Discharge Properties of Neurons in the Rostral Superior Colliculus of the Monkey During Smooth-Pursuit Eye Movements

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Krauzlis, Richard J., Michele A. Basso, and Robert H. Wurtz. Discharge properties of neurons in the rostral superior colliculus of the monkey during smooth-pursuit eye movements. J Neurophysiol 84: 876–891, 2000. The intermediate and deep layers of the monkey superior colliculus (SC) comprise a retinotopically organized map for eye movements. The rostral end of this map, corresponding to the representation of the fovea, contains neurons that have been referred to as “fixation cells” because they discharge tonically during active fixation and pause during the generation of most saccades. These neurons also possess movement fields and are most active for targets close to the fixation point. Because the parafoveal locations encoded by these neurons are also important for guiding pursuit eye movements, we studied these neurons in two monkeys as they generated smooth pursuit. We found that fixation cells exhibit the same directional preferences during pursuit as during small saccades—they increase their discharge during movements toward the contralateral side and decrease their discharge during movements toward the ipsilateral side. This pursuit-related activity could be observed during saccade-free pursuit and was not predictive of small saccades that often accompanied pursuit. When we plotted the discharge rate from individual neurons during pursuit as a function of the position error associated with the moving target, we found tuning curves with peaks within a few degrees contralateral of the fovea. We compared these pursuit-related tuning curves from each neuron to the tuning curves for a saccade task from which we separately measured the visual, delay, and peri-saccadic activity. We found the highest and most consistent correlation with the delay activity recorded while the monkey viewed parafoveal stimuli during fixation. The directional preferences exhibited during pursuit can therefore be attributed to the tuning of these neurons for contralateral locations near the fovea. These results support the idea that fixation cells are the rostral extension of the buildup neurons found in the more caudal colliculus and that their activity conveys information about the size of the mismatch between a parafoveal stimulus and the currently foveated location. Because the generation of pursuit requires a break from fixation, the pursuit-related activity indicates that these neurons are not strictly involved with maintaining fixation. Conversely, because activity during the delay period was found for many neurons even when no eye movement was made, these neurons are also not obligatorily related to the generation of a movement. Thus the tonic activity of these rostral neurons provides a potential position-error signal rather than a motor command—a principle that may be applicable to buildup neurons elsewhere in the SC.

INTRODUCTION

The monkey superior colliculus (SC) has long been known to be important for the generation of saccades—those discrete eye movements that quickly direct the eyes toward an eccentric visual target (for reviews, see Moscovikis and Hightgen 1994; Sparks and Hartwich-Young 1989; Sparks and Mays 1990; Wurtz and Albano 1980). The intermediate and deep layers of the SC comprise a retinotopically organized map for saccadic eye movements as demonstrated by the metrics of the saccades evoked by microstimulation (Robinson 1972; Stryker and Schiller 1975) and the movement fields exhibited by single neurons at different sites across the SC (Schiller and Koerner 1971; Sparks et al. 1976; Wurtz and Goldberg 1972). Based on their discharge patterns during saccades, several types of movement-related neurons have been identified (Mohler and Wurtz 1976; Schiller and Koerner 1971; Sparks 1975; Sparks et al. 1976; Wurtz and Goldberg 1971, 1972), These neurons have recently been divided into two broad classes—burst and buildup neurons (Munoz and Wurtz 1995), although the classes probably represent the ends of a continuum. Burst neurons emit a burst of spikes immediately before saccades of a particular size and direction and may also exhibit a visual response, but display little or no tonic activity. Buildup neurons also show the visual and saccade-related activity and, in addition, have tonic low-frequency activity that increases before saccades to temporally predictable targets. The activity of these saccade-related neurons can directly influence the programming of eye movements through projections to the premotor saccade circuitry contained within the paramedian pontine reticular formation (PPRF) and the rostral interstitial nucleus of the medial longitudinal fasciculus (riMLF) (Harting 1977).

An additional class of neurons has been described in the rostral SC, the region corresponding to the foveal portion of the retinotopic map. In contrast to neurons located in the caudal SC, these neurons are typically active during periods of steady fixation and pause or decrease their discharge during most saccades in both cats (Munoz and Guitton 1989; 1991; Peck 1989) and monkeys (Munoz and Wurtz 1992, 1993a). Because these neurons maintain their discharge when the visual stimulus is removed—as long as the animal maintains fixation—these neurons have been referred to as “fixation cells” and have been hypothesized to be part of a fixation system that determines when saccades are initiated. Consistent with this inter-
pertation, activation of the rostral SC increases the latencies of large saccades, and stimulation applied during a saccade interrupts the movement in mid-flight (Munoz and Wurtz 1993b; Munoz et al. 1996). Conversely, inactivation of the rostral SC decreases the latencies of large saccades and reduces the ability to suppress unwanted saccades (Munoz and Wurtz 1992, 1993b).

Although the rostral SC is often referred to as the “fixation zone,” the activity of neurons in this region is not always strictly related to maintaining fixation. Although fixation cells pause during ipsiversive saccades, many also increase their discharge rate during small contraversive saccades (Anderson et al. 1998; Munoz and Wurtz 1993a). Fixation cells therefore appear to possess movement fields, like buildup neurons elsewhere in the SC, albeit ones that abut the fovea. Stimulation of the rostral SC not only interrupts saccades but can also alter their trajectory, suggesting the idea of a continuous representation of saccade size from caudal to rostral SC (Gandhi and Keller 1999). In addition, we recently reported that fixation cells change their discharge rate for small mismatches between eye and target position, even when these mismatches do not elicit a saccade, and that these neurons are modulated by the similar mismatches that occur during pursuit eye movements (Krauzlis et al. 1997). Based on those findings, we suggested that these neurons might encode a general error signal that could be used by multiple eye movements, including pursuit, rather than commands specifically for saccades and fixation. However, an alternative explanation for these recent findings is that the activity observed during pursuit reflects the programming of small saccades that are planned but not executed. Thus although these results suggested that the rostral SC might play a role in the control of pursuit eye movements, the issue is far from resolved.

