Response Properties of Pretectal Omnidirectional Pause Neurons in the Behaving Primate

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Mustari, Michael J., Albert F. Fuchs, and Milton Pong. Response properties of pretectal omnidirectional pause neurons in the behaving primate. J. Neurophysiol. 77: 116–125, 1997. We have identified a region in the pretectum of rhesus monkeys (Macaca mulatta) that contains units that evince a complete cessation in firing immediately after saccades. The pause occurs for saccades to target steps and catch up saccades during smooth pursuit, spontaneously in complete darkness or after quick phases of nystagmus. Because the pause in unit firing always follows saccade onset, we call these neurons following omnidirectional pause neurons (FOPNs). Because the pause also occurs with saccades in the dark, it is related to the saccade per se and is not a visually contingent response. The duration of the pause in firing exceeded the duration of all saccades up to 40 deg. For targeting saccades, the start of the pause was locked rather tightly to the beginning of the saccade but began an average of 51 ms after the saccade did. The end of the pause was linked only loosely to either the beginning or end of the saccade. About half (54%) of our 59 FOPNs also discharged a distinct burst of firing that preceded the pause. In different units, the burst preceded saccade onset by from 0 to 20 ms with an average of 11 ms and therefore could signal the occurrence of an impending saccade. The presaccadic burst was not correlated with any parameter of the saccade. Most FOPNs were found 278 μm, on average, dorsal to the direction-selective units characteristic of the pretectal nucleus of the optic tract (NOT) and occasionally slightly beyond the anterior-posterior and medial-lateral borders of the NOT. The FOPN region does not coincide with any known anatomically or functionally delineated pretectal nucleus. Because the characteristics of the FOPN pause are not reflected in the characteristics of the saccade and the FOPN pause occurs well after the saccade is over, it is unlikely that the pause in pretectal FOPNs is involved with saccade generation. On the other hand, the leading burst exhibited by the majority of FOPNs reliably signals that a saccade is occurring but neither its size nor direction. Perhaps this signal indicating the occurrence of all saccades is routed to visual relay neurons to effect saccadic modification of visual pathways. The substantial efferent connections of the FOPN/NOT region to the pregeniculate nucleus and the saccadic discharge of pregeniculate cells are discussed in the context of this suggestion.

METHODS

The role of the pretectum in the processing of visual information and the control of eye movement has received considerable attention in recent years (see Simpson et al. 1988 for review). The primate pretectum consists of five well-recognized divisions, including the anterior, medial, and posterior pretectal nuclei, the nucleus of the optic tract (NOT) and the pretectal olivary nucleus (PON) (Weber 1985). The NOT, PON and the posterior pretectal nuclei receive direct visual inputs mostly from the contralateral retina (Benevento and Standage 1983). In addition, the NOT and possibly some of the other pretectal nuclei receive descending visual inputs from the ipsilateral striate and extrastriate visual cortices (Hoffmann et al. 1991; Mustari et al. 1994a). The various pretectal nuclei apparently subserve quite independent and completely different roles. For example, single unit recording (Clarke and Ikeda 1985; Gamlin et al. 1995) and lesion studies (Carpenter and Pierson 1973) have demonstrated that neurons in the PON and posterior pretectal nuclei form part of the afferent limb of the pupillary light reflex. In contrast, single unit recording and lesion studies have shown that the NOT plays an essential role in the control of optokinetic eye movements (Hoffmann et al. 1988; Mustari and Fuchs 1990; Schiff et al. 1990). Therefore, it is clear that at least some of the pretectal nuclei play roles as diverse as the control of eye movements and the regulation of the light intensity reaching the retina.

