Activity of Smooth Pursuit-Related Neurons in the Monkey Periarcuate Cortex During Pursuit and Passive Whole-Body Rotation

KIKURO FUKUSHIMA, TOSHIKAZU SATO, JUNKO FUKUSHIMA, YASUHIRO SHINMEI, AND CHRIS R. S. KANEKO

Department of Physiology, Hokkaido University School of Medicine, Sapporo 060-8638, Japan; and Department of Physiology and Biophysics and Regional Primate Research Center, University of Washington, Seattle, Washington 98195

INTRODUCTION

Accurate visual information about a moving object can be obtained using smooth-pursuit eye movements. During movement of the head and/or whole body, the smooth-pursuit system does not work independently but interacts with the vestibular system to maintain the precision of eye movements in space (i.e., gaze) (Robinson 1981). This interaction requires calculation of gaze to match the eye-velocity-in-space to the actual target velocity. Target-velocity-in-space can be computed by adding retinal-image-velocity, head (i.e., vestibular) velocity, and eye velocity. The latter two signals are used to calculate gaze-velocity. To drive ocular motoneurons during smooth gaze movement, two stages of further signal conversion are necessary: omnidirectional gaze-velocity signals must be sorted into roughly horizontal and vertical components and such gaze-velocity components must be converted into oculomotor signals.

The importance of gaze-velocity signals for generating smooth tracking of a moving target has been suggested by studies of the cerebellar floccular lobe. It contains many horizontal gaze-velocity Purkinje cells (Lisberger and Fuchs 1978; Miles and Fuller 1975; Miles et al. 1980, Stone and Lisberger 1990), and lesions severely impair smooth pursuit (Zee et al. 1981). Smooth tracking of a moving object during whole-body rotation also is impaired severely (Zee et al. 1981). Because preferred directions of gaze-velocity signals in the floccular lobe are either horizontal or vertical (Fukushima et al. 1999a; Krauzlis and Lisberger 1996; Miles et al. 1980, Shidara and Kawano 1993; Stone and Lisberger 1990), the first sorting largely already has taken place by the floccular lobe. This suggests that the conversion of retinotopic (i.e., omnidirectional) visual into gaze-velocity signals may be generated upstream to the floccular lobe (Fukushima et al. 1999a).

Retinal image- and gaze-velocity signals are found in the posterior parietal cortex, particularly in the medial superior temporal (MST) area (Kawano et al. 1984; Komatsu and Wurtz 1988; Newsome et al. 1988; Sakata et al. 1983; Their and Erickson 1992; see Anderson 1997 for review). Gaze movement might be driven by the omnidirectional signals represented in the MST and the dorsolateral pontine nucleus (e.g., Kawano et al. 1992), which receives direct projections from the MST and projects directly to the floccular lobe (see Keller and Heinen 1991 for review). However, the origin of eye-velocity signals in the MST is still unknown (e.g., Their and Erickson 1992).

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obarbital sodium (Nembutal, 25 mg/kg ip) under aseptic conditions.

**METHODS**

**General procedures**

Two Japanese monkeys (*Macaca fuscata*, 5.0 and 6.5 kg) were
used. All experiments were performed in strict compliance with the
Guide for the Care and Use of Laboratory Animals (DHEW Publica-
tion NIH85-23 1985). Specific protocols were approved by the Ani-
mal Care and Use Committee of Hokkaido University School of
Medicine (9290). For surgery, each monkey was sedated with ket-
amine hydrochloride (5 mg/kg im), and then anesthetized with pen-
tobarbital sodium (Nembutal, 25 mg/kg ip) under aseptic conditions.
Atropine was administered subcutaneously (0.1 mg/kg). Electrocar-
diogram and expired CO2 were monitored continuously during the
surgery, and additional anesthesia (0.5–1.0% halothane mixed with
50% nitrous oxide and 50% oxygen) was administered as necessary.
Analgesics and antibiotics were administered postoperatively to reduce
pain and prevent infection. Two head-holders were installed over the
skull, and a scleral search coil was implanted on the right eye to record
vertical and horizontal components of eye movement (Fuchs and
Lynch 1996a). Despite these detailed studies, important ques-
tions still remain. In particular, it is unknown whether pursuit
neurons in the periarcuate areas carry signals related to eye
movement in the orbit or eye movement in space. It is also
unknown whether or not they carry target velocity information
as well. Answers to these questions are essential to understand
the role of the periarcuate areas in pursuit-vestibular interac-
tions and their relationship with the MST.

