Smooth-Pursuit Eye-Movement-Related Neuronal Activity in Macaque Nucleus Reticularis Tegmenti Pontis

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Suzuki, David A., Tetsuto Yamada, and Robert D. Yee. Smooth-pursuit eye-movement-related neuronal activity in macaque nucleus reticularis tegmenti pontis. J Neurophysiol 89: 2146–2158, 2003; 10.1152/jn.00117.2002. Neuronal responses that were observed during smooth-pursuit eye movements were recorded from cells in rostral portions of the nucleus reticularis tegmenti pontis (rNRTP). The responses were categorized as smooth-pursuit eye velocity (78%) or eye acceleration (22%). A separate population of rNRTP cells encoded static eye position. The sensitivity to pursuit eye velocity averaged 0.81 spikes/s per °/s, whereas the average sensitivity to pursuit eye acceleration was 0.20 spikes/s per °/s². Of the eye-velocity cells with horizontal preferences for pursuit responses, 56% were optimally responsive to contraversive smooth-pursuit eye movements and 44% preferred ipsiversive pursuit. For cells with vertical pursuit preferences, 61% preferred upward pursuit and 39% preferred downward pursuit. The direction selectivity was broad with 50% of the preferences, 61% preferred upward pursuit and 39% preferred downward pursuit. The directional selectivity was broad with 50% of the preferences.

INTRODUCTION

Smooth-pursuit eye movements are frequently generated to keep our attention focused on moving objects of interest. Visual motion information is utilized in initiating and maintaining this tracking behavior. Thus one cortico- ponto-cerebellar pathway of import to the control of smooth-pursuit eye movements routes visual motion and visuo-oculomotor signals from middle temporal/medial superior temporal (MT/MST) to the dorsolateral pontine nucleus (DLPN) and thence to oculomotor-related parts of the cerebellum (e.g., Brodal 1978, 1979; Glickstein et al. 1980; Komatsu and Wurtz 1988; Langer et al. 1985; Lisberger and Fuchs 1978; Maunsell and Van Essen 1983; Miles and Fuller 1975; Mustari et al. 1988; Newsome and Wurtz 1988; Suzuki and Keller 1984, 1988a,b; Suzuki et al. 1990; Thier et al. 1988). That this pathway is not the sole pathway underlying cortico-ponto-cerebellar control of smooth-pursuit eye movements was indicated by the recovery of pursuit behavior following bilateral lesions placed in DLPN (May and Keller 1988).

A good candidate for a parallel pathway was thought to be from the frontal and supplementary eye fields (FEF, SEF) to nucleus reticularis tegmenti pontis (NRTP) to ocular motor-related regions of the cerebellum. The FEF and SEF have been shown to contain cells that are responsive to smooth-pursuit eye movements (Gottlieb et al. 1994; Heinen and Liu 1997; MacAvoy et al. 1991) and lesions therein cause deficits in pursuit behavior (Keating 1991; Lynch 1987). Microstimulation in NRTP evoked slow, pursuit-like eye movements (Yamada et al. 1996), and pharmacological lesions placed in NRTP resulted in deficits in smooth-pursuit eye movements (Suzuki et al. 1999). NRTP is known to receive inputs from the FEF and SEF (Brodal 1980a; Giolli et al. 2001; Huerta et al. 1986; Künzle and Akert 1977; Shook et al. 1990) and to project to the floccular region and to vermal lobules VI and VII (Brodal 1980b, 1982), the eye movement-related regions of the cerebellum (Lisberger and Fuchs 1978; Miles and Fuller 1975; Suzuki and Keller 1988a,b).

The presence of smooth-pursuit eye-movement-related modulations in NRTP activity would support the notion of a FEF/SEF-NRTP-cerebellum pathway that parallels the MT/MST-DLPN-cerebellum path. Thus the goal in this study was to characterize neuronal responses in NRTP during maintained smooth-pursuit eye movements. Responses of NRTP cells were related to pursuit eye velocity and pursuit eye acceleration. In addition, a separate population of cells encoded static eye position. The results complemented the growing body of evidence implicating NRTP involvement in a wide range of motor behaviors including saccadic eye movements (Crandall and Keller 1985), vergence eye movements (Gamlin and Clarke 1995), and active head movements (Suzuki et al. 1996).
SMOOTH-PURSUIT RESPONSES IN MACAQUE NRTP

Betelak et al. (2001). Employing this improved method for more than 6 yr has resulted in zero implant failures. In brief, a multi-phase process began with the implantation of titanium flange fixtures as anchors followed by a several-month period during which the bone grew into the outer threads of the flange fixtures. The second phase involved surgical implantation of scleral eye coils and attachment of the prefabricated skull cap. A recording chamber was finally attached following a variable length training period. All procedures were completed under aseptic conditions and isoflurane gas anesthesia.

