesis, we inactivated cells in the rostral pole of one SC by injecting minute quantities of muscimol, an agonist of the inhibitory neurotransmitter γ-aminobutyric acid (GABA) (Andrews and Johnston 1979).

The muscimol injection had a dramatic effect on the monkey's ability to maintain fixation as shown in Fig. 3. The histograms show the frequency of 20° contraversive saccades at different latencies, measured from onset of the T (left column, incorrect saccades) or offset of the FP (right column, correct saccades), for the task illustrated in Fig. 1. Before the injection (top row, control), the monkey performed the task correctly on 98% of the trials (39 correct/40 attempted): it delayed making saccades to the location of the T until after the FP went off. After the injection (bottom row, muscimol), the number of incorrect saccades increased dramatically. The monkey only performed the task correctly on 44% of the trials (39 correct/88 attempted) when the T was located contralateral to the site of the injection. When the T was presented ipsilateral to the injection, the monkey performed the task correctly on 83% of the trials (38 correct/46 attempted).

Most of the incorrect saccades had a short latency from the onset of the peripheral T; the average latency was 134 ± 86 (SD) ms ($n = 49$). The latency on 40% of these incorrect trials fell within the 80 to 100-ms range of express saccades. For comparison, in the control condition the latency to initiate a saccade to a visual target that appeared at the same time as the FP was turned off was always >100 ms; the average was 222 ± 24 (SD) ms ($n = 36$), which was significantly different from the incorrect responses shown in Fig. 3 (t test, $P < 0.0005$).

When the monkey did execute the task in Fig. 1 correctly, the average latency from FP offset to saccade onset was 196 ± 43 (SD) ms ($n = 39$) before and 232 ± 86 (SD) ms ($n = 39$) after injection of muscimol. This latter difference was not significant (t test, $P > 0.01$).

DISCUSSION

We conclude that the discharge characteristics of collicular fixation cells and the reduced ability to fixate that resulted from their removal indicates that the SC is directly involved in the control of visual fixation and saccade suppression. Furthermore, the occurrence of many short-la-

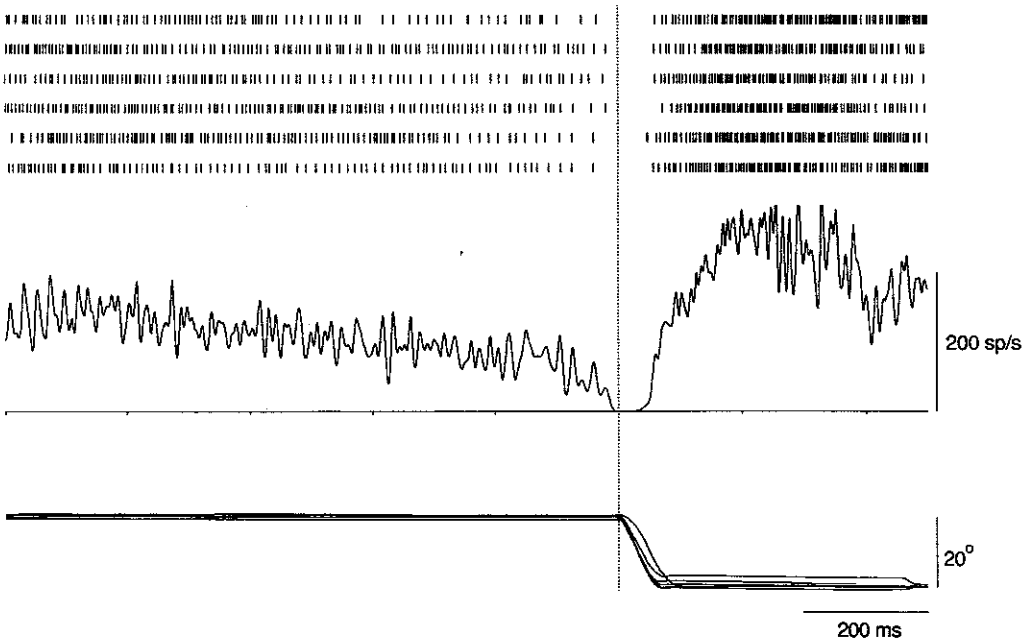

FIG. 2. Discharge of a fixation cell recorded in the right SC when a monkey performed the memory-guided saccade paradigm. Shown from top to bottom are the rasters, the spike density profile, and the horizontal eye position traces aligned on the onset of the saccade to the remembered location of the target flash.