In this study, by assigning the monkeys the behavioral tasks
that dissociate eye movement in the orbit from eye movement
in space, we were able to show that pursuit-related neurons in the
periarcuate areas carry not only eye-velocity signals as previously reported (Gottlieb et al. 1994; MacAvoy et al. 1991; Tanaka and Fukushima 1998), but also vestibular signals and that the activity of the majority of them is related to gaze-
velocity. Moreover, when the monkeys fixated a stationary target, half of them discharge in proportion to retinal image-
motion of the second, test target. These results suggest that
both retinal-image- and gaze-velocity signals carried by single
pursuit-related neurons in the periarcuate areas can provide
target-velocity-in-space during pursuit-vestibular interactions.
Some of these results have been presented in preliminary form

**Training procedures**

Our training procedures were described elsewhere (Fukushima et al. 1996). Monkeys’ heads were restrained firmly in the primate chair in the stereotaxic plane. The monkey chair was fixed to the turntable that had two degrees of freedom of motion (horizontal and vertical
rotation) under computer control. The interaural midpoint of the
animals’ head was brought close to the axis of vertical and horizontal
rotation. The chair was rotated sinusoidally in the vertical, horizontal,
or oblique planes. Rotation in the oblique planes was applied by
combining vertical and horizontal rotations. A tangent screen was
positioned 75 cm in front of the animals’ eyes and subtended 60 by
80° of visual angle, and the monkeys were trained to track in darkness
a laser spot (0.2° diam) back-projected onto the tangent screen for
apple juice reward. The target moved either sinusoidally or stepwise
in vertical, horizontal, or two oblique directions at 45 and 135° polar
angle. Reward circuits compared target position signals with the
monkeys’ gaze position signals. The latter signals were calculated
electronically as the sum of eye position and chair position. If the
monkeys’ gaze was within the error window of ±1° for 0.5–1 s, a
drop of apple juice was delivered automatically to the animal. Target
position signals were calibrated first before a recording session by
placing the target at known horizontal and vertical locations (0, 10, ±20°). Eye position signals then were calibrated to the target by
requiring the animal to fixate the stationary target or pursue a slowly
moving one. After the animals were trained, a recording chamber was
installed over a hole cut in the skull at Ant. 25 and Lat. 10–15 to allow
single-cell recording in the periarcuate cortical areas in both monkeys
as previously described (Tanaka and Fukushima 1998).

**Recording procedures and behavioral paradigms**

All stimuli were applied sinusoidally. For our search stimulus, the
target was moved obliquely (at 0.5 Hz, ±10°) in association with
chair rotation at the same frequency either in the yaw or pitch plane.
Once responsive single cells were encountered as judged visually and
on the audio monitor (e.g., Fig. 1 B), smooth-pursuit responses were
tested in four planes (vertical, horizontal, and two oblique planes at
45° angles) at 0.5 Hz (±10°) to determine the preferred direction for
pursuit activation without chair rotation (Fig. 1 B1). To dissociate eye
movement in the orbit from that in space (i.e., gaze), we employed three
tracking conditions (Fig. 1 A, 2–4). In the vestibuloocular reflex
(VOR) suppression task (Fig. 1 A2), the monkeys tracked a target that
moved in space with the same amplitude, direction and phase as the
chair. This condition required the monkeys to suppress the VOR so
that the eyes remained virtually motionless in the orbit and gaze
therefore moved with the chair (Fig. 1, A2 and B2). In the VOR
enhancement (×2) task (Fig. 1 A3), the target moved in space with the
same amplitude as the chair but in antiphase. This condition required
the monkeys to increase eye movement in the orbit to twice the chair
movement but with the opposite direction and thereby caused a gaze
movement equal to that produced during VOR suppression but in the
direction opposite to the chair movement (Fig. 1, A3 and B3). In the
third condition (Fig. 1 A4, VOR ×1), the target moved stationary in
space during chair rotation, which required perfect VOR and no gaze
movement (Fig. 1, A4 and B4). For many neurons, responses to a
variety of frequencies were examined (0.1–1.0 Hz, at ±10°) for each of
the tracking conditions (Fig. 1 A, 1–4).

Chair rotation was applied either horizontally (yaw) or vertically
(pitch) in the first monkey so that the three conditions with chair
rotation (Fig. 1 A, 2–4) were tested either vertically or horizontally,
whichever was closer to the preferred activation directions of indi-
vidual neurons. In the second monkey, chair rotation was applied in
the oblique planes as well as horizontally and vertically so that the
tree tasks that included chair rotation (Fig. 1 A, 2–4) also were tested
in the oblique planes. To examine vestibular responses, chair rotation
also was applied in complete darkness. The monkeys were not re-
quired to perform any particular task during this condition but were
kept alert by occasional drops of apple juice.

To examine the importance of a visual target during gaze tracking,
the target was briefly extinguished (“blanking”) during smooth pursuit
or VOR suppression (Fig. 1 A, 1 and 2). We tested blanking effects
using shorter duration blanking periods (200 or 800 ms) than our
previous study (100–200 ms) (Tanaka and Fukushima 1998). In
particular, to examine the voluntary nature of initiating smooth gaze
tracking without a target, we extinguished the visual target shortly
before it changed direction during sinusoidal movement at 0.5 Hz.
The monkeys were required to continue smooth-gaze tracking by changing direction without the target.