Teflon-covered stainless steel wire was used to construct the scleral eye coils that were implanted under the conjunctiva at the junctions of the eye muscle insertions of the right eye (Judge et al. 1980). The recording chambers (17 mm diam) were attached to the skull with dental resin and centered at stereotaxic anterior 6.5 mm with a 20° off-vertical angle in the coronal plane. Two small-diameter, stainless steel cylinders were transversely embedded in the skull cap to allow immobilization of the head relative to the monkey chair. All sutured incisions were treated with antibiotic ointments, and during recovery, buprenex was given for analgesia and penicillin or cefazolin was administered for prophylaxis.

Before surgical preparation, the monkeys were trained to enter a primate chair from their home cages. After recovery from the surgical procedures, the animals voluntarily entered, on a daily basis, the primate chair that was then placed within the experimental setup. After each daily experimental session, the animals were taken back to their home cages for the remainder of the day. In their home cages, they had access to foraging boards and toys. The health status of the animals was monitored daily. The experimental and surgical protocols were approved by the Indiana University School of Medicine Animal Care and Use Committee and complied with the policies of The American Physiological Society and the United States Public Health Service concerning the care and use of laboratory animals.

Recording

The microelectrodes were fabricated from tungsten rods and insulated with Isonel-31. They were lowered within and together with a 23-gauge stainless steel guide tube to a point 10 mm dorsal to the oculomotor (IIIrd) nucleus. The microelectrode was hydraulically driven out of the guide tube with a Kopf stepper-motor, micromanipulator system. The location of the IIIrd nucleus, with its characteristic eye-movement-related activity, was first determined to establish a stereotaxic reference structure that aided the subsequent localization of NRTP. Tracks aimed at NRTP ran ventrolateral to the IIIrd nucleus.

Paradigms

The monkeys were trained with standard conditioning techniques to fixate and track small (0.25°) laser-generated spots of light that were back projected onto a tangent screen and moved with an X,Y-mirror galvanometer system. The tangent screen was 90° × 90° and located about 60 cm in front of the monkeys in a dark room. An Apple Macintosh IIfx computer running LabView controlled the presentation of the visual targets, monitored behavior, and rewarded correct task performance. Liquid intake was controlled for 5 days each week and freely available on weekends. During the experimental period, the extent of liquid intake was self-determined by the animals, who received performance-dependent liquid rewards until they were satisfied. Reward delivery was contingent on eye position being within a small electronic “window” surrounding the position of the fixation spot. Window size was dependent on target speed and could be set to 2–4° after a couple of months of training. Eye positions were determined with a phase-angle coil system (CNC Engineering) using the magnetic-field search-coil method (Robinson 1963) with a resolution of 0.25° and a calibration accuracy of 0.5° or less.

The monkeys were required to perform two basic tasks. Smooth-pursuit eye movements: the animals were trained to pursue periodic target motion oscillating with an amplitude of 10–20°. A trial began with the initial fixation of a stationary target. After a random interval, the target started moving and the monkeys were required to initiate smooth-pursuit eye movements within 200 ms of target motion onset. Different eye velocities were elicited by target motion at different frequencies with target excursion amplitude held constant. Target motion amplitude was typically 10° and the frequency ranged from 0.2 to 1.0 Hz. The direction of target movement could be selected from any of four different planes set 45° apart. Other directions could also be set with the use of a joystick. When studying the effects of eye position on pursuit responses, the center of the target motion was moved to either side of screen center. Stationary fixation: the animals were required to fixate a stationary target located at different positions on the screen.

Data acquisition and analysis

Analog signals, filtered at 202 Hz (Frequency Devices, 8-pole Bessel), and unfiltered, discriminated neuronal pulses (Bak DIS-1) were sampled at 2 kHz/channel. Horizontal and vertical eye positions, target positions, the discriminated neuronal pulses, and timing pulses were stored on a magneto-optical disk (Pinnacle Micro REO-650) for later off-line analysis. Data were analyzed with a “pentium” microcomputer employing analytical software that was developed with the Ortho-based ASYST (Keithley). Eye velocity was calculated with a differentiation algorithm supplied with ASYST. This algorithm interpolated a second-degree polynomial through consecutive (eye position) data points and then differentiated the polynomial (Blahut 1984). Eye velocity was differentiated to yield eye acceleration. To smooth the eye velocity and eye-acceleration signals, the data were filtered with a 40-Hz low-pass filter using a Blackman window supplied with ASYST. This implementation of a FIR filter did not shift the data in time.