A possible role for the rostral SC in the control of pursuit is also suggested by the effect of position errors during pursuit. Although pursuit eye movements are driven primarily by visual motion inputs, they can also be driven by the differences between target and eye position that occur during tracking. Position errors have been shown to cause smooth changes in pursuit eye velocity in both monkeys (Krauzlis and Miles 1996c; Morris and Lisberger 1987; Segraves and Goldberg 1994) and humans (Barnes and Asselman 1992; Barnes et al. 1987; Carl and Gellman 1987; Pola and Wyatt 1980). These corrective changes in smooth eye velocity act to recenter the target’s image on the fovea and are mostly observed for position errors <3°. Position signals have been incorporated into several models of pursuit eye movements in primates (Lisberger et al. 1987; Pola and Wyatt 1997; Wyatt and Pola 1987) and into models of smooth and saccadic gaze movements in cats (Cova and Galiana 1995; Galiana and Guittion 1992; Lefèvre and Galiana 1992; Lefèvre et al. 1994). Unlike the pathway mediating the visual motion signals for pursuit in the monkey, which includes the middle temporal (MT) and medial superior temporal (MST) areas of cortex (Dürsteler and Wurtz 1988; Dürsteler et al. 1987; Newsome et al. 1985) and which reaches the motor nuclei for pursuit via projections through the pontine nuclei (May et al. 1988), the pathway mediating the position signals for pursuit has not been identified. However, the correspondence between the range of effective position errors for pursuit and the locations of response fields for fixation cells suggests that the rostral SC might be part of this pathway.

To test whether neurons in the rostral SC might contribute a position signal for pursuit, we have now examined their activity in more detail. Our current results show that the discharge of fixation cells is modulated during the programming of smooth-pursuit eye movements and provide evidence that this activity is not caused by the execution or planning of small saccades that often accompany smooth eye movements. These changes in discharge rate during pursuit can be largely accounted for by the neurons’ tuning for target location, consistent with the idea that they provide a position signal for the pursuit system. Our results therefore also confirm that the activity of fixation cells has characteristics similar to buildup neurons located more caudally in the SC. Finally, because the parafoveal response fields of these neurons can be associated with pursuit, saccades, or fixation, these neurons appear to convey information concerning the location of the target rather than commands for a specific motor outcome.

METHODS

Recording procedures

Data were collected from two adolescent rhesus monkeys (Macaca mulatta), weighing 4–9 kg. All experimental protocols 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. The monkeys were under the care of the Institute veterinarian. Under isoflurane anesthesia and aseptic conditions, we attached a pedestal to the head of each monkey with titanium screws and dental acrylic; this pedestal allowed us to fix the head in the standard stereotaxic position during experiments. A recording chamber for SC single neuron recording was affixed to skull with dental acrylic and additional titanium screws. The chamber was angled 38° to the posterior of vertical and directed at the midline 15 mm above and 1 mm posterior to the interaural line. A scleral search coil was implanted around each eye, using the technique of Judge et al. (1980). The coils were used to monitor eye position with the electromagnetic induction technique (Fuchs and Robinson 1966). The AC voltages induced in the search coils were routed to a phase detector circuit that provided separate DC voltage outputs proportional to horizontal and vertical eye position (CNC Engineering). These outputs were low-pass filtered (6-pole Bessel, ~3 dB at 240 Hz) and then sampled at 1 kHz (A/D converter: National Instruments). The coil output voltages were calibrated with respect to eye position by having the animal fixate small LED targets at known eccentricities along the horizontal and vertical meridia.

The discharge of single neurons was recorded using tungsten microelectrodes (Frederick Haer) with impedances of 0.7–1.5 MΩ measured at 1 kHz. Electrodes were advanced through stainless steel guide tubes (23 gauge) with a microdrive mounted on top of the recording chamber. The guide tubes were held fixed in the chamber with a delrin grid system (Crist et al. 1988). Extracellular neuron activity was passed through a standard head stage, amplified, and converted into trigger pulses with a window discriminator applying both time and amplitude criteria (Bak Electronics). The time of each action potential was stored with 1-ms resolution.

Behavioral paradigms

The monkeys were seated in a standard primate chair and viewed stimuli projected onto a translucent tangent screen located 57 cm in front of the animal. Stimuli for the pursuit and visually guided saccade tasks consisted of 0.1° spots, which were generated with light-emit-
neurons position provided by transducers in the galvanometer systems, were low-pass filtered (6-pole Bessel, ~3 dB at 240 Hz) and then digitized to a resolution of 16 bits, sampling at 1 kHz (A/D converter: National Instruments). All data were stored on disk during the experiment and later transferred to a Unix-based system for subsequent off-line analysis.

An interactive analysis program was used to filter, display, and make measurements from the data. Signals encoding horizontal and vertical eye velocity were obtained by applying a 29-point finite impulse response (FIR) filter (~3 dB at 54 Hz) to the signals encoding horizontal and vertical eye position, respectively. Signals encoding eye acceleration were then obtained by applying the same FIR filter to the signals encoding velocity. For detecting saccades, the computer applied a set of amplitude criteria to the eye velocity and acceleration signals, as described previously (Krauzlis and Miles 1996b). Using the FIR filter described in the preceding text, this algorithm permitted us to detect saccades with amplitudes as small as 0.15–0.2° (Krauzlis and Miles 1998). The onset of pursuit was estimated using an algorithm previously described in detail (Krauzlis and Miles 1996b); briefly, we determined the point of intersection between the baseline eye velocity (0–64 ms after target motion onset) and a linear regression applied to the first 64 ms of the pursuit response exceeding 4.5 SD of the mean baseline eye velocity. Average traces were obtained by aligning the data with respect to either target motion onset or pursuit onset and calculating the mean and SD within each ms of the data. Statistical significance of differences between measurements was assessed with either a Mann-Whitney test for single comparisons or a Kruskal-Wallis test for multiple comparisons. Correlations between data sets were assessed by measuring the Pearson correlation coefficient. Statistical tests were performed with commercially available statistical software (SigmaStat).