In our previous study of direction selective neurons in the NOT, we recorded the activity of other neurons that exhibited a pause in firing after saccades in all directions (Mustari and Fuchs 1990). This firing pattern was not due to vision per se as it was similar when saccades were executed spontaneously in complete darkness. The existence of these cells and the extensive connections between the pretectum and the lateral geniculate nucleus (Kubota et al. 1987; Mustari et al. 1994a) suggest an additional role for the pretectum in the gating of visual information flowing through the lateral geniculate nucleus. Our detailed consideration in this paper of the response properties of these following-omnidirectional pause neurons (FOPNs) has allowed us to address this possibility. A preliminary report of this material has appeared in abstract form (Mustari et al. 1994b).
aspirin) and antibiotics were provided if the animal showed any signs of discomfort. The animals were cared for by the respective veterinary staffs of the Regional Primate Research Center at the University of Washington and the University of Texas Medical Branch (UTMB). They were housed under conditions that comply with National Institutes of Health standards as stated in the ‘Guide for the Care and Use of Laboratory Animals’ (Department of Health Education and Welfare Publication NIH85-23, 1985), Institutional Animal Care and Use Committee recommendations, and American Association for Accreditation of Laboratory Animal Care accreditation standards for animals of this species. All experimental procedures were approved by the animal care and use committees at the University of Washington and University of Texas Medical Branch.

During behavioral training and single-unit recording sessions, the monkeys sat in a sound-attenuated and light-proof booth facing a tangent screen upon which the target spot and other visual stimuli were projected from the rear. Eye movements were measured with the electromagnetic search coil technique (Fuchs and Robinson 1966). Dedicated electronics rewarded the monkey for aiming its eye at the target spot by comparing signals proportional to target and eye position. After the animal was well trained, we could measure the horizontal and vertical components of eye position to within ±0.5 deg of arc, and the animal was rewarded for keeping its eye within ±1 deg of the target. The monkeys were trained to track a jumping or smoothly moving target spot and to fixate a stationary target spot while other visual test stimuli, projected through a separate optic bench, were moved upon the tangent screen. The target spot and visual test stimuli could be moved in various directions and velocities (1–200 deg/s) with either sinusoidal, triangle-wave, or constant-velocity ramps by means of x-y mirror galvanometers (General Scanning). In some cases, spontaneous saccadic eye movements in complete darkness also were recorded.

Extracellular single-unit action potentials were recorded with tungsten microelectrodes by conventional methods (Fuchs and Luschei 1970). Target- and eye-position signals, unit discharge, and other relevant signals were saved on tape for subsequent computer digitization and quantitative analysis. Eye- and target-position data were sampled at 1 kHz, and the time of occurrence of action potentials was determined to the nearest 10 μs by an interrupt driven system. Data were analyzed off-line by means of interactive analysis programs, which automatically selected saccades as they were scrolled across a video display terminal. A wide range of saccade sizes were included in our analysis, including all saccades to moving targets and the small re-fixation saccades to stationary targets. We rejected saccades that were made within 150 ms of a preceding saccade because within this time unit firing often had not recovered from the pause in activity associated with the first saccade.

We located our recording sites in each animal by placing electrolytic lesions (10–30 μA dc for 10–30 s) on several electrode tracks at known depths with respect to FOPNs. At the conclusion of an experimental series, we killed each animal with a lethal dose of barbiturate and perfused it with saline followed by 10% formalin. Frozen sections were cut in the stereotaxic plane every 50 μm, mounted on microscope slides, and stained with cresyl-violet or neutral red for histologic reconstruction of electrode tracks and unit locations.

**RESULTS**

**General characteristics of FOPNs**

The defining discharge characteristic of all 59 of our FOPNs is a cessation of firing or pause in activity after the onset of saccades in all directions. The pause occurred for all the different types of saccades we tested, including those to jumping targets, i.e., targeting saccades, those executed in complete darkness, i.e., dark saccades, and those made in pursuit of a slowly moving target. The behavior of a typical FOPN during these various saccadic situations is illustrated in Fig. 1. Whether the saccades occurred to jumping targets (A), spontaneously in the dark (B), or in an attempt to catch a slowly moving target (C), they always were accompanied by a pause in firing as may be seen in the histograms, which are aligned on saccade onset. The pause in unit firing was complete and occurred for saccades of all sizes and directions. In almost all cases, the pause exceeded the duration of the saccade. Every saccade was accompanied by an attendant pause.