To examine whether periarcuate pursuit-related neurons receive retinal image information about target movement (Fig. 1A5), the stationary monkeys were rewarded for fixating a stationary laser spot (1st target, 0.2° diam) while a second laser spot (0.6° diam) moved sinusoidally along one of the four directions. For some cells in this task (Fig. 1A5), the second laser spot moved with a variety of frequencies (0.1–3.0 Hz, at ±10°, typically 0.3–1.5 Hz) and amplitudes (±1.25–±30° at 1 or 2 Hz, typically ±5–±20°) while the monkeys fixated the first spot. For assessing the affects of amplitude, a higher stimulus frequency was used because it was easier for the monkeys to fixate the stationary target without being disturbed by the second laser spot. The first target occasionally was extinguished while the second laser spot was presented continuously. This procedure was used to reward the monkeys for pursuing the second laser spot so that the second laser spot would not become behaviorally meaningless. We also tested cell responses to the second laser spot by extinguishing it briefly (200 ms) while the monkeys fixated the first spot.

Responses to saccades also were examined. The monkeys first fixated a stationary target at the center of the screen. After 1–2 s, the target jumped to a new position 5 or 10° away from the center, and the monkeys made a saccade to the visible target as described previously (Tanaka and Fukushima 1998).

Data analysis

The data were analyzed off-line as previously described (Fukushima et al. 1995, 1999a). Cell discharge was discriminated with a dual time-amplitude-window discriminator and digitized together with eye-, chair-, and target-position signals at 500 Hz using a 16-bit A/D board. All position signals were differentiated by software to

**Fig. 1.** A: behavioral paradigms. A, 1–5: idealized movement of the target and chair during each of the 5 tasks (1st column), the eye (2nd column), and gaze (3rd column). B, 1–4: representative discharge of a periarcuate pursuit-related neuron responding to the different task conditions (A, 1–4). VOR, vestibuloocular reflex.
obtain velocity. Gaze velocity was calculated as the sum of eye velocity and chair velocity. In addition, eye-position signals were differentiated by analogue circuits (DC-50 Hz, −12 dB/octave) to obtain eye velocity for the task conditions with “blanking” (e.g., Fig. 12). Saccades were marked with a cursor on eye- and gaze-velocity traces and were removed using an interactive computer program (Fukushima et al. 1995, 1999a). Those occasional bursts or pauses in cell discharge associated with saccades were marked manually and removed from the analysis. Rasters and histograms were constructed by averaging between 10 and 30 cycles. Each cycle was divided into 64 equal bins together with averaged velocity. Marked bursts or pauses in discharge did not contribute to the histograms, although they are shown in the cycle rasters.

To quantify responses, a sine function was fit to the cycle histograms of cell discharge, exclusive of the bins with zero spike rate, by means of a least-squared error algorithm. Responses that had a harmonic distortion (HD) of >50% or a signal-to-noise ratio (S/N) of <1.0 were discarded; S/N was defined as the ratio of the amplitude of the fitted fundamental frequency to the root mean square amplitude of the third through eighth harmonics and HD as the ratio of the amplitude of the second harmonic to that of the fundamental. The phase shift of the peak of the fitted function relative to upward or rightward stimulus velocity was calculated as a difference in degrees. Gain was calculated as the peak amplitude of the fundamental component fitted to the cycle histogram divided by the peak amplitude of the fitted stimulus velocity (i.e., target velocity for pursuit and chair velocity for other tasks during chair rotation, Fig. 1A). Gain ≥0.10 spikes/s per °/s was taken as significant modulation. The program also calculated mean discharge rate of each cycle histogram. For responses with oblique stimulus directions, radial stimulus velocity first was calculated as a square root of the sum of the squares of the vertical and horizontal components, and gain was calculated by dividing amplitude of modulation of cell activity by radial stimulus velocity. The phase shift of cell response with oblique preferred direction was calculated relative to the rightward component of eye, gaze, or stimulus velocity. Eye- and gaze-velocity responses were calculated similarly after deleting saccades. Velocity sensitivity of a cell’s response was the slope of the linear regression fit to the amplitude of modulation versus eye- or gaze-velocity.

Preferred direction of a cell’s response was estimated by the method of Krauzlis and Lisberger (1996) using a Gaussian function. Discharge rate of each cell during straight-ahead gaze immediately before each series began was used as the resting rate. Responses to eight polar directions along the four stimulus planes were examined. Resting discharge rates were usually similar to mean discharge rates of the corresponding cycle histograms. However, for some cells in which resting rates changed considerably during testing the eight directions, we estimated the Gaussian fit by plotting gain (re stimulus velocity). Gain values were plotted as positive for the increasing discharge and as negative for the direction to which discharge rate decreased.

To analyze retinal image-motion response (Fig. 1A5), all traces were aligned with the second stimulus cycles. Traces that contained saccades or slow eye movement were removed because they were indicative of the monkeys’ failure to fixate the stationary target, and only those traces with eye position changes of <1° during each cycle were analyzed (see Fig. 14). Paired or unpaired Student’s t-tests were used for statistical analysis.