RESULTS

Activity of rostral buildup neurons during pursuit eye movements

The majority of rostral buildup neurons had significant changes in discharge rate during smooth-pursuit eye movements. Figure 1, A and B, shows the activity recorded from one neuron as the monkey followed a target that was initially stationary and then started to move at a constant speed of 10°/s along the horizontal meridian toward the ipsilateral (Fig. 1A) or contralateral (Fig. 1B) side. During the period of fixation prior to the onset of target motion (defined as time 0), the neuron had a tonic discharge of 20–25 spikes/s. During the initiation of pursuit (approximately 100–200 ms after target motion onset), the neuron decreased its discharge rate for ipsiversive pursuit and increased its discharge rate for contraversive pursuit. During maintained pursuit (300–600 ms after target motion onset), the discharge rate remained generally lower during ipsiversive pursuit and elevated during contraversive pursuit, although additional changes in discharge rate continued until the end of the trial, particularly during contraversive pursuit. These time-varying changes in discharge rate accompany the changes in position error (“target minus eye position”) and eye velocity (“average eye velocity”) that occur during the trial. Figure 1, C and D, shows the activity from this same neuron as the monkey made 2° horizontal saccades to the ipsilateral (Fig. 1C) or contralateral (Fig. 1D) side. Consistent with its activity during pursuit, the neuron decreased its discharge slightly for ipsiversive saccades and increased its activity before and during contraversive saccades.
We quantified the changes in discharge rate during pursuit by measuring the firing rate in two intervals: a 100-ms "fixation" interval ending just as the target motion started, and a 100-ms "pursuit initiation" interval beginning at the onset of pursuit on each trial. Importantly, any trials that contained saccades within 20 ms of either interval, or saccades between the two intervals, were excluded from the analysis. Comparison of the measurements in these two intervals shows that the majority of neurons exhibited significant decreases (59%) in discharge rate during ipsiversive pursuit (Fig. 2A) and significant increases (71%) in discharge rate during contraversive pursuit (Fig. 2B). A minority of neurons showed significant decreases during both directions of pursuit (12%).

Although these data suggest that rostral buildup neurons exhibit pursuit-related activity, it is possible that these changes in discharge rate actually derive from saccade-related activity that is correlated with pursuit. As mentioned in the preceding text, our measurements excluded any motor activity related to the immediate execution of saccades, but it is possible that they included preparatory activity related to saccades made subsequently. To address this possibility, we examined the occurrence of saccades during pursuit in more detail. While recording from the neuron illustrated in Fig. 3A, the monkey did not make any saccades during pursuit trials toward the ipsiversive side, as indicated by the superimposed traces of eye velocity. Despite the complete absence of saccades, the neuron exhibited...
a significant decrease in discharge rate during pursuit that accompanied the changes in position error (target minus eye position). When the target was stepped 2° in the ipsilateral direction during fixation (Fig. 3B), producing a similarly sized position error, the same neuron again exhibited a significant decrease in discharge rate. The superimposed traces of eye velocity measured for fixation remain near 0°/s, indicating that these changes in discharge rate cannot be attributed to saccades or to changes in eye velocity.

Although we routinely recorded eye movements with no saccades during the onset of pursuit, small catch-up saccades often occurred later during maintained pursuit. Therefore to examine the effect of saccades on the pursuit-related activity for most neurons, we divided the trials from each neuron into two sets: those that contained “early” saccades and those that did not. We defined “early” as within 300 ms of target motion onset to produce a sufficient number of trials in both sets for the largest number of neurons. If the changes in discharge rate during the initiation of pursuit were due to the preparation of saccades, we would expect larger changes on trials that contained early saccades than on those trials that did not. Figure 4 shows an example of this segregation of the data from one neuron. The large deflections in the traces of eye velocity identify those trials that did not (Fig. 4A) and did (Fig. 4B) contain early saccades. Despite the difference in the timing of saccades, the discharge rates during the initiation of pursuit were nearly identical across the two sets of trials as indicated by the pairs of rasters and spike density traces. During maintained pursuit, there are slight differences; the discharge rate on trials without early saccades remained elevated longer, a difference that reflects the increased position error (target minus eye position) that also persists later on these trials. Similar results were obtained for the other neurons analyzed in this way. For the majority of neurons (28/33), the discharge rates during pursuit initiation were not significantly different between trials with and without early saccades, and three of the five neurons that did show a significant difference had higher discharge rates on trials without early saccades.

Activity of rostral buildup neurons after small target displacements

The rostral buildup neurons that we studied during pursuit eye movements belong to the same class of neurons that have been previously studied during fixation and saccades (Munoz and Wurtz 1992, 1993a). These neurons typically exhibited a tonic discharge rate during maintained fixation but increased their discharge during small contraversive saccades (e.g., Fig. 3).
We examined this selectivity for small target steps by displacing a fixated target by varying amounts (0.2–10°) along the horizontal meridian to either the contralateral or ipsilateral side. In addition to the changes in discharge rate associated with saccades already noted, neurons exhibited changes immediately after the change in stimulus location and during the interval preceding the small corrective saccades. For example, the neuron illustrated in Fig. 5 markedly increased its discharge rate 50–75 ms after small contraversive steps (0.6–4°, Fig. 5A), and these changes persisted for tens or hundreds of milliseconds prior to the initiation of a small corrective saccade. These changes in firing were distinct from, and preceded, the changes in discharge rate associated with the generation of the actual corrective saccades (Fig. 5B) but exhibited the same preference for small contraversive steps.

To quantify these changes, we measured the average discharge rate in three different intervals: a visual interval, 50–100 ms after the change in target position (based on the visual latency of these neurons), a delay interval, starting at 120 ms after the change in target position and lasting either until 170 or 20 ms before the onset of the corrective saccade (to exclude the saccade-related burst), whichever came first, and a saccade interval, spanning 8 ms prior to saccade onset until 8 ms prior to saccade end (to include peri-saccadic burst activity). Measurements from the neuron illustrated in Fig. 5 are shown in Fig. 6 for the visual (A), delay (B), and saccade (C) intervals and are plotted as a function of target location. As compared with the discharge rate during fixation of the target at 0°, the firing of the neuron increased for target locations around 1° in the contralateral hemifield, with lesser increases for more eccentric target locations, during each of the three intervals. For target locations in the ipsilateral hemifield, the discharge rate showed no change or small decreases.