The firing in the interval between saccades was not related to slow eye velocities as can be seen in Fig. 1D, where the neuronal activity during several cycles of smooth pursuit to a horizontally moving target has been averaged (note, time scale change). We removed all saccades before computing average eye position during pursuit. The gaps in unit firing visible in the individual rasters were associated with the deleted saccades (see also Fig. 1C). The 16 other FOPNs tested also exhibited a lack of modulation, suggesting that FOPN firing is insensitive to eye movements of low velocity (30 deg/s). Nor was firing related to eye position. For 25 units, we tested possible eye position sensitivity directly by requiring the monkeys to fixate stationary targets, which were held at a variety of locations within ±20 deg of the primary direction of gaze. The average firing rates of none of these cells were related to eye position. Finally, the average resting rates of these 25 cells, measured during periods of steady fixation, ranged from 50 to 110 spikes/s with an average of 71 ± 21 spikes/s (mean ± SD).

Certain aspects of the discharge patterns accompanying saccades of the same size and direction were quite consistent. Figure 2 illustrates the response of another FOPN during targeting saccades to leftward and rightward target steps of 5, 10, and 15 deg (Fig. 2, B, C, and D, respectively) and for the small saccades used to maintain fixation after the eye had landed on target (Fig. 2A). The rasters of action potentials and the average perisaccadic firing rate histogram for ~15 saccadic trials are aligned on saccade onset (vertical lines). Several observations can be made. First, the pause accompanied saccades in both horizontal directions. Second, the pause started after the saccade was over for movements of all sizes. Third, the onset of the pause occurred at a rather fixed latency relative to saccade onset. Fourth, the resumption of firing, i.e., the pause end, on the other hand, was more variable and therefore was coupled much more loosely with saccade onset. After the pause, firing rates typically remained lower than the resting rate for 50–100 ms before returning to the levels associated with steady fixation. Fifth, for this unit and many others, the pause often was preceded by a burst of firing, which frequently started before the saccade.

The pause in firing was not a visual response associated with movement of the visual surround across the retina during a saccade. We examined the discharge patterns of 23 FOPNs in complete darkness during either spontaneous saccades or saccades made to auditory stimuli. All continued to exhibit a saccade-related pause in firing. Therefore we
FIG. 1. Discharge patterns of a representative following omnidirectional pause neuron (FOPN) during saccades to a variety of target steps (A), saccades in dark (B), and saccades associated with horizontal smooth pursuit (C). In A–C, traces from top to bottom are horizontal (H) and vertical (V) eye position (upward deflections represent movements to right and up), rasters of spikes of individual trials associated with those eye movements and an averaged histogram (8 ms/bin). D: eye movements during horizontal smooth pursuit, indicating lack of eye position or eye velocity sensitivity. Traces are averaged horizontal target (T) and eye (E) position, their associated rasters (AP) and an average response histogram (8 ms/bin) from 17 cycles of smooth pursuit. D: pauses in firing in each raster are associated with small catch-up saccades (see C), which have been removed from individual position traces contributing to averaged eye position. Note, time scale for D is different than that of A–C. Eye position calibrations are {10 deg. Scale bars on all histograms represent 50 spikes/s.

conclude that the pause of FOPNs is not a visual response related to the target or dim background surroundings but rather must be related to the saccade itself.

Comparison of pause and saccade duration

The duration of the pause in firing was not correlated with saccade duration. Figure 3A shows the relation between pause and saccade duration for saccades to targets jumping horizontally and saccades made in the dark for a typical FOPN. For targeting saccades, the correlation coefficient of the pause duration vs. saccade duration relation was 0.06. For the 23 FOPNs examined during horizontal or oblique targeting saccades and dark saccades, low correlation coefficients were observed ($r = 0.1 \pm 0.12$). For 12 additional units examined only during horizontal targeting saccades, $r = -0.035 \pm 0.113$. For saccades in the dark, the correlation coefficient of the relation between pause and saccade duration for the unit in Fig. 3A was $-0.08$. Therefore, for all 23 units, pause duration was not significantly correlated with or dependent on saccade duration of either targeting or dark saccades.