Neuronal activity was collected during sinusoidal smooth-pursuit eye movements. The data were analyzed with a discrete Fourier analysis program that yielded values for the amplitude of the fundamental response, the dc firing rate, harmonic distortion, and the phase shift of the neuronal activity with respect to eye velocity. Smooth-pursuit eye movements at 0.4 Hz ± 10° were routinely used as the search stimulus to locate responsive cells.

Histology

Electrolytic lesions (anodal constant current, 20 μA for 30 s) were made at selected NRTP sites. After 1–3 wk, the monkeys were given a lethal injection of pentobarbital and perfused rapidly through the left ventricle with 1 l of buffered isotonic saline followed by a rapid perfusion of 2 l, then slow perfusion of two additional liters of buffered 10% formalin. The brain was blocked, frozen, and cut in the coronal plane in 40-μm sections. The resulting sections were stained with cresyl violet, and recording sites were reconstructed with reference to the electrolytic lesions (Fig. 1). The stereotaxic coordinate planes of the schematized sections were determined from the coordinates of the recording chamber and the track locations of the marking lesions.

RESULTS

Location and population

Data were acquired from four macaques (3 Macaca fascicularis and 1 M. nemestrina) for 204 NRTP units and written descriptions of the activities of an additional 38 units were logged. Of these 242 units, the activities of 183 (76%) were modulated during smooth-pursuit eye movements and a separate subpopulation of 27 (11%) exhibited saccadic eye-move-
ment-related responses. Of the remainder, the activities of 16 (5%) were related to eye position, 2 appeared to be related to
blinks, 9 to fixation or task performance, and 5 to some kind of
non-oculomotor “motor” responses. The exact nature of these
“motor” responses was unclear but appeared to be related to
mouth movements during sucking on the reward delivery tube
or to limb movements partially viewed with an infrared video
camera and displayed on a TV monitor. Enough data were
collected for 157 of the 183 NRTP pursuit-related cells to
permit some level of quantitative analysis. In this paper, atten-
tion was focused on these 157 cells responsive during smooth-
pursuit eye movements and on 16 cells encoding eye position.

The recording sites were reconstructed as shown in Fig. 1 for
one animal. Each schematized section indicates the location of
the recording sites within 0.5 mm anterior and posterior to the
stereotaxic level indicated in the drawing. Most of the record-
ing sites were in the rostral regions of NRTP (rNRTP) from
anterior 8.5–11.5. Some sites appeared to be in rostral dorso-
medial pontine nuclei where the border between pontine gray
and NRTP is ill-defined (section A 11.0).

In the four macaques, pursuit-related activity was observed
over approximately 3 mm somewhere between anterior 8.0 and
12.0, depending on the individual macaque. We are aware that
these coordinates are significantly anterior to those indicated in
the atlases for M. fascicularis and M. nemestrina (Shantha et
al. 1968; Winters et al. 1969) where NRTP is visible from
anterior 2.0 to 6.5 or anterior 5.0 to 7.0, respectively. Weight
differences alone could not explain the differences. The coor-

FIG. 1. Histological reconstruction of recording sites in 1 animal. The 2 marks on the same microelectrode track in the
photograph indicate micro-lesions separated by 5 mm. Recording sites within ±0.5 mm of the illustrated sections were plotted. The
histological section in the photograph corresponds to stereotaxic anterior 10 and is represented by the A10.0 drawing (left). Py,
Pyramidal tract; DM, dorsomedial pontine gray; NRTP, nucleus reticularis tegmenti pontis; OMN, oculomotor nucleus.
dinates for rNRTP in the four macaques were relatively consistent and were based on stereotaxic settings for the recording chamber, stereotaxic locations of recording tracks, and histological verification of marking lesion locations. This consistency was observed even though two subspecies of macaques were used. In earlier papers, we matched the appearance of our histology to the sections in the atlases, a procedure that resulted in more caudal stereotaxic figure labels (Suzuki et al. 1999; Yamada et al. 1996).

Three categories were identified for classification of the rNRTP activities of interest. Of the 157 pursuit cells, 78% (122/157) appeared to encode smooth-pursuit eye velocity and 22% (35/157) were responsive to pursuit eye acceleration. The third category was the eye-position cells of which there were 16 as mentioned in the preceding text. Division into presumed velocity and acceleration responses was based on phase shifts re: peak pursuit eye velocity determined by Fourier analysis. Velocity or acceleration responses were taken as those with peak firing rates that were within ±45° of peak smooth-pursuit eye velocity or acceleration, respectively. For putative acceleration responses, sensitivity to static eye position was tested by requiring the animal to fixate stationary targets at positions eccentric from the center of the screen. None of the acceleration units exhibited eye-position-related modulations in firing rate.