Across the sample of neurons tested with multiple target locations, we found a range of preferred target locations within the central few degrees. For each neuron, the “best location” for each of the three intervals was determined from the peaks of the curves such as those shown in Fig. 6. A–C. Consistent with the rostral placement of our recording sites, the best target locations for most neurons were close to the center of the visual field as indicated in the bar graph for the sample of 27 neurons in Fig. 6, D–F. The majority of neurons in our sample had best locations in the contralateral visual field, although a minority exhibited a preference for slightly ipsilateral locations. As indicated by the partial overlap between the three distributions,
the best target locations were similar across the measurement intervals, although they were not always identical. Like buildup neurons elsewhere in the SC (Munoz and Wurtz 1995), these neurons therefore exhibited activity during the period prior to saccade generation as well as during the saccade itself.

The differences between those neurons with best locations near the fovea and those with best locations further eccentric were marked by quantitative, rather than qualitative, changes in discharge rate during different epochs of the trials, as illustrated by four sample neurons in Fig. 7. Neurons with best locations near 0° (e.g., Fig. 7A) exhibited elevated activity when the target was fixated directly or placed slightly eccentric (0.2–0.6°) and decreased activity for all eccentric target locations during saccades. At the other end of our distribution, neurons with best locations near 5° (e.g., Fig. 7D) exhibited little activity for target locations near 0° and increased activity for eccentric target locations on the contralateral side. For these two neurons, elevated activity was correlated either with maintaining fixation (Fig. 7A) or with programming a saccade (Fig. 7D). However, the activity of neurons with intermediate preferred locations was not predictive of a command to maintain fixation. For example, the neuron shown in Fig. 7C maintained a tonic discharge rate during both fixation and 5° contraversive saccades but increased its firing during smaller contraversive saccades and decreased its firing during ipsiversive saccades. Although this pattern of activity does not obey a dichotomy based on maintaining fixation versus programming saccades, it does fit within the graduated changes observed as one moves from foveally tuned (Fig. 7A) to eccentrically tuned neurons (Fig. 7D).

As a general test of whether these changes in discharge rate were associated with preferences for target location or with the programming of saccades, we compared activity for target locations in and around the “dead zone” for saccades (Fig. 8A). This dead zone reflects the monkeys’ threshold for making saccades. For target displacements >1–2°, the monkeys made saccades on 100% of the trials. However, for smaller target displacements, the percentage of trials with saccades decreased and was close to 0% for displacements of 0.2°. If the activity of these neurons was associated with the programming of saccades rather than a preference for target location, there should be no change in activity when saccades are never made. To the contrary, we found that for approximately half of the neurons tested with these small displacements (13/25), the changes in discharge rate during the delay interval were significantly greater after 0.2° contralateral steps than after 0.2° ipsilateral steps (Fig. 8B) even though these steps almost never result in saccades. Conversely, for most of the neurons (23/25), the changes in discharge rate were not significantly different in the delay intervals after 0.2 versus 0.6° contralateral steps (Fig. 8C) even though this increase in displacement amplitude produced a large change in the frequency of saccades (5 vs. 77%). The dead zone for saccades thus provides additional evidence that the activity of these neurons is related to target location rather than to the programming of saccades.

For neurons with a tonic discharge rate during fixation, we used fixation blink trials to test whether this activity depended on the visual stimulus provided by the fixation point (Munoz and Wurtz 1993a). In this paradigm, the monkey fixates a visual target that is extinguished briefly (600–800 ms) and then reappears. We measured the average discharge rate in two intervals: a 500-ms fixation interval as the monkey viewed the target spot and a 500-ms blink interval beginning 100 ms after the target was extinguished. Comparison of the measurement in these two intervals shows that the neurons did not decrease their discharge rate with the extinction of the visual stimulus.
We summarized these measurements with a fixation index, defined as the average discharge rate during the blink interval divided by the average discharge rate during the fixation interval (Munoz and Wurtz 1993a). The distribution of index values (Fig. 9B) shows that none of the neurons decreased their discharge rate by more than 50% during the blink interval, confirming that our sample of neurons is likely the same class of neurons previously described as fixation cells (Munoz and Wurtz 1993a).

Comparison of activity during pursuit and after small displacements of the target

The discharge of rostral buildup neurons during pursuit was affected by the speed of target motion in a manner analogous to the effects described in the preceding text for small displacements of the target. The neuron illustrated in Fig. 10 is the same neuron whose activity during small displacements is shown in Fig. 7A—this neuron was tuned for target locations near 0°. The traces of eye motion and discharge rates are aligned on the onset of target motion and represent averages from individual traces that were either completely saccade-free or were truncated 20 ms prior to any saccades. For 1°/s targets (Fig. 10, A and B), this neuron exhibited a discharge rate during pursuit that was slightly elevated from the tonic rate exhibited during fixation. For pursuit at 5°/s (Fig. 10, C and D), the discharge rate fluctuated during the initiation of pursuit but was
Elevated during maintained pursuit. For pursuit at 10°/s (Fig. 10, E and F), the discharge rate increased transiently during the initiation of pursuit before decreasing during maintained pursuit. This pattern of activity is consistent with the tuning of the neuron—slower target motions keep the target near its best location, whereas faster target motions sweep the target outside of its best location and into eccentric inhibitory locations.

To test the idea that the activity of rostral buildup neurons during pursuit was due to their tuning for target location, we calculated the retinal location of the target during pursuit trials by subtracting eye position from physical target location. Figure 11 shows the results of this subtraction for the neuron illustrated in Fig. 10 for ipsiversive (A) and contraversive (B) pursuit at 10°/s. Target location on the retina (thin traces labeled “no shift”) initially had a value of 0°, as the monkey fixated the stationary target, but increased steadily from 0° in either the ipsiversive (negative) or contraversive (positive) direction after the onset of target motion at 0 ms. Following the initiation of pursuit at 100–120 ms, the increase in retinal target location slowed and then decreased slightly but remained nonzero for the remainder of the trial.