It is possible that pause duration is better related to the durations of saccades in certain directions. Indeed, the ipsilateral targeting saccades in Fig. 2 appear to have longer durations than do the contralateral saccades. For 21/32 units tested, the duration of the pause of 10 deg ipsilateral saccades was significantly different ($P < 0.05$) than that of 10 deg contralateral saccades. For those units, the ratio of contralateral to ipsilateral pause duration averaged $0.74 \pm 0.11$. However, after we sorted saccades according to direction, a more robust pause versus saccade duration relation did not result for either targeting or dark saccades. On average, the correlation coefficients for ipsilateral and contralateral targeting saccades were $0.068 \pm 0.22$ and $-0.025 \pm 0.213$ ($n = 13$), respectively, whereas those for dark saccades sorted according to ipsilateral and contralateral components were $0.081 \pm 0.221$ and $0.080 \pm 0.236$, respectively.

When targeting and dark saccades are considered together, the correlation between pause and saccade duration improves to 0.36 for the unit of Fig. 3A and to 0.32 $\pm 0.17$ for all 13 neurons. The improved correlation results because dark saccades have longer durations and longer associated pauses. However, we feel that pauses associated with targeting and dark saccades should not be considered as part of the same population of saccades. For example, when targeting saccades with long durations ($\sim 50$ ms) occasionally occurred in Fig. 3A, their associated pause durations were still much shorter than the pauses accompanying dark saccades of similar durations. For other units like that in Fig. 3B, the difference in pause duration associated with dark and targeting saccades of equal durations was very striking. Consequently, we feel that discharge patterns associated with saccades in the dark must be considered separately from those during targeting saccades.

The greater pause duration for saccades in the dark than
FIG. 2. Response properties of a typical FOPN during targeting saccades of different sizes to left (left) and right. A: refixation saccades 1 deg. B–D: horizontal saccades to targets of 5, 10, and 15 deg amplitudes. Traces as in Fig. 1; calibration for eye position is 10 deg and for histograms, 50 spikes/s.

for those to targets might be due to several factors, such as decreased alertness during saccades in the dark or the fact that most saccades in the dark were oblique. To keep the animals alert during the FOPN testing, we either tapped on the sound-deadened chamber with a variety of objects such as keys, mallets, or sticks or sat in the chamber with the monkey and made noises, e.g., whistles, grunts from a variety of locations. In spite of these alerting maneuvers, the durations were longer. To address the latter possibility, we required other monkeys to make saccades to targets appearing at a variety of oblique angles relative to horizontal. The average correlation coefficient for the relation between pause and saccade duration for the 10 units thus tested was 0.144 ± 0.25 for oblique targeting saccades and 0.301 ± 0.231 for dark saccades. It is unclear why the average correlation for saccades in the dark was higher than that obtained under similar conditions from the other monkey. One factor might be that the average number of saccades constituting this data was half that for the 13 units in the other monkey. In any event, even for dark saccades, a linear fit accounted for only 9% of the variance in the data. Therefore correlations between pause and saccade duration were again poor for both oblique targeting saccades and saccades made in the dark.

The poor correlation between pause and saccade duration indicates that pause duration was essentially constant for all targeting saccades and for all dark saccades. We used the intercept of the pause duration/saccade duration relation as an estimate of the constant dark and targeting saccade durations. For the entire population of 23 neurons in both conditions, the average intercept was 159 ± 110 (n = 23) for dark saccades and 118 ± 61 for targeting saccades. Because the duration of even the largest dark saccades examined here usually was <100 ms, pause duration almost always was greater than saccade duration.
Relative timing of the pause and the saccade