**Histological procedures**

Near the conclusion of the recording period in each monkey, the sites of pursuit-related cell activity were marked by iron deposits produced by passing positive current (10–15 µA for 60–100 s; 800–1200 µ Coulombs) or by electrolytic lesions produced by passing negative current through the microelectrode (20 µA for 30 s). After recording was completed, each monkey was anesthetized deeply by Nembutal (50 mg/kg ip). After histological fixation, coronal sections were made at 100 µm thickness on a freezing microtome. The sections then were stained for cell bodies and fibers, and the locations of recording sites were verified microscopically.

### RESULTS

We recorded a total of 110 neurons in the periarcuate areas of two monkeys that responded during ocular tracking of a sinusoidally moving target spot and whole-body rotation. Of these, 103 neurons responded to smooth pursuit (e.g., Fig. 1B1), and the remaining 7 did not. Two of the seven responded during VOR suppression but not during other conditions; responses of the other five during chair rotation (Fig. 1A, 2–4) were similar regardless of the behavioral conditions, suggesting primarily vestibular origin of their responses. Of 103 pursuit-responding neurons, 100 were recorded long enough to allow analysis. Preferred activation directions (see METHODS) were determined for 96, but were indeterminate in the remaining 4 neurons.

Of the 100 pursuit-related neurons, 92 responded during VOR suppression (e.g., Fig. 1, A2 and B2, see METHODS). For the remaining eight, the activity of six cells was modulated during VOR suppression but with HD > 1.0 (typically −2), indicating biphasic responses. Only two of the eight showed no modulation in discharge rate during VOR suppression. Of the 92, preferred activation directions for 59 were determined from their response during VOR suppression in two (yaw, pitch) or four rotation planes (yaw and pitch plus 2 oblique directions at 45° angles, see METHODS). For the remaining neurons, their responses were recorded in the plane close to the preferred activation directions for smooth pursuit as judged visually and by the audio monitor.

Table 1 summarizes overall mean (±SD) eye gains during different task conditions (Fig. 1A, 1–4) and chair rotation in complete darkness.

**Comparison of preferred activation directions of periarcuate pursuit-related neurons during smooth-pursuit and VOR suppression tasks**

Gaze movement can be performed either by eye movement alone without head movement (Fig. 1, A1 and B1) or during whole-body movement without appreciable eye movement by
suppressing the VOR (Fig. 1, A2 and B2). To examine how periarcuate pursuit-related neurons respond during gaze movement, we first compared preferred activation directions of individual cells during these two tasks. The majority of them showed similar preferred directions during these tasks. A representative cell is shown in Fig. 2 during eye or gaze movement to different directions (Fig. 2, A, I–4, and B, I–4). Its preferred direction during smooth pursuit was downward with the peak discharge near peak eye velocity (Fig. 2A1). The preferred direction during VOR suppression was also downward with the peak discharge near peak gaze velocity (Fig. 2B1). Figure 3 shows examples of directional tuning of three representative cells (A–C) with leftward (Fig. 3, A, I vs. 2, and B, I vs. 2) and downward (Fig. 3C, I vs. 2) preferred directions (cf. Krauzlis and Lisberger 1996). For cells that changed resting rates during these tasks, we plotted their responses as gains (re stimulus velocity) and determined their preferred directions (Fig. 3C, I, and 2, see METHODS).

Figure 4 summarizes preferred directions of individual cells during smooth pursuit (Fig. 4A) and VOR suppression (Fig. 4B) in a polar format with respect to the recording side. Preferred directions for individual cells were distributed evenly for all directions. Figure 4C compares preferred directions for individual neurons. In 23 of the 59 neurons (Fig. 4C, ○), preferred directions during VOR suppression were determined from their response in two (yaw, pitch) rotation planes, thus from four directions. In the remaining 36 (Fig. 4C, ●), preferred directions were determined from their response in four rotation planes (8 directions; see METHODS). The points are distributed around the unity slope line confirming that the preferred directions are similar in the two tasks. Only six neurons showed oppositely directed preferred directions (Fig. 4C, *).

**Classification of periarcuate pursuit-related neurons during pursuit-vestibular interactions: gaze-velocity neurons and eye/head-velocity neurons**

The similar preferred activation directions (Fig. 4C) suggest that the activity of most periarcuate pursuit-related neurons may be related to gaze. To test this possibility, we examined responses of each cell during the three tasks that dissociate eye movement in the orbit from eye movement in space (Fig. 1A, 2–4). We classified pursuit-related cells as “gaze-velocity” if they met the following criteria that characterized the horizontal gaze-velocity Purkinje cells of Lisberger and Fuchs (1978; also Fukushima et al. 1999a): 1) modulation occurred for movements of the eye (smooth pursuit) and the head (VOR suppression) in the same direction, 2) modulation during one of these two tasks was less than twice that during the other, and 3) modulation during the VOR × 1 was less than that during VOR suppression. In addition, we examined responses during VOR enhancement (×2) in which the target moved with equal amplitude as, but in the opposite direction to, the chair. Gaze-velocity neurons responded maximally for opposite directions (i.e., phase reversal) during VOR ×2 and suppression (Fig. 1A, 2 vs. 3). Based on these criteria, 66 of the 100 (66%) were classified as gaze-velocity neurons.