We next directly compared the discharge rate to retinal target location, but to compensate for the visual delay in processing retinal target location, we used a copy of retinal target location that was temporally delayed by 55 ms. As explained in more detail below, the value of 55 ms produced the best correlation between the pursuit tuning curves and the tuning curves measured for small target displacements. Plotting the spike density traces as a function of this temporally shifted signal produced the two plots shown in Fig. 11, C and D, which confirm that the discharge of this neuron was elevated for target locations near 0° and decreased for target locations further eccentric than about 1°. We performed a similar transformation on the spike density and eye movement traces from each of the 14 pursuit conditions (2 directions at 7 speeds: 1, 2, 3, 4, 5, 10, and 15°/s). Finally we pooled the data points from all of the conditions, sorted them according to retinal target location, and computed the mean discharge rate associated with each retinal target location. For the neuron illustrated in Fig. 10, this analysis produced a tuning curve with a peak just slightly contralateral of 0° (Fig. 11E).

The tuning curves generated by this analysis of our pursuit data provided a good match to the tuning curves described in the preceding text (Figs. 5–7) for the activity after small displacements of the target. For three neurons, the three plots in Fig. 12 compare the tuning curves obtained from our analysis of saccade-free pursuit (filled circles) to the tuning curves measured from the visual (gray lines), delay (thick solid lines) and saccade (thin lines) intervals after target displacements.

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**FIG. 10.** Activity of a rostral buildup neuron during pursuit at different speeds. Target moved at 1 (A and B), 5 (C and D), and 10°/s (E and F) toward either the ipsilateral (A, C, and E) or contralateral (B, D, and F) side. Top traces: target position (---) and average eye position; bottom traces: target position minus average eye position (---, 0 error). Traces are aligned on the onset of target motion, indicated by ↑.

**FIG. 11.** Discharge rate during pursuit plotted as a function of position error. A and B: position error, defined as target position minus average eye position, is shown along with spike density function for ipsiversive (A) and contraversive (B) pursuit at 10°/s. Target location on the retina (thin traces labeled “no shift”) initially had a value of 0°, as the monkey fixated the stationary target, but increased steadily from 0° in either the ipsiversive (negative) or contraversive (positive) direction after the onset of target motion at 0 ms. Following the initiation of pursuit at 100–120 ms, the increase in retinal target location slowed and then decreased slightly but remained nonzero for the remainder of the trial.

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correlation with the tuning measured during the delay interval illustrated in Fig. 12, the pursuit tuning showed a consistent curve and each of the three other curves. For the three neurons data, we measured the correlation between the pursuit tuning obtained during the delay period.

Activity after small displacements of the target, especially those pursuit data closely matched those from measurements of the neurons, the shapes of the tuning curves calculated from the illustrate the analysis method in Fig. 11. For each of the The neuron shown in Fig. 12 is the same neuron used to
each graph plots firing rate as a function of position error (target minus eye position). Four sets of data superimposed in each plot were obtained from pursuit trials (filled circles), visual interval (gray), delay interval (thick black), and saccadic interval (thin black).

The neuron shown in Fig. 12A is the same neuron used to illustrate the analysis method in Fig. 11. For each of the neurons, the shapes of the tuning curves calculated from the pursuit data closely matched those from measurements of the activity after small displacements of the target, especially those obtained during the delay period.

To quantify the degree of correspondence between these data, we measured the correlation between the pursuit tuning curve and each of the three other curves. For the three neurons illustrated in Fig. 12, the pursuit tuning showed a consistent correlation with the tuning measured during the delay interval ($r^2$: 0.86, 0.95, and 0.72 for the neurons in Fig. 12, A–C, respectively, Pearson product moment correlation), the visual interval (0.48, 0.84, and 0.91) and the saccade interval (0.86, 0.96, and 0.62). These results were typical of our sample, although the correlation on average was best for the delay interval. Overall, the pursuit tuning curves were significantly correlated with the delay interval tuning for 67% (18/27) of the neurons (mean $r^2$: 0.58), as opposed to 41% (11/27) for the visual interval (mean $r^2$: 0.34), and 48% (13/27) for the saccade interval (mean $r^2$: 0.49).

The higher correlation observed between the pursuit tuning curves and the delay interval was not the result of applying a particular temporal delay to retinal target location. The delay of 55 ms was selected after testing temporal delays ranging from 25 to 100 ms (in 5-ms steps), performing the analysis described in the preceding text on the pursuit data from each neuron and measuring the correlation between the resulting pursuit tuning curves and the three curves obtained from the activity after small displacements of the target. We found that a temporal delay of 55 ms produced the best average correlation coefficient across all neurons and tuning curves. Moreover, the average correlation was not much altered by small changes in the temporal delay applied to retinal target location—it remained within 1% of the best value for delays ranging from 45 to 65 ms. This insensitivity to absolute delay may have resulted from the fact that the slow continuous target motions we used to elicit pursuit produced retinal target locations that were relatively constant over tens of milliseconds as indicated by the traces of target minus eye position.

We next tested whether variables other than target location might be equal or better predictors of discharge rate during pursuit and after target displacements. In particular, given the general similarity between the time-varying profiles of target location and eye velocity (e.g., Fig. 1), we tested whether either eye velocity or eye position could account for the discharge rate recorded from rostral buildup neurons. This analysis of our pursuit data was identical to the one described in the preceding text used to generate tuning curves for target location with two exceptions: we sorted the discharge rates according to average eye velocity and position rather than retinal target location and we did not temporally shift the traces of eye velocity and position because we were testing for a correlation between discharge rate and the concurrent eye movement. To generate comparable measurements from the data obtained with small displacements of the target, we reanalyzed the data presented for the delay interval in Figs. 5–7, sorting the measured discharge rates for each neuron according to either eye velocity or position. Together these analyses produced a pair of discharge rate curves—one measured during saccade-free pursuit and one measured during the delay interval after target displacements—as a function of both eye velocity and position.