Clearly the duration of the pause in FOPN firing is correlated poorly with saccade duration. Perhaps the important feature of the pause is its timing relative to the beginning or end of the saccade. The start of the pause (pause start) appears rather tightly correlated with saccade onset as judged by the rather precipitous end of the preparuse activity in most trials for saccades of the same size and direction (Fig. 2). In contrast, the end of the pause (pause stop) appears more loosely locked to saccade onset and also, apparently, to saccade end. To quantify these qualitative observations, we determined the timing between the pause and the saccade for all targeting saccades. Pause start (Fig. 4A, top) and pause stop (Fig. 4B, top) relative to saccade onset and end, respectively, were calculated for an average of 59 saccades of different sizes for each of the 59 units shown. Figure 4C, bottom, illustrates that the pause did not start, on average, before or at saccade onset for any unit. Across all the units, pause start lagged saccade onset by from 29 to 81 ms with an average of 51 ± 10 ms. Pause onset time and the variability of such times was not dependent on saccade amplitude on an individual unit basis. For most units, the start of the pause was better timed with the start of the saccade, based on visual inspection of raster diagrams. Most (86%) of the neurons illustrated in Fig. 4, showed less variable timing in pause start with respect to saccade start than in pause stop relative to saccade end. The average standard deviation of pause start times (±18 ms) was almost half that for pause stop times (±35 ms). These data indicate that the pause in firing of FOPNs is best related to saccade onset.

No unit resumed its firing before the end of a saccade. Across our population of 59 FOPNs, the average pause stop time lagged the end of the saccade by from 40 to almost 400 ms, indicating that different FOPNs exhibited considerable variation in the timing between saccade end and pause end (Fig. 4C, right). The source of this large unit to unit variation is unclear but cannot be explained either by differences in pause start times or differences in saccade duration. The pause ended an average of 151 ± 71 ms after the saccade had landed, so, unlike the pause of omnipause neurons (OPNs) in the pons (Evinger et al. 1982), the return to firing of FOPNs can have nothing to do with terminating the saccade.

Burst discharge of FOPNs

Like the neurons of both Figs. 1 and 2, slightly more than half (54%) of the FOPNs we encountered (n = 59) exhibited a burst of spikes that preceded the pause for saccades. The burst was omnidirectional in 27 of 32 units. To obtain an impression of the range of burst responses, we constructed histograms of neuronal discharge during saccades of roughly 3–7 deg in both horizontal directions. Based on histograms like those of Fig. 5A, we determined that the burst of different FOPNs varied considerably in strength.

The burst in different FOPNs began at different times relative to the start of the saccade. From histograms like those of Fig. 5A, we designated the onset time of the burst as the first bin in which the firing rate clearly was elevated above the discharge rate associated with the previous steady fixation. We had to resort to using the average histograms rather than designating burst onset on individual trials because burst onsets often were difficult to specify for single saccades. Because a bin width of 8 ms was required to obtain smooth averages with our usual number of trials, we could determine the timing of the burst only to the nearest 8 ms. Figure 5B illustrates the distribution of burst leads for the 32 FOPNs with clearly discernible bursts. The bursts of all but two preceded saccade onset by ≥8 ms. The average lead for all 32 FOPNs was 11.5 ± 5.3 ms. The burst in firing present during targeted saccades either disappeared or was reduced in about half of the FOPNs (48%) tested during spontaneous saccades in complete darkness. The loss of the burst in firing did not seem to be related to an animal’s attentional state but we can not rule out this possibility completely.

Because the burst was quite variable from saccade to saccade and often showed up clearly only after averaging (see Fig. 5A), we were unable to perform a fine-grained comparison of burst and saccade characteristics. Based on the histograms, however, no robust relations between the pause and saccade metrics were apparent. For example, the average
maximum burst frequency as derived from the histograms was related to neither saccade size nor direction. Therefore we averaged the peak rates for all the conditions for each unit. The average across all units was 122 ± 38 spikes/s.