**Eye-velocity pursuit cells**

During smooth-pursuit eye movements, the activities of some rNRTP cells appeared to encode eye velocity as shown in Fig. 2. The responses were evident on a cycle-to-cycle basis with the majority of the activity occurring for pursuit in a preferred direction. For the unit response shown in Fig. 2A, an increased firing rate was temporally correlated with peak pursuit eye velocity in the left-downward direction indicated by the vertical dotted lines in each cycle. Figure 2B presents the average horizontal and vertical eye behaviors for nine cycles of smooth pursuit while the associated per-cycle responses are shown in the raster of Fig. 2C. Again, the vertical dotted line running through Fig. 2B–D denotes average peak eye velocity in the preferred direction of the response.

Results obtained from Fourier analysis (dotted curve in Fig. 2D) indicated that the peak response (amplitude of the fundamental plus the dc firing rate) had a firing rate of 153 spikes/s

![Fig. 2](http://jn.physiology.org/)

**FIG. 2.** Smooth-pursuit eye-velocity responses of a cell in rostral NRTP (rNRTP). A: several cycles of smooth-pursuit eye movements and the associated neuronal responses. Each tick-mark indicates the occurrence of an action potential. Dotted line, sinusoidal target motion at an oblique, 45° angle at 0.4 Hz ±10°. Thin line, horizontal eye position. Thick line, vertical eye position. Vertical dotted lines, indicate occurrences of peak left-down pursuit eye-velocity. B: average horizontal eye (HE, thin line), vertical eye (VE, thick line), and target positions (Tar, dotted line) for nine cycles of pursuit. C: raster of per-cycle neuronal responses indicated by tick-marks. D: histogram indicating average response over 9 cycles. The dotted line indicates the sinusoidal fit to the histogram determined by Fourier analysis. Time scale (A) applies to B–D. The convention in this and all subsequent figures is positive position values indicate right or up positions.
and led peak pursuit eye velocity by 8.2°. From the peak response, we subtracted the average “spontaneous” firing rate of 11 spikes/s, determined during inter-trial intervals, which yielded an adjusted peak response of 142 spikes/s. Average peak eye velocity was about 24°/s, slightly less than the peak target velocity of 25°/s. The velocity-response gain was taken as the Fourier-based, adjusted peak firing rate divided by peak eye velocity, which for this unit was 5.9 spikes/s per °/s. The harmonic distortion of this response was 24.8%.

The relationship to pursuit eye-velocity was studied in 20 units for which responses to three or more different velocities could be tested. Over at least part of the tested velocity range, firing rate increased with increases in peak pursuit eye-velocity as shown in Fig. 3A. The firing rate of some of the units appeared to saturate or decline for higher speeds. In Fig. 3B are presented the results of averaging the firing rate over the tested velocity range (average FR) and the average normalized response (normalized average). The latter was obtained by assigning a value of one to the peak response for each unit, normalizing the remaining firing rate values, and then averaging the normalized results for all 20 units. Excluded from the averaging were the results for peak eye velocities above 70°/s because the number of data points was less than half of the number of cells represented in the figure. From both the average firing rate and the normalized average response, it was apparent that rNRTP activity increased with increases in the velocity of smooth-pursuit eye velocity, over the range from 12 to 60°/s. Above 60°/s, it was uncertain if the population response saturated, declined, or continued increasing.

The sensitivities of rNRTP cells to pursuit eye velocity was taken as the slopes of the linear regression lines fitted through the curves plotted in Fig. 3A. The sensitivity to pursuit eye velocity calculated in this manner was found to range from 0.29 to 1.97 spikes/s per °/s (r = 0.89–0.99). The slope of the average FR curve in Fig. 3B indicated an average sensitivity to pursuit eye velocity of 0.81 spikes/s per °/s (r = 0.99).

The velocity-response gain of rNRTP activity to peak pursuit eye velocity was determined from 60 units studied during maintained smooth-pursuit eye movements with peak eye velocities near 25°/s. For each unit, cumulative histograms were constructed from at least 5 and typically 10 or more cycles of pursuit, and the peak response was determined from Fourier analysis. The velocity-response gain ranged from 0.6 to 6.2 spikes/s per °/s and averaged 2.8 spikes/s per °/s (Fig. 4). The SD was 1.4 spikes/s per °/s.

**Eye-acceleration pursuit cells**

An example of a smooth-pursuit eye-acceleration unit is shown in Fig. 5. Peak activity in this cell was observed near the time of the ipsi-to-contraversive (rightward-to-leftward) turn-about point (see tick-marks, Fig. 5A). The acceleration response was observed for each cycle as shown in Fig. 5A and the per-cycle rasters in Fig. 5C.