Figure 5A shows activity of a representative gaze-velocity neuron the preferred direction of which during smooth pursuit was upward and in phase with stimulus velocity (Fig. 5A1). During VOR suppression, it also responded well during upward pitch with phase shift of only 23° (re stimulus velocity) compared with its response during pursuit (Fig. 5A, I vs. 2). During VOR enhancement (×2, Fig. 5A3), the response reversed its phase compared with that during VOR suppression (Fig. 5A2). During the VOR × 1 (target stationary in space) condition, in which gaze was nearly stable (Fig. 5A4, gaze vel), the modulation was minimal. Thus the activity of this cell during these conditions defines an upward gaze-velocity neuron.

As described in the preceding text, the activity of all but 2 of the remaining 34 cells was modulated during VOR suppression, although 6 of the 34 showed biphasic modulation so that their responses were not well-fit by a sinusoid. The response during VOR suppression suggests that the great majority (32/34) of non-gaze-velocity neurons, like the gaze-velocity neurons, have vestibular sensitivity but their magnitudes and/or preferred directions are not consistent with the gaze-velocity criteria, so we called these cells eye/head-velocity neurons (cf. Scudder and Fuchs 1992) as in our previous study (Fukushima et al. 1999a). Of the 26 cells that responded during VOR suppression without biphasic modulation, 13 preferred pursuit and VOR suppression in the same direction but did not satisfy all of the criteria for gaze-velocity neurons described in the preceding text. The remaining 13 had oppositely directed eye- and head-movement sensitivity during pursuit and VOR suppression.

Figure 5B shows the activity of a representative eye/head-velocity neuron the preferred direction of which during pursuit was leftward (Fig. 5B1). Although it increased activity during leftward gaze movement during VOR suppression (Fig. 5B2), a phase reversal was not observed during VOR enhancement (×2, Fig. 5B3). Furthermore it responded clearly during the VOR × 1 condition when the chair moved toward the left (and the eyes moved toward the right) side (Fig. 5B4) with magnitude comparable to that during pursuit (Fig. 5B1). Thus responses of this cell are not related to gaze movement.

Responses of the two types of neurons during these four task conditions (Fig. 1A, I–4) are summarized in polar plots in Fig. 6 where the radius is the gain and the angle is the phase shift (re stimulus velocity). Gaze-velocity neurons showed similar distributions during smooth pursuit and VOR suppression (Fig. 6A, I vs. 2). During VOR enhancement (×2), many gaze-velocity neurons showed responses in the quadrant opposite to that seen during VOR suppression (Fig. 6A, 3 vs. 2), whereas their responses were minimal during the VOR × 1 condition (Fig. 6A4). In contrast, eye/head-velocity neurons showed larger responses during the VOR × 1 condition than gaze-velocity neurons (Fig. 6, B4 vs. A4), and their responses were largest during VOR ×2 (Fig. 6B, I–4). Table 1 summarizes mean (±SD) gains for the two types of cells at 0.5 Hz (±10°). The average gains for the first three conditions for gaze-velocity neurons were similar but there was no significant modulation for VOR (×1). Mean gains for eye/head-velocity neurons indicated significant differences from gaze-velocity cells during the VOR (×1) condition (P < 0.001).

Mean discharge rates (see METHODS) during these tasks were similar for the two types of neurons. Overall mean (±SD) discharge rates during smooth pursuit and VOR suppression were 18.5 ± 11.7 and 19.2 ± 12.7 spikes/s for gaze-velocity neurons and 17.6 ± 10.0 and 21.5 ± 10.5 spikes/s for eye/ head-velocity neurons.
To examine more directly whether the activity of periarcuate gaze-velocity neurons indeed code gaze-velocity during pursuit-vestibular interactions, in Fig. 7 we plotted amplitude of modulation of 10 representative cells of this group against peak gaze-velocity obtained at different stimulus frequencies (Fig. 8) during our various tasks (Fig. 1A, 2–4).
changed the amplitudes of target movement to twice or half of the chair movement to provide a wider range of gaze velocities. According to the convention described by Lisberger and Fuchs (1978), responses were plotted as positive for phase shifts in the direction of those during VOR suppression and as negative for those with opposite phase. Discharge modulation was significantly linearly correlated with gaze-velocity; correlation coefficients ranged from 0.85 to 0.99 (Fig. 7).
FIG. 4. Summary of preferred directions of periarcuate pursuit-related neurons during smooth pursuit (A) and VOR suppression (B) and comparison of preferred directions for individual neurons (C). D and E: comparison of preferred direction for gaze-velocity neurons (D) and eye/head-velocity neurons (E). *, cells that showed oppositely directed preferred directions. For further explanation, see text.
FIG. 5. Discharge patterns of representative gaze-velocity neuron (A) and eye/head-velocity neuron (B) recorded in the left periarcurate area during different behavioral conditions (1–4) and chair rotation in complete darkness (5). Traces as in Fig. 2. Stimulus directions for B, 1 and 2, are presented oppositely to show cell responses clearly. For further explanation, see text.
FIG. 6. Polar plots of phase and gain of the response of periarcuate gaze-velocity neurons (A) and eye/head-velocity neurons (B) during different task conditions (1–4). For further explanation, see text.
Frequency response