**Anatomic location of FOPNs**

We used several clues to help us place the FOPNs within the pretectum. First, we located them relative to the neurons of the NOT, whose cells we identified by their characteristic activity during smooth pursuit and large-field background motion (Mustari and Fuchs 1990). On >60 penetrations, we recorded the activity of both an FOPN and an NOT neuron. The FOPN was encountered just dorsal to the NOT unit in most cases (58 of 60 pairs). On average, the FOPN lay 278 ± 178 μm dorsal to the first NOT neuron encountered. For two pairs, the FOPN lay 50 μm ventral to the first putative NOT neuron. Although we often found FOPNs and NOT units on the same electrode penetration, there were instances when we recorded FOPNs without encountering a subsequent NOT unit. In those cases, FOPNs typically lay at depths within 300 ± 150 μm of FOPNs located on neighboring tracks. Usually, we encountered only one FOPN per penetration, suggesting that they are distributed in a thin sheet. However, at some locations, two or more FOPNs were isolated in a single track. At these locations, nearby tracks also tended to have more than one FOPN. Therefore, the locus of FOPN neurons appears to be thicker in some regions of the pretectum. However, we saw no evidence that FOPNs constitute an anatomically identifiable group of cells. Finally, we also placed electrolytic lesions on some electrode tracks and used depth measurements taken from microdrive readings to reconstruct the location of FOPNs on histological sections of the midbrain. These lesion data supported our conclusion that FOPNs constitute a thin sheet of cells located in the posterior part of the pretectum on the dorsal border of the NOT. Figure 6 shows an example of our pretectal anatomy where a lesion was placed at the depth of a direction selective NOT unit. The lesion is located in the thickest part of the NOT immediately above the pretectal olivary nucleus (see Mustari et al. 1994a).

**DISCUSSION**

**FOPNs are concerned with saccades**

We have discovered a novel omnidirectional pause neuron that is located in the primate pretectum. Because the pause was similar for saccades in all directions and always followed the start of the saccade, we have classified this cell as a following omnidirectional pause neuron (FOPN). The pause was always longer than the durations of all targeting saccades we tested, i.e., ±15 deg and also longer than the durations of all but the very largest saccades in the dark. Although the pause was linked tightly to saccade onset, it lagged it by an average of 50 ms for targeting saccades. The end of the pause was correlated poorly with the end of the saccade. In addition, many FOPNs also discharged a burst of spikes before the pause. Unlike the pause, the burst, which reached an average of 122 ± 38 spikes/s, actually began before the saccade by an average of 11 ms. Finally, the tonic discharge rate in the isolated in a single track. At these locations, nearby tracks also tended to have more than one FOPN. Therefore, the locus of FOPN neurons appears to be thicker in some regions of the pretectum. However, we saw no evidence that FOPNs constitute an anatomically identifiable group of cells. Finally, we also placed electrolytic lesions on some electrode tracks and used depth measurements taken from microdrive readings to reconstruct the location of FOPNs on histological sections of the midbrain. These lesion data supported our conclusion that FOPNs constitute a thin sheet of cells located in the posterior part of the pretectum on the dorsal border of the NOT. Figure 6 shows an example of our pretectal anatomy where a lesion was placed at the depth of a direction selective NOT unit. The lesion is located in the thickest part of the NOT immediately above the pretectal olivary nucleus (see Mustari et al. 1994a).
FIG. 5. Examples of presaccadic bursts in 3 representative FOPNs (A) and burst lead relative to saccade onset (B). Our qualitative assessment of burst strength is indicated under each unit in A. B: distribution of burst leads determined from histograms like those in A for 32 FOPNs.

associated with equal-sized targeting saccades. Also, in about half of the neurons tested, the burst was reduced significantly or disappeared altogether in the dark. The disappearance of the burst cannot be attributed to a visual sensitivity produced by image motion associated with the high-velocity saccade because the burst typically began before the saccade started (Fig. 5). The quantitative difference in both the pause and burst accompanying dark saccades and targeting saccades may reflect changes in the state of alertness in the animal. Many FOPNs become inactive if the monkey falls asleep. We attempted to maintain a constant state of alertness by providing a variety of auditory stimulation when the monkey was in complete darkness. The metrics of saccades made in complete darkness also may contribute to the differences in firing seen in FOPNs in the light and dark. For example, the peak velocity of saccades made in the dark tend to be lower than saccades of comparable size in the light.