**FIG. 3.** rNRTP responses as a function of smooth-pursuit eye velocity. A: the responses of 20 cells recorded over a range of pursuit eye-velocities. B: averaged firing rates and normalized responses. For the 20 units, the firing rates were averaged at each velocity for the lower curve (error bars, SDs). Top: fractions of the maximal firing rate response which was given a value of 1. The resultant normalized responses were averaged for each velocity yielding a representation of the rNRTP pursuit eye-velocity response.

**FIG. 4.** Velocity-response gains of rNRTP smooth-pursuit eye-movement responses. The response gain was calculated as the ratio of peak response firing rate to peak eye velocity at a specific velocity. The responses of 60 units with peak smooth-pursuit eye velocities at/near 25°/s were used in determining the plotted response gains.
The Fourier determined peak firing rate was 96.2 spikes/s (Fig. 5D) and peak smooth-pursuit eye acceleration was about 60°/s per s². The spontaneous firing rate was 21 spikes/s. Thus the “acceleration response gain” (Fourier-based peak response minus the spontaneous firing rate divided by peak eye acceleration) of this unit to pursuit eye acceleration was 1.25 spikes/s per °/s². The peak response lagged peak eye acceleration by 9.6°. The dotted curve in Fig. 5D was the fit, determined by Fourier analysis, to the data in the histogram. The harmonic distortion was 25.6%.

The isolation of 12 rNRTP cells was maintained long enough to study the smooth-pursuit eye-acceleration responses at three or more values of peak eye acceleration. The results are presented in Fig. 6A. rNRTP firing rate, in general, increased for increases in peak pursuit eye acceleration between 16 and 250°/s². The firing rate of some of the units appeared to saturate or decline for higher peak accelerations. The sensitivities to pursuit eye acceleration, taken as the slopes of these curves, ranged from 0.02 to 0.93 spikes/s per °/s² (r = 0.93–0.99) and averaged 0.20 spikes/s per °/s².

The acceleration response gains were determined for 20 rNRTP units that had peak pursuit eye accelerations near 63°/s². The results are shown in Fig. 6B. For this subpopulation of rNRTP cells, the smooth-pursuit eye-acceleration response gains averaged 0.78 ± 0.33 (SD) spikes/s per °/s². Eye-acceleration response gains ranged from 0.22 to 1.45 spikes/s per °/s².

Phase shift and harmonic distortion

The phase shift re: peak eye velocity was determined for all the rNRTP cells that were recorded when peak pursuit eye velocity was around 25°/s. The distribution of the phase shifts for 83 cells is shown in Fig. 7. The mean phase shift re: peak eye velocity was a lead of 1.5° ± 36.9°. This distribution included 27 presumed pursuit eye-acceleration cells that had phase shifts, re: peak eye velocity, of more than ±45°. The distribution indicates that there is a continuum in phase shifts from those in phase with peak pursuit eye velocity (0 phase shift) to those in phase with peak pursuit eye acceleration (±90° phase shift re: eye velocity). The harmonic distortion of the responses averaged 38.2 ± 15.8% and ranged from 11.0 to 99.8%. Unit responses with harmonic distortions of less than 50% comprised 80% of the results.
Direction selectivity

Rostral NRTP responses were observed for all directions of smooth-pursuit eye movements. The directional responses of five pursuit eye-velocity units are presented in Fig. 8. Response amplitudes were fairly high even for directions relatively distant from that which yielded the maximal response amplitude. For 18 rNRTP cells whose smooth-pursuit eye-velocity responses could be studied in eight or more directions, the half-height width averaged 170°. The half-height width was the width, in degrees, of the directional “tuning” curve at 50% of the maximal firing rate. The half-height widths ranged from 121 to 221° giving quantitative confirmation of the impression, derived from Fig. 8, of rather broad direction selectivity for the rNRTP pursuit responses.

The approximate preferred directions for 122 rNRTP smooth-pursuit eye-velocity cells were determined and the results presented in Fig. 9. Although the directional preferences could be quantified with a resolution of 22.5–30° for only 18 units, the “best” response direction could be determined to within ±45° for the remaining 104 units. During a recording session, whenever a unit was isolated, a quick determination of the “best” response direction was made by trying horizontal, vertical, and two diagonal (45° left-up and right-up) directions, i.e., eight directions. All velocity data were then collected for only the best direction among those tested. If isolation was still maintained, then additional data were acquired for other directions of smooth-pursuit eye movements. Both ipsiversive (0°) and contraversive (180°), as well as vertical pursuit directions were well represented within our sample of rNRTP eye-velocity cells. 56% (23/41) of the eye-velocity cells with horizontal preferences were optimally responsive to contraversive smooth-pursuit eye movements and 44% (18/41) preferred ipsiversive pursuit. Among cells with vertical pursuit preferences, 61% (19/31) preferred upward pursuit and 39% (12/31) preferred downward pursuit.