To study frequency response during the four tasks (Fig. 1A, 1–4), each cell was examined at different stimulus frequencies at a constant amplitude. Figure 8 summarizes phase (top) and gain (middle) and amplitude of modulation (bottom) against stimulus frequency for individual cells. Since discharge did not vary with preferred directions, their data were combined. Responses of gaze-velocity (■) and eye/head-velocity neurons (□) were similar except that the former tended to show greater modulation, thus higher gains, at higher stimulus frequencies during pursuit and VOR suppression (Fig. 8, A and B) and that many of the latter responded during the VOR ×1 (Fig. 8D) as expected (see Fig. 6B). Phases of the two types of neurons were fairly constant over the wide frequency range, either near 0° or ±180°, suggesting that their responses correspond mostly to stimulus velocity (see following text). Gains of the majority of neurons were constant except at the lowest frequency of 0.1 Hz, particularly during VOR suppression. This also is shown as an increase in amplitude of modulation at higher frequencies, suggesting that velocity sensitivity of the majority of cells is constant (Fig. 8).

Comparison of response properties of periarcuate gaze-velocity neurons and eye/head-velocity neurons during pursuit-vestibular interactions

PREFERRED ACTIVATION DIRECTIONS. Periarcuate gaze-velocity neurons and eye/head-velocity neurons showed many differences in their response properties. Figure 4 (D and E) compares preferred directions of smooth pursuit and VOR suppression for these two groups. For gaze-velocity neurons, the two directions were well correlated (Fig. 4D, r = 0.97) with the slope of the least-squares linear regression close to one (0.95). In contrast, six eye/head-velocity neurons had opposite preferred directions (Fig. 4E, *), and no significant correlation was observed between the two variables.

EYE MOVEMENT AND VESTIBULAR-RELATED ACTIVITY. Periarcuate gaze-velocity neurons tended to show more lead than eye/head-velocity neurons during smooth pursuit although phase shifts were distributed widely. We calculated the phase shifts of individual neurons relative to eye velocity and gaze velocity, respectively, in their preferred directions. Figure 9 (A, 1–2, and B, 1–2) summarizes their responses during pursuit (A1 and B1) and VOR suppression (A2 and B2) at 0.5 Hz. The mean phase shifts during pursuit (re eye-velocity) were 14 ± 42° (mean ± SD) lead for gaze-velocity neurons (Fig. 9A1) and 15 ± 49° lag for eye/head-velocity neurons (Fig. 9B1). The difference between the two groups was significant (P < 0.05). During VOR suppression, both types of cells showed similar distribution with mean phase leads of 6 ± 43° and 17 ± 38° (re gaze-velocity), respectively (Fig. 9, A2 and B2, P > 0.05).

Gains (re stimulus velocity) during suppression and pursuit are better correlated for gaze-velocity than eye/head-velocity neurons, while gains during the VOR (×1) and pursuit are better correlated for eye/head-than gaze-velocity neurons. For the former analysis, Fig. 9A3 plots gain during VOR suppression against their gain during pursuit. Significant correlation was observed between the two with a correlation coefficient of 0.78 for gaze-velocity neurons (Fig. 9A3), whereas similar
analysis for eye/head-velocity neurons did not reveal any significant correlation (Fig. 9B3). For the latter, we examined whether gains during pursuit are correlated with gains during the VOR (×1). As plotted in Fig. 9B4, eye/head-velocity neurons showed significant correlation between the two, whereas the correlation for gaze-velocity neurons (Fig. 9A4) was significant but had a very shallow slope (0.16).

**VELOCITY SENSITIVITY.** We also examined whether gaze- and eye/head-velocity neurons could be distinguished on the basis of their velocity sensitivity (see METHODS). Comparing the modulation of each cell during smooth pursuit against peak eye velocity at different stimulus frequencies revealed 15/16 gaze-velocity neurons and 4/7 eye/head-velocity neurons (Fig. 10A, *) that had a linear relationship between amplitudes of modulation and peak eye velocity. Mean eye-velocity sensitivity for the two groups was not significantly different (P > 0.05); the overall mean was 0.53 (±0.30 SD) spikes/s per °/s. During VOR suppression, 14/14 gaze-velocity and 3/6 eye/head-velocity neurons showed linear relationships between amplitudes of modulation and peak gaze velocity (Fig. 10B). Mean gaze-velocity sensitivity of the two groups was not significantly different (P > 0.1); the overall mean was 0.50 ± 0.44 spikes/s per °/s.