Neurons that change their activities transiently for saccades might play a variety of roles. These include controlling the metrics of the saccade, providing a corollary discharge signal related to an ongoing eye movement, and gating visual signals. We now will consider whether FOPNs could be engaged in any of these activities.

**FOPNs are ill suited to control saccadic metrics**

Neurons, which pause for saccades in all directions (OPNs) and lie on the midline of the pontine reticular formation have been implicated in the control of saccadic metrics (Fuchs et al. 1985; Keller 1974; Langer and Kaneko 1990). The discharge of FOPNs, however, differs in several important respects from that of pontine OPNs. First, the pause of FOPNs begins too late to control saccade initiation. Second, FOPN pause duration is correlated poorly with saccade duration and, on average, greatly exceeds saccade duration. Third, the end of the pause occurs too late to play a role in saccade termination. Fourth, saccades are thought to be controlled by feedback from a neural integrator, which provides a signal proportional to current eye position (Becker and Jürgens 1979). After a saccade, this integrator must be discharged or “reset.” The FOPN can not participate in this resetting, which begins long before the pause in FOPN discharge starts.
There are no FOPNs specific to saccade size or direction. Therefore we conclude that the pause of FOPNs can have nothing to do with controlling the characteristics or ‘‘metRICS’’ of the saccade.

FOPN discharge also appears to have little in common with the firing patterns of pause neurons found in the rostral colliculus (Munoz and Wurtz 1993a). Collicular ‘‘fixation’’ neurons, which have been implicated in controlling the transition from the end of the saccade to the subsequent fixation of the target, cease firing before saccade onset and display a pause whose duration increases, at least weakly, with saccade duration. In contrast, the pause in FOPN activity usually begins after the saccade has landed. Therefore the discharge patterns of FOPNs do not resemble those of collicular fixation neurons and would not be expected to play a similar role. On our penetrations, which run in the frontal stereotaxic plane, we occasionally first encountered FOPNs and then collicular fixation neurons more ventrally. Despite their proximity, FOPNs could be distinguished easily from fixation neurons at the time of recording.

**FOPNs are ill suited to provide corollary discharge about saccades**

For the same reasons that FOPNs cannot provide signals related to saccade metrics, their discharge would be inappropriate as a corollary discharge for saccades. Not only is the pause nonspecific with regard to saccade size and direction, but for most movements within the oculomotor range, the pause begins only after the saccade is over. Although the burst preceding the pause leads saccade onset, it too is insensitive, on average, to either saccade size or direction. Therefore, no aspect of the discharge pattern of FOPNs communicates precise information about the saccade. However, it is possible that the burst could be used to indicate only that a saccade (of unspecified characteristics) was to occur. Such a signal might be useful to modify the transmission of visual information.

**Can FOPNs participate in the modification of visual information?**

We will address this question by first considering where FOPNs might have their effect. While charting the efferent and afferent connections of the NOT (Mustari et al. 1994a), we discovered a prominent connection to the vicinity of the pregeniculate nucleus (PGN), a thin sheet of cells forming a cap over the dorsal lateral geniculate nucleus (LGN\(_d\)). We were initially surprised to find this NOT to PGN projection because the PGN region had long been implicated in saccade-related activities, whereas all other sites receiving NOT inputs had been implicated in visual motion processing or the optokinetic response. Because our findings in this paper indicate that the FOPNs constitute a thin band of cells in close dorsal proximity to the NOT, we now realize that any injections centered on the NOT also would have involved the saccadic FOPN region.

Neurons in the PGN region have discharge patterns that are reminiscent of those of FOPNs in that most have phasic responses, which follow saccades in all directions (Büttner and Fuchs 1973). The saccade-related activity can be either a pause in steady firing or a burst of spikes. For all the PGN burst neurons and most of the PGN pause neurons, the change in firing occurs after saccade onset. The burst begins \(\sim 85\) ms after saccade onset and the pause from \(50\) to \(200\) ms after saccade onset. For many of the PGN burst and pause neurons, the change in activity is much longer than the duration of the accompanying saccades and is roughly constant for saccades of all sizes (and therefore durations). For some cells, the saccade-related activity persists in the dark. Therefore it is possible that the activity of PGN burst neurons could reflect a release of firing due to a pause in inhibitory FOPN inputs.