For pursuit eye-acceleration cells, the distribution of preferred turnabout directions was also nonspecific for a specific direction. Four eye-acceleration units respond best for contraversive to ipsiversive turnabouts, seven units for diagonal, contraversive-down to ipsiversive-up, four units for down-up, two units for ipsiversive-down to contraversive-up, five units for ipsiversive to contraversive, five units for ipsiversive-up to contraversive-down, four units for up to down, and four units for contraversive-up to ipsiversive-down. Thus all turnabout directions tested had representative cells with that turnabout preference.

Eye-position cells

The responses of 16 rNRTP cells were investigated for the relationship of their activities to static eye position. While modulations in firing rate were observed during smooth-pursuit eye movements, peak firing rate for eye position cells did not increase with increases in peak eye acceleration. These obser-
observations, together with the lack of response of eye-acceleration cells to static eye position, indicated that the population of eye-position-related rNRTP cells did not overlap the populations of pursuit eye-acceleration nor eye-velocity cells. For most of the cells observed (11/16), the eye-position response extended across the center by at least 10° (Figs. 10 and 11).

The eye-position responses appeared to be approximately linear at least over a significant portion of the tested eye-position range.

Two cells were initially thought to encode eye position. However, the sensitivity plot for one of these units was flat as shown in Fig. 10A, ○ (slope = −0.25 spikes/s per deg, r = 0.70). This unit became active during task performance regardless of the position of the eyes. In another unit, the threshold for a possible eye-position response was eccentric (Fig. 10B, ○). This unit showed a dramatic response during fixation of a target at ipsilateral 25°. However, over most of the eye-position range tested, this unit was only weakly active and did not encode eye position. Because eccentric eye positions at more than 25° were not tested, it was uncertain whether this unit would have exhibited an increase in firing rate for eye positions more eccentric than ipsilateral 25°. For clarity, the eye-position responses were illustrated separately for cells with increasing firing rates for contralateral eye positions (Fig. 10A) and for ipsilateral eye positions (Fig. 10B). Two rNRTP cells exhibited eye-position sensitivities for up eye positions (···, Fig. 10B).

The responses to varied locations in two dimensions (2D) was tested for seven cells. For five of these cells, the encoding of eye position was consistent and formed a plane when firing rate was added as a third axis to 2D plots of eye position (Fig. 11, A and B, for 2 examples). Because the graphs were planar, a cross-section through the plane yielded the eye-position sensitivity curves presented in Fig. 11C. The graphs for two of the seven cells were not planar and did not appear to encode eye position.

SENSITIVITY TO EYE POSITION. The relationship between rNRTP firing rate and eye position was approximately linear over much of the tested eye-position range and appeared to saturate.
at lower firing rates (Figs. 10A and 11C). The sensitivity of rNRTP cells to eye position was determined from linear regression lines fitted to the data presented in Figs. 10 and 11C. Excluded from the calculation were units with only two usable data points (Fig. 10B, ● and ○) and data points within the saturation zones (Figs. 10A and 11C: ▲, lowest 2 values; Fig. 11C: ○, lowest value). The sensitivity to eye position averaged 2.1 spikes/s per deg (mean r = 0.99), determined by averaging the slopes of the linear regression lines. Eye-position sensitivity ranged from 0.7 to 3.5 spikes/s per deg.

Eye-position effects

The effects of initial eye position on the smooth-pursuit related responses were determined by centering the target motion at positions eccentric to the center, e.g., at left or right 20° in addition to screen center (Fig. 12, top). Thus for 0.6-Hz ±10° smooth-pursuit eye movements centered at left 20°, the target excursion was between left 10° and left 30°. Under these conditions, the smooth-pursuit behavior was approximately the same but with an eccentric position offset. As exemplified by the unit responses shown in Fig. 12, the pursuit responses of some rNRTP cells were affected by the eye-position offsets. The intensity of the response, indicated by the number and density of the tick marks, was clearly greater for a right (ipsilateral) 20° offset than for a left (contralateral) 20° offset for the smooth-pursuit eye movements. The effect on response amplitude of any idiosyncratic differences in pursuit gain, i.e., different peak eye velocities for each centered position, was

FIG. 10. Eye-position responses of rNRTP cells. ●, ▲, ■, cells that appeared to encode static eye position over a range of eye positions. ○, 2 cells that either had a weak eye-position response (A) or had a limited range over which an eye-position sensitivity appeared to exit (B). · · ·, 2 cells with vertical eye-position sensitivities. Each point denotes the firing rate averaged over 250 ms or more of fixed eye position. A: cells with higher activity for contralateral eye positions. B: cells with higher activity for ipsilateral or up eye positions.