To compare velocity sensitivity during pursuit and VOR suppression further, in Fig. 10C, we plotted their values for individual cells. In addition to the velocity sensitivities calculated by linear regressions (Fig. 10C, ■, n = 10), this figure plots velocity sensitivity calculated at 0.5-Hz pursuit and VOR suppression for 66 gaze-velocity (○) and 26 eye/head-velocity neurons (●). The former neurons showed significant correlation between the two variables (r = 0.55, 0.84, P < 0.005), whereas the latter neurons showed no correlation (P > 0.1). These results indicate that for gaze-velocity (but not eye/head-velocity) neurons there is a significant correlation between eye-velocity sensitivity and gaze-velocity sensitivity.

**VESTIBULAR RESPONSES IN COMPLETE DARKNESS.** Gaze-velocity responses require vestibular input (Fig. 5, A2 and B2). To examine the nature of that input further, the animals were rotated without the target in complete darkness. A total of 43 cells (23 gaze-velocity, 20 eye/head-velocity) was examined by applying rotation in the plane close to their VOR suppression preferred direction (Fig. 4, D and E). Representative responses are shown in Fig. 5. These cells showed a range of responses from weakly but clearly (Fig. 5A5) to strongly modulated (Fig. 5B5). Figure 11 (A and B) summarizes gain and phase (re chair velocity) of the 43 cells. The majority (28/43 = ~65%) responded (Fig. 11, A and B, top), and the mean gain for the responsive cells was 0.30 ± 0.16 spikes/s per °/s (n = 28). Eye/head-velocity neurons (15/20 = 75%) tended to respond with higher gains (re chair velocity) than gaze-velocity neurons (13/23 = ~57%). The mean (±SD) gains
(including 0 values) for the two groups were 0.27 ± 0.21 and 0.15 ± 0.15 spikes/s per °/s, respectively (Table 1) with the overall mean for all cells tested of 0.18 ± 0.18 spikes/s per °/s (n = 43). The difference in gain between the two groups is significant (P < 0.02). Phases were distributed widely and almost uniformly (Fig. 11, A and B, bottom) unlike their responses during VOR suppression (Fig. 8B, top), but similar to their responses during VOR ×1 (Fig. 8D, top).

The difference in responses between the two groups of pursuit-related neurons is also shown by comparing their responses in complete darkness to responses during the VOR ×1 condition (Fig. 1A4). Figure 11 (C and D)summarizes the results. We first compared eye gain during these two conditions. Eye gain during chair rotation in complete darkness was correlated significantly with eye gain during the VOR ×1 with a slope close to one (0.91, Fig. 11C),
and these values were distributed similarly for the two groups of neurons (Fig. 11C, □ and ■). Plotting gaze gain instead of eye gain gave similar results (not shown). As shown in Fig. 11D, gains (re chair velocity) of eye/head-velocity neurons showed a significant correlation between the two stimulus conditions (□, slope 0.77 r = 0.77), reflecting eye gain. For gaze-velocity neurons, the correlation was weak but significant (Fig. 11D, ■, r = 0.43, n = 23), due to a single outlying cell (Fig. 11D, ←), suggesting that their activity does not reflect gaze gain despite the fact that eye- and gaze-velocity sensitivity of these two groups of cells were similar (Fig. 10, A and B). These results show a difference in discharge properties between eye/head-velocity neurons and gaze-velocity neurons. The former neurons seem to reflect eye gain regardless of the behavioral conditions, whereas gaze velocity related activity of the latter neurons is specific to the behavior required of the monkeys. Figure 11B (□) also includes four neurons that responded to chair rotation but had no clear correlation with eye movement.

We also observed a peculiar behavior in three (2 eye/head-velocity and 1 gaze-velocity) neurons during complete darkness. Two of them stopped firing completely when the laser spot was turned off so that the monkey did not perform any task. In contrast, one eye/head-velocity neuron increased resting discharge rates three to five times (∼20 vs. 60–100 spikes/s) in complete darkness compared with their resting rates with a target present. Such behavior was consistently and repeatedly observed for the three cells by turning off the target spot, suggesting that some periarcuate pursuit-related neurons carry signals other than eye- or gaze-related information.

**Maintenance of gaze-tracking-related activity of periarcuate pursuit-related neurons**

By briefly extinguishing the tracking target during step-ramp pursuit tracking, we have shown recently that periarcuate pursuit-related neurons maintain their discharge without a tracking target (Tanaka and Fukushima 1998). In this study, we used the same technique to examine the discharge of a total of 20 (15 gaze-velocity and 5 eye/head-velocity) neurons during smooth tracking of a visual target with or without chair rotation (see METHODS). The majority (13/20 cells during smooth pursuit, 7/9 cells during VOR suppression) continued to discharge during the 200-ms blanking period without consistent change in their activity (e.g., Fig. 12B1). In the remaining seven cells, their activity decreased after 100–150 ms after target offset (e.g., Fig. 12A, 1 vs. 2). To quantify the blanking effects for the seven cells, we compared mean discharge rates during the last 100 ms of the 200-ms blanking period with mean rates for an equivalent portion of the tracking cycle without blanking. During pursuit, discharge rates decreased on the average by 48% (range 21–73%), whereas during VOR suppression discharge rates decreased by 35%. Thus change in discharge rate during blanking tended to be less during VOR suppression than during pursuit not only in its occurrence (2/9 vs. 7/20 cells) but also in its magnitude (35 vs. 48%).