Examples of the eye velocity and eye position curves are shown in Fig. 13 for the same three neurons whose target location tuning curves were shown in Fig. 12. For eye position, two of the three neurons (Fig. 13, A and E) did not display consistent tuning within the range of eye positions tested in our experiments and a poor correspondence between the measurements obtained during pursuit (–●–) and those obtained after target displacements (—). This lack of correspondence is substantiated by the negative correlation coefficients for the two pairs of curves ($r^2$: −0.10 and −0.75 for A and E, respectively). The discharge rate of the third neuron (Fig. 13C) did show some relationship to eye position, and this was reflected in a
saccades that accompanied pursuit. Thus, in contrast to the discharges that were phasic and occurred only during the catch-up movements of the target. These neurons were better associated with target location than with either eye position or eye velocity.

The results from the three sample neurons were representative of the total sample. Overall, eye position was a poor predictor of discharge rate between the pursuit and target displacements ($r^2: 0.19$) or eye velocity ($B, D,$ and $F$). Two sets of data superimposed in each plot were obtained from pursuit trials (——) and the delay interval after step displacements (—).

**Activity of rostral burst neurons during pursuit**

While searching for rostral buildup neurons, we also recorded from seven rostral burst neurons. These neurons sometimes discharged during pursuit eye movements, but these discharges were phasic and occurred only during the catch-up saccades that accompanied pursuit. Thus, in contrast to the discharge rate before small contraversive saccades. Activity during pursuit and after target displacements ($r^2: 0.92$). For eye velocity (Fig. 13, B, D, and F), this same neuron (Fig. 13B) exhibited a preference for contraversive eye velocity both during pursuit and after target displacements ($r^2: 0.94$). However, the other two neurons showed a poor correlation between the two sets of data ($r^2: 0.19$ and $-0.40$ for $B$ and $F$, respectively). The results from the three sample neurons were representative of the total sample. Overall, eye position was a poor predictor of discharge rate between the pursuit and target displacement experiments; significant correlations were found for $26\%$ ($7/27$) of the neurons. Eye velocity was somewhat better, resulting in significant correlations for $41\%$ ($11/27$) of the neurons. Of these 11 neurons, 10 also showed a significant correlation when analyzed with respect to retinal target location for one or more of the three intervals after small displacements of the target. Thus, the discharge rates of these neurons were better associated with target location than with either eye position or eye velocity.

**Rostral buildup neurons and position error**

The neurons that we studied in the rostral SC had the same characteristics as the fixation cells identified previously (Munoz and Wurtz 1993a): they had tonic activity during fixation, even in the absence of a visual stimulus, and their discharge paused during the most saccades. This distinguishes them from the saccade-related neurons in the caudal SC that typically increase their activity during saccades to eccentric targets. These caudal saccade-related neurons are otherwise either largely silent (burst neurons) or show an increase of activity even in the absence of a visual stimulus, and their discharge rate before small contraversive saccades. Activity dur-

**DISCUSSION**

Our current results demonstrate that the discharge rates of fixation cells in the rostral SC are modulated during pursuit eye movements. We found that these neurons exhibit the same directional preferences during pursuit as during small saccades—they increase their discharge during movements toward the contralateral side and decrease their discharge during movements toward the ipsilateral side. This pursuit-related activity was observed regardless of the presence or absence of small catch-up saccades during pursuit, arguing that this activity was not related to the execution of saccades during pursuit or even to the programming of saccades that were planned but not executed. When we plotted the discharge rate from individual neurons during pursuit as a function of target location, we found tuning curves with best locations within a few degrees contralateral of the fovea. We then compared this tuning for target location measured during pursuit to that exhibited during the visual, delay, and peri-saccadic intervals on interleaved saccade trials. Although the activity during each of the three intervals sometimes showed similar tuning for target location as that measured during pursuit, the best correlation for most neurons was found for the delay period activity recorded as the monkey viewed parafoveal stimuli while maintaining fixation. The pursuit-related activity is therefore best explained by the tuning of these neurons for target locations within a few degrees contralateral of the fovea rather than by visual responses to the appearance of the stimulus or by motor activity related to the preparation of saccades. These results are consistent with the idea that neurons with fixation-related activity in the SC signal the presence of small discrepancies between the currently foveated location and the actual position of the target stimulus. We will first outline the implications of these results for the functional organization of the rostral SC, then discuss how these findings might be related to the role of position errors in the pursuit system, and finally consider some of the other factors that might have influenced our results.
ing these small saccades directly contradicts the idea that these neurons promote fixation because even very small saccades are associated with increases in the discharge of brain stem burst neurons and with pauses in the discharge of omnipause neurons as is also observed with larger saccades (Keller 1974; Van Gisbergen and Robinson 1977; Van Gisbergen et al. 1981). In addition, we were able to plot tuning curves not only for the peri-saccadic interval, as shown previously (Munoz and Wurtz 1993a), but also for the visual and delay intervals preceding the saccade. These rostral neurons therefore possess a property that is the defining characteristic of buildup neurons: they continue to discharge in the interval between the appearance of the visual stimulus and the onset of the saccade. These results indicate that these rostral neurons are not an extension of the buildup neurons but are buildup neurons themselves and do not comprise a separate specialized class devoted to visual fixation. This interpretation is further supported by our observation that these neurons change their activity during pursuit eye movements because pursuit has motor properties that are distinct from both fixation and saccades. Although it has sometimes been assumed that fixation is essentially pursuit of a stationary target, several observations indicate that pursuit, like saccades, also requires a break from fixation (Goldreich et al. 1992; Krauzlis and Miles 1996c; Luebke and Robinson 1988; Robinson 1965; Schwartz and Lisberger 1994).

We suggest that the buildup activity of rostral SC neurons does not provide a command for a specific type of eye movement but instead encodes position errors. We found that this activity generally did not depend on whether the monkey generated pursuit, made a saccade, or maintained fixation. Similarly, previous studies found that buildup activity in the caudal SC is often observed even when no saccade is made (Basso and Wurtz 1998; Munoz and Wurtz 1995). However, we did find that the activity of rostral buildup neurons was tuned for target location and that this tuning could explain the changes in discharge rate observed during pursuit, prior to saccades and during fixation. Thus the rostral SC may contribute to fixation by virtue of the small position errors encoded by the buildup neurons at these sites and the fact that monkeys in these experiments tend not to make saccades to these locations, reflecting a behavioral dead zone for saccades (e.g., Fig. 8). Admittedly, the term position error could be viewed as a slight misnomer because it may suggest a signal that should always generate a corrective response—a property that is expressly contradicted by the activity of buildup neurons. It might be more accurate to view buildup activity as encoding potential or candidate position errors, the behavioral consequences of which depend on the activity of other neurons in the SC and elsewhere.