FIG. 11. Eye-position responses over a range of horizontal-plus-vertical eye positions. A and B: contour plots of eye-position-related rNRTP responses over a range of 2-dimensional eye positions. The relation to eye position was approximately planar. C: results obtained from a cross-section of eye-position response planes for 5 cells. ●, ▲, ■, responses for horizontal eye positions. ○, ●, ▲, ■, results for the unit shown in A. ○, ▲, ■, results for the unit shown in B.
considered but could not account for the differences in eye-
position-dependent pursuit response amplitude. It should be
emphasized that the units that exhibited an effect of eye posi-
tion on velocity-response amplitudes did not exhibit a static
eye-position signal per se.

Unit isolation was maintained long enough for 29 cells to
test for an eye-position effect. Of these, the pursuit responses
of 23 units (79%) appeared to be affected by differences in the
center position of the smooth-pursuit eye movements. The
results for these 23 units are shown in Fig. 13. An effect of eye
position was observed over at least three positions for the unit
results illustrated in Fig. 13A. In Fig. 13B are shown curves for
cells that showed a clear eye effect for only two positions with
an ambiguous position effect in the opposite direction. For the
remaining six units tested, but whose results are not shown, the
results were either ambiguous or no differences were observed
in the response amplitudes associated with pursuit centered at
different position.

As in the example shown in Fig. 12, most of the units
represented in Fig. 13 exhibited the strongest response when
pursuit was centered in the direction opposite to the preferred
direction for the pursuit response. Thus if the preferred pursuit
response direction was contraversive or down, then the eye
effect was such that the maximal response was observed when
pursuit was centered at eccentric positions that were ipsilateral
or up-above screen center. Four exceptions to this were the
results indicated by Fig. 13 (---).

Two measures of the effect of eye position on rNRTP pursuit
responses were quantified. We determined the average sensi-
tivity of the response to eye position and also the average
change in response amplitude relative to the response with
pursuit centered at screen center. In the first case, a linear
regression line was fit through the data points for each unit in
Fig. 13A. For the curves in Fig. 13B, the regression line was
drawn through the two data points indicating the largest eye-
position effect. The slopes of the regression lines were taken as
a measure of response sensitivity to eye position. The average
sensitivity for all the units shown in Fig. 13 was 1.9 spikes/s
per deg. For the cells shown in Fig. 13A, with eye effects that
spanned the center of the screen, the average sensitivity of the
eye effect was 1.4 spikes/s per deg (mean r = 0.997). The
sensitivities ranged from 1.0 to 2.6 spikes/s per deg. Similarly,
for Fig. 13B, the sensitivity averaged 2.2 spikes/s per deg and
ranged from 1.1 to 5.1. Because only two values were used per
unit for the latter average, calculation of an average regression
coefficient was moot.

To compare response amplitudes for eccentric pursuit posi-
tions with the response obtained for pursuit at screen center,
the responses were normalized with respect to the amplitude of
the response for smooth pursuit of the target centered at screen
center. These normalized results indicated that, relative to the
response amplitude for pursuit centered at screen center, the
response for the weaker eccentricity was 73% of the center

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FIG. 12. Example of effect of eye position on pursuit eye-
velocity sensitivity. Top: illustration of the paradigm that re-
quired the monkey to elicit smooth-pursuit eye movements for
the same target movement frequency and amplitude but cen-
tered at different positions. For this example, the responses of
a rNRTP cell are shown for smooth pursuit centered at right
20°, center, and left 20°. . . , target motion of 0.6 Hz ±10°. —,
horizontal eye position. |, spike occurrences.
response, while the response for the stronger eccentricity was 127\% of the center response.

**DISCUSSION**

The observation of smooth-pursuit eye-movement-related neuronal discharges in rNRTP supports the notion that this structure is part of a cortico-ponto-cerebellar pathway involved with controlling pursuit behavior. This study has shown that, NRTP activity is not only involved in saccadic eye movements (Crandall and Keller 1985), vergence eye movements (Gamlin and Clarke 1995), and active pursuit head movements (Suzuki et al. 1996) but has responses related to eye velocity and eye acceleration during smooth-pursuit eye movements. In addition, a separate population of cells encoded static eye position. The bias toward acquiring data for a greater number of pursuit-related cells than saccade-related units was presumably due to recording from rostral NRTP. The microstimulation results of Yamada et al. (1996) but has responses related to eye velocity and eye acceleration during smooth-pursuit eye movements. In addition, a separate population of cells encoded static eye position.