We also used an 800-ms blanking period that was applied shortly before the target changed direction and required the monkeys to continue tracking (see METHODS). In eight (5 gaze-
velocity, 3 eye/head-velocity) neurons, blanking was timed so it occurred before they normally increased their activity (e.g., Fig. 12, A3 and B2). Gaze-velocity neurons increased activity during smooth pursuit (Fig. 12A1) and VOR suppression (Fig. 12B1) and also discharged during blanking (Fig. 12, A3 and B2). Their activity without a visible target during VOR suppression (Fig. 12B2) cannot be due to vestibular input alone since chair rotation in complete darkness induced only a minimum response (Fig. 12B3). Figure 13 compares responses of the same cell during pursuit and VOR suppression with and without blanking together with the corresponding eye (A) and gaze velocity (B). Cell activity during blanking (thick lines) was associated with slower eye (A, thick lines) and gaze velocity (B, thick lines) compared with its activity without blanking (thin lines, open arrows).

To quantify the blanking effects, we compared mean discharge rates during the last 200 ms of the 800-ms blanking period with mean rates for an equivalent portion of the tracking
cycle without blanking for the eight cells. During smooth pursuit, the overall mean discharge rate decreased by 30% (range 0–52%) and the mean eye velocity decreased by 45% (range 13–72%). During VOR suppression, the overall mean discharge rate decreased by 9% (range: 21% increase to 36% decrease) and the mean gaze-velocity decreased by 14% (range 8–48%). Thus the decrease of discharge rate during blanking was associated with reduced eye- or gaze-velocity, but the reduction was much larger during smooth pursuit than VOR suppression. Phase shifts of each cell’s response relative to eye or gaze-velocity remained virtually unchanged (range 17° lead to 14° lag) compared with the control values. Because eye-velocity sensitivity and gaze-velocity sensitivity of these neurons were similar (see preceding text), the difference in their behavior during blanking during pursuit and VOR suppression cannot be explained by their discharge sensitivity to eye velocity and gaze velocity alone. Thus these results suggest that periarcuate pursuit-related neurons initiate discharge associated with voluntary smooth gaze tracking even without a visible target (see DISCUSSION).

**FIG. 12.** Maintenance of discharge in a representative gaze-velocity neuron recorded in the left periarcuate area during smooth pursuit and VOR suppression. **A:** horizontal smooth pursuit without (A1) and with blanking (A, 2 and 3). **B:** yaw VOR suppression with different blanking period (B, 2 and 3). B2: yaw rotation in complete darkness. Traces as in Fig. 2. All analogue signals were superimposed to show eye-velocity changes during blanking and onset of saccades for individual trials. Saccade velocities are clipped. For further explanation, see text.
mean phase of 10 ± 89° lead. Gaze-velocity neurons and eye/head-velocity neurons showed similar phase and gain distributions. Representative activity is shown in Fig. 14A for a gaze-velocity neuron that increased activity during leftward pursuit (Fig. 14A) and VOR suppression (not shown). During testing with the second spot, the same cell increased activity when it moved toward the left (Fig. 14A2), and its response magnitude increased with significant phase lag when the frequency of sinusoidal movement of the test spot was increased (Fig. 14A, 3 and 4). The monkey fixated the stationary target well in all these conditions (Fig. 14A, 3 and 4). Thus the modulation of cell activity during this task cannot reflect eye velocity. Rather, it codes retinal image-motion of the second laser spot.

As illustrated in Fig. 15A, preferred activation directions for retinal image-motion of the second spot (at 0.5–0.7 Hz) were similar to preferred directions of individual cells during smooth pursuit and VOR suppression (Fig. 15A, 1 vs. 2 and 3). For the population of tested neurons, Fig. 15 (B and C) shows that the preferred directions are similar (at 0.5–0.7 Hz) particularly for gaze-velocity neurons (■; \( r = 0.95, 0.94 \); slope close to 1).

Figure 16 summarizes the frequency response for retinal image-motion-related discharge of 11 cells; 9 were gaze-velocity neurons (■, Fig. 16, A–C). Phases were mostly constant 1 Hz, some showed considerable phase lag (Figs. 14A, 3 and 4, and 16A). Gains of the majority of cells were constant over the frequency range tested (Fig. 16B), which is consistent with an increase in amplitude of modulation of many neurons at higher stimulus frequencies (Fig. 16C). We calculated velocity sensitivity