The PGN region receiving NOT/FOPN input consists of two parts: a portion of the reticular nucleus of the thalamus and the primate homologue of the feline ventral lateral geniculate nucleus (LGN\(_v\)). The reticular nucleus has extensive connections with the LGN\(_d\), including GABAergic connections to its relay neurons (see Sherman and Koch 1986 for review). Therefore the reticular part of the PGN could gate the flow of visual information through the LGN\(_d\). The LGN\(_v\) is connected reciprocally with the reticular nucleus. At least in the cat, many of the neurons from the NOT to the LGN\(_v\) are GABAergic (Cucchiaro et al. 1991; Hada et al. 1986). Finally, in the prosimian primate (Galago), neurons from the pretectum, including the NOT, provide synapses with inhibitory morphologies to all types of LGN\(_d\) neurons, including those in magnocellular and parvocellular layers (Feig and Harting 1994). Although we could find only a weak input to the ipsilateral LGN\(_d\) from our NOT/PGN injections in the rhesus monkey (Mustari et al. 1994a), a recent study in which horseradish peroxidase was injected into the LGN\(_d\) reported finding labeled neurons in the NOT (Wilson et al. 1995). Thus the NOT and presumably also the FOPNs could effect transmission through the LGN\(_d\) by means of a pathway through the reticular nucleus, a pathway involving first the LGN\(_v\), and then the reticular nucleus, and also through a direct pathway.
Burst might be a key feature of FOPN discharge

Thus far, we have concentrated on the potential role of the pause in FOPN activity. It has been difficult to propose a role for the pause because it occurs so late. However, about half of FOPNs also discharge a burst of spikes, which, on average, leads the saccade by ~11 ms. Perhaps the burst is an important element of the FOPN discharge pattern. Unfortunately, like the pause, the properties of the burst are not well related to the metrics (duration, size) of the saccade. Perhaps, the burst simply signals that a saccade is occurring but does not specify either its size or direction. How might the brain make use of such information? One possibility is that the knowledge that a saccade is occurring could be used to inform visual pathways to ignore the detected motion because it is generated by eye movement rather than movement of the visual world.

Unfortunately, there also are several problems with this scenario. First, only a small number of pause neurons in the PGN show any change in activity before and during a saccade (cf., Büttner and Fuchs 1972, Fig. 8). Furthermore, if the major target of the reticular portion of the PGN indeed is the LGN, only a small minority of cells there show a change in activity before saccades. Therefore it is difficult to conclude that the burst in firing of FOPNs projecting to the PGN plays a role in gating visual information during a saccade.

Another possibility is that the burst exists only to help better define the start of the pause. Indeed, we have seen that the most salient feature of the FOPN discharge pattern is the reliability with which the pause retrospectively indicates saccade onset. Perhaps the burst is present only to increase the firing rate near saccade onset so the cessation of discharge can be more precisely specified.

A definitive role for FOPNs clearly requires further experiments. For example, it might be informative to inactivate the FOPNs pharmacologically or to provide brief stimulus trains to the FOPNs during and after saccades. However, it seems likely that a significant fraction of the FOPNs must be affected to produce an effect. Unfortunately, such experiments will be difficult to carry out because FOPNs are distributed so sparsely. Furthermore, they lie in close proximity to NOT neurons. Consequently, to generate a noticeable effect by either stimulating FOPNs electrically or inactivating them pharmacologically, one must use current or agents in such amounts that the nearby NOT surely will be strongly influenced. Because stimulation of the NOT region elicits a vigorous optokinetic nystagmus and inactivation of one NOT causes an ipsilaterally beating nystagmus, both of these manipulations would produce optokinetic eye movements that probably would obscure any effects on saccades. Consequently, some new strategies must be developed before we gain any further insights into the role of pretectal FOPNs in saccadic or visual function.

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