**Position error for pursuit**

The tuning of rostral buildup neurons for parafoveal locations suggests that they could participate in the control of pursuit eye movements by providing a position-error signal. Although visual motion is the primary sensory input for pursuit, several behavioral studies have shown that the visual position of the target can also have potent effects on pursuit eye movements (Barnes and Asselman 1992; Barnes et al. 1987; Carl and Gellman 1987; Krauzlis and Miles 1996c; Morris and Lisberger 1987; Pola and Wyatt 1980; Segraves and Goldberg 1994). Pursuit responses to position errors per se have been demonstrated by imposing target displacements under electronically stabilized conditions in which the visual consequences of any evoked movement are cancelled (Morris and Lisberger 1987; Pola and Wyatt 1980; Segraves and Goldberg 1994). With this technique, position errors can be imposed for hundreds of milliseconds, and the sustained responses to visual position can be dissociated from the transient responses to the target step. Under these conditions, position errors produce a continuous change in eye velocity, similar to the changes in eye velocity caused by visual motion. Our current results indicate that buildup neurons in the rostral SC are one possible source of this position information used by the pursuit system. We found that buildup neurons in the rostral SC are tuned for exactly those locations known to be effective in guiding pursuit. The range of position errors that can modify pursuit partly depends on experimental conditions, but can be as large as 2–3° (Morris and Lisberger 1987; Segraves and Goldberg 1994). This range of amplitudes coincides with the distribution of best locations that we observed for buildup neurons in the rostral SC neurons that also exhibited pursuit-related activity and matches the movement fields found in previous studies for SC neurons with fixation-related activity (Munoz and Wurtz 1993a). In corroboration of this circumstantial evidence, recent experiments involving activation and inactivation of the rostral SC in monkeys provide direct evidence that this region plays a causal role in pursuit (Basso et al. 1997, 1998).

Although the SC in the monkey has never figured prominently in descriptions of the pathways for pursuit eye movements (Keller and Heinen 1991; Lisberger et al. 1987), there are several possible pathways through the SC that could convey visual position information for the pursuit system. A major input to the SC comes from the frontal eye fields (FEF) and supplementary eye fields (SEF) (Leichnetz and Gonzalo-Ruiz 1996; Stanton et al. 1988), which contain subdivisions involved with pursuit eye movements (Gottlieb et al. 1994; Heinen and Liu 1997; MacAvoy et al. 1991; Tian and Lynch 1996). The superficial layers of the SC receive a strong projection from the middle temporal area (MT) and a weaker projection from the medial superior temporal area (MST) (Boussaoud et al. 1992; Ungerleider et al. 1984); both regions are known to process visual motion information that is crucial for pursuit eye movements. The cell bodies of the neurons we studied lie deeper than the termination sites from MT and MST, but the dendrites of these neurons likely extend into these superficial layers (Moschovakis et al. 1988a,b). The SC also projects to nuclei in thepons (Harting 1977), such as the dorsolateral pontine nuclei (DLPN) and the nucleus reticularis tegmenti pontis (NRTP), and to the deep cerebellar nuclei, such as the fastigial nucleus, of which have been implicated in the control of pursuit (Fuchs et al. 1994; May et al. 1988; Mustari et al. 1988; Robinson et al. 1997; Yamada et al. 1996). Currently it is unclear how the putative position information conveyed by such pathways could alternately produce either saccades or pursuit, but recent data suggest that this motor decision might be regulated by the cerebellar vermis (Krauzlis and Miles 1998).

A separate line of evidence from studies in the cat also supports the idea that the SC is involved in the control of smooth eye movements. Some models of combined eye and head movements in the cat place the SC within a feedback loop
that provides a continuously updated position-error signal (Cova and Galiana 1995; Galania and Guitton 1992; Lefevre and Galiana 1992; Lefevre et al. 1994). Typically, this error signal produces saccade-like gaze shifts, but if the saccade is terminated before the position error is eliminated, the movement is completed with a slow, smooth gaze shift. These models therefore predict that the SC in the cat can contribute to smooth eye movements, at least under some conditions. Consistent with this idea, microstimulation in the intermediate layers of the cat SC can produce smooth eye movements in the wake of saccades (Missal et al. 1996, but see also Breznen et al. 1996), similar to the “slow correcting movements” often observed after visually guided saccades (Missal et al. 1993). Furthermore, many saccade-related projection neurons in the SC fire both during saccades and during the slow correcting movements that sometimes follow the saccade (Oliver et al. 1993). Although the relationship of these smooth movements in the cat to pursuit movements in the primate is not yet resolved (Evinger and Fuchs 1978; Missal et al. 1995), these results argue that the SC of the cat, like that of the monkey, conveys a position-error signal that can drive smooth, as well as saccadic, eye movements.