The direction selectivity of rNRTP smooth-pursuit eye-movement responses was broad as shown for individual cells (Fig. 8) and as implicated by the number of degrees of pursuit directions that would yield a response that was 50\% of maximum response. Smooth-pursuit eye-velocity and -acceleration responses

Two basic response types were observed during maintained smooth-pursuit eye movements. Some rNRTP cells appeared to encode pursuit eye velocity, whereas other cells encoded pursuit eye acceleration. The fact that the distribution of phase shifts reflects peak eye velocity (Fig. 7) is a continuum indicates that this dichotomy may just be a reflection of the tendency to categorize responses. Although the phase shifts comprise a continuum, it is clear that the response of some rNRTP cells encode pursuit eye velocity, whereas other cells could encode pursuit eye acceleration.

The magnitude of some neuronal responses in rNRTP was shown to increase with increases in the velocity of smooth-pursuit eye movements up to about 60°/s. More than 60°/s, the responses may saturate (Fig. 3), although more data are needed for a definitive conclusion. This velocity sensitivity range is within the velocity range for high gain, smooth-pursuit eye movements (reviewed in Leigh and Zee 1999). Similarly, increases in smooth-pursuit eye acceleration resulted in increases in the firing rate of eye-acceleration cells over a range that extended, on average, up to about 250–300°/s² (Fig. 6).

**Direction selectivity**

The direction selectivity of rNRTP smooth-pursuit eye-movement responses was broad as shown for individual cells (Fig. 8) and as implicated by the number of degrees of pursuit directions that would yield a response that was 50\% of maxi-
mal. This latter number averaged 170°, indicating that a pursuit direction that was 85° away from the optimal direction would still yield a substantial response. The observation of cells that preferred contraversive directed pursuit as well as cells preferring ipsiversive pursuit was consistent with inputs from the frontal eye fields on both sides (Stanton et al. 1988).

The distribution of preferred pursuit directions was important because speculation about this distribution arose in a study of the effects of microstimulation in rNRTP on eye movements (Yamada et al. 1996). rNRTP microstimulation evoked slow, pursuit-like eye movements predominantly in the upward direction. It was argued that a propensity for evoking vertical eye movements would result if activation of approximately equal numbers of contraversive- and ipsiversive-selective cells resulted in mutual cancellation of horizontal effects. This rationale was supported by the observation of a substantial number of eye-velocity cells that were selective for pursuit in the contraversive direction and in the ipsiversive direction (Fig. 9). However, the explanation for the preponderance of upward evoked pursuit-like eye movements (Yamada et al. 1996) required a greater number of upward-selective pursuit cells than downward. While we did observe 58% (19 vs. 12) more cells with upward preferred directions than downward (Fig. 9), the difference was only indicative and not definitive. A larger sample is necessary for a definitive conclusion regarding the relative numbers of cells with upward versus downward preferred pursuit directions.

Eye-position effects

Of the rNRTP cells tested for the effects of eye position on the pursuit response, 79% (23/29) exhibited a clear effect of eye position on the eye-velocity response (Fig. 12). On average, the response when the pursuit trajectory was centered to one side of center was 73% of the response amplitude with smooth pursuit centered at screen center. When pursuit was centered on the other side of screen center, the amplitude of the response was 127% that of screen center. It is important to note that these cells did not exhibit any sensitivity to stationary eye position.

The results obtained in the current study are consistent with those obtained with microstimulation of rNRTP. Yamada et al. (1996) found that the velocity of pursuit-like slow eye movements evoked with rNRTP microstimulation was dependent on the initial eye position just before microstimulation was delivered. The rationale for an eye-position dependence remains to be determined. On the speculative side, perhaps such a dependence helps localize the smooth-pursuit eye-velocity vector in 3D space.

Cerebellar gaze-velocity Purkinje cells

NRTP is known to project to the floccular region and to vermis-VI, VII (Brodal 1980b, 1982). These anatomic observations, together with the results of the current study, strongly suggest that rNRTP is a source of the smooth-pursuit eye-velocity signal that is known to exist in these two cerebellar structures (Lisberger and Fuchs 1978; Miles and Fuller 1975; Suzuki and Keller 1988a,b). The current results also complement the observation of pursuit head-velocity cells that have been recorded in rNRTP (Suzuki et al. 1996). Thus rNRTP is a major source of important pursuit-related signals recorded in the floccular region and vermis-VI, VII.

Conclusion

The results complement observations of rNRTP neuronal responses during active smooth-pursuit head movements, microstimulation evoked pursuit-like eye movements, deficits in smooth pursuit resulting from ibotenic acid induced lesions, and the observed pursuit-like gaze movements evoked with microstimulation in head-unrestrained macaques (Suzuki et al. 1996, 1999; Yamada et al. 1996). Arguments have been strengthened for a FEF/SEF-rNRTP-cerebellum pathway that regulates pursuit behavior and that parallels an MT/MST-DLVPN-cerebellum route. The emerging view of NRTP is that this structure is involved in global motor control involving the coordination of eye, head, and perhaps hand/limb movements.

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REFERENCES