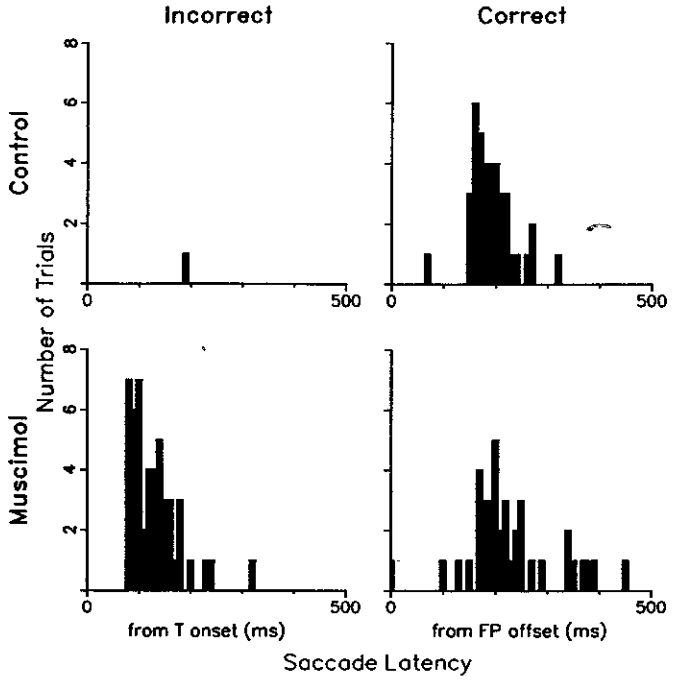

FIG. 3. Effect of muscimol injection into the rostral pole of the left SC. Latency to initiate saccade to T, measured from T onset to saccade onset for incorrect trials and from FP offset to saccade onset for correct trials before (control) and after (muscimol) the injection.

tency (<100 ms) saccades after muscimol injection strongly suggests that the rostral SC is necessary to suppress the occurrence of express saccades. This is particularly striking in light of the previous observation that removal of one SC eliminates contraversive express saccades (Schiller et al. 1987).

We suggest that the rostral SC is part of a fixation system that is required for normal oculomotor function. Indeed, cells in several brain regions of the monkey discharge in a tonic manner during active fixation and pause during saccades (Bruce and Goldberg 1985; Hikosaka and Wurtz 1983; Keller 1974; Luschei and Fuchs 1972; Lynch et al. 1977; Sakata et al. 1980). In either the SC or the frontal eye fields, the threshold for eliciting saccades with microstimulation is elevated when a monkey is attentively fixating a visual target (Goldberg et al. 1986; Schiller and Sandell 1983; Sparks and Mays 1983). Furthermore, ibotenic acid lesions placed in the visual association area V4 increase the frequency of express saccades (Weber and Fischer 1990) just as muscimol injection into the rostral SC does. The hypothesized fixation system would work in a reciprocal manner with the saccade generating system not only at the level of the SC, as we have demonstrated, but at other cortical and subcortical levels as well.

D. P. Munoz was supported by a Fellowship from the Medical Research Council of Canada.

Present address of D. P. Munoz: MRC Group in Sensory-Motor Physiology, Queen's University, Kingston, Ontario, K7L 3N6 Canada.

Address for reprint requests: R. H. Wurtz, Laboratory of Sensorimotor Research, National Eye Institute, National Institutes of Health, Bldg. 10, Room 10c101, Bethesda, MD 20892.

Received 24 December 1991; accepted in final form 21 January 1992.

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