**Common position signal for pursuit and saccades?**

The position signal we observed on rostral buildup neurons during pursuit and saccades might act to coordinate the two types of movements, thereby avoiding the deleterious visual consequences that would follow if the two systems operated completely independently. In particular, this common signal might be a part of a mechanism for ensuring that both eye movements share the same goal (Krauzlis and Stone 1999; Krauzlis et al. 1997). Several studies have shown that saccadic latencies are increased when subjects are required to search for a unique target among a field of distracting stimuli (Ottes et al. 1985; Williams 1967), and similar increases in pursuit latencies occur when subjects must choose between two stimuli moving in opposite directions (Ferrera and Lisberger 1995; Krauzlis et al. 1999). These latency increases likely reflect the additional time required to select the target, but it is unsettled whether these effects reflect independent albeit similar processes for pursuit and saccades, an interaction between saccade selection and the gating of visual inputs for pursuit (Lisberger 1998) or the use of shared inputs for target selection (Krauzlis and Miles 1996b; Krauzlis et al. 1999). The activity of buildup neurons in the SC could be part of this selection mechanism for saccades because they exhibit graded responses that depend on the probability that the stimulus in their response field is the target either from a priori information (Basso and Wurtz 1998; Glimcher and Sparks 1992) or from a posteriori analysis of a sensory cue about target location (Horwitz and Newsome 1999). Our current finding that rostral buildup neurons encode position information during both pursuit and saccades suggests that these neurons might be involved in the selection mechanism for both types of eye movements. Conversely the latencies of pursuit and saccades are both reduced when the fixated stimulus is extinguished prior to the appearance of the target (Fischer and Boch 1983; Fischer and Ramsperger 1984; Knox 1996; Krauzlis and Miles 1996a,b; Saslow 1967), presumably because the early departure of the fixation stimulus facilitates the selection of the new target. The pause in rostral buildup neuron discharge rate during larger saccades is correlated with this “gap effect” (Dorris and Munoz 1995). Because our results indicate that these neurons encode a general position signal, their discharge rate might be correlated with the gap effect for pursuit as well as for saccades.

**Other possible contributions to SC activity during pursuit**

Several aspects of our data indicate that the pursuit-related activity we observed was distinct from motor activity related to the execution of saccades. Rostral buildup neurons often increased their discharge rate during small contraversive saccades, as noted previously (Munoz and Wurtz 1993a), but pursuit-related activity was typically more sustained and of lower amplitude than that associated with saccades. In a direct comparison between the activity during pursuit and that associated with saccades, we found that the pursuit-related activity was better correlated with activity during the delay period preceding saccades than with the saccade period coincident with saccade execution. Moreover we can rule out the possibility that the observed modulation was associated with the motor execution of saccades because we found significant changes in discharge rate during the onset of pursuit even after those epochs containing saccades were excluded from analysis. In contrast, we found that saccade-related burst neurons, whose activity is directly related to saccade generation (Munoz and Wurtz 1995; Schiller and Koerner 1971; Sparks 1975, 1978; Wurtz and Goldberg 1971, 1972), responded during the catch-up saccades that accompanied pursuit but did not exhibit pursuit-related activity. Might the pursuit-related activity have been related to saccades that were prepared but not executed? To address this issue, we reasoned that if the pursuit-related modulation was related to saccade preparation, it should be higher on those trials in which the putative pursuit activity was soon followed by a saccade than on those trials in which it was not. However, we found that there was no significant difference between the pursuit-related activity in these two conditions for most neurons (28/33). We believe these results provide strong, albeit indirect, evidence that the pursuit-related activity we measured were not associated with the preparation of the saccades that accompany pursuit.

Might the activity observed during pursuit be related to visual inputs to these neurons, rather than to pursuit activity per se? In the earlier studies that noted pursuit-related activity in the SC, some of the responses appeared to be due to the presence of the visual stimulus, leading to the conclusion that the activity might not have been related to the pursuit movement itself (Wurtz and Goldberg 1972). Unfortunately, unlike saccades, the generation of pursuit generally requires the presence of a visual stimulus to initiate and sustain the movement, making it difficult methodologically to dissociate visual from motor activity during pursuit. In our current data, we addressed this issue by using the fixation blink paradigm in which a fixated visual stimulus is briefly extinguished. As found previously with fixation cells, we observed that most buildup neurons in the rostral SC maintained or increased their discharge when the visual stimulus was removed (Munoz and Wurtz 1993a), indicating that their activity did not depend on the presence of the visual stimulus. These results suggest that the activity we observed during pursuit also did not depend on the presence of the visual stimulus, but instead was related to...
position error—exactly analogous to the activity previously described for “quasi-visual” saccade-related neurons in the caudal SC (Mays and Sparks 1980). However, we cannot rule out the possibility that the activity during pursuit was at least partially driven by visual inputs because we did not apply this test during pursuit itself. Indeed recent data indicate that even the saccade-related activity of SC neurons is enhanced by the presence of a visual stimulus (Edelman and Goldberg 1997).

Might the pursuit-related activity be due to motor factors rather than information about target location? For example, there is evidence that the level of burst activity at the SC site determines the velocity of the saccade (Stanford et al. 1996) and that the discharge rate during saccade-related bursts is influenced by the orbital position of the eyes (van Opstal et al. 1995). However, we found that neither eye velocity nor eye position provided a consistent explanation for the discharge rates we observed as the monkey smoothly pursued compared with that as he fixated. Whereas target location provided a significant correlation in 67% of the cases, eye velocity and position provided significant correlations in only 41 and 26% of the cases, respectively. These results are not entirely surprising, because the pursuit-related activity was most similar to that during the delay period preceding saccades, whereas the previous data concerning eye velocity examined activity concurrent with saccade generation. Similarly, previous data concerning eye position effects involved displacements as large as 20° (van Opstal et al. 1995), whereas the largest displacement we studied was 10°. Although we cannot completely rule out the contribution of other factors, we conclude that the pursuit-related activity we observed is most consistent with the neurons’ tuning for target location.

Together, these data and analyses clarify observations made nearly 30 years ago in the earliest studies of the role of the SC in orienting movements (Schiller and Koerner 1971). These authors observed that SC neurons with receptive fields within 5° of the fovea were tonically active during smooth tracking eye movements (e.g., their Fig. 11). Although their recordings did not disambiguate pursuit from small saccades during tracking, our current results confirm their suggestion that the rostral SC is involved in programming both types of small eye movements. The most direct way to substantiate the causal relation between the rostral SC neurons and pursuit is to alter the activity of these neurons and determine whether pursuit is modified, and the results of such experiments are reported in the next paper (Basso et al. 2000).

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REFERENCES


MISIAL M, ROMMELINCK M, ROUCOUX A, AND DÉCOSTRE MF. Slow correct.

KELLER EL. Participation of medial pontine reticular formation in eye move-


MAYS LE AND SPARKS DL. Dissociation of visual and saccade-related re-


MESSAL M, LEFEVRE P, DELINTE A, CROMMELINCK M, AND ROUCOUX A. Smooth eye movements evoked by electrical stimulation of the cat’s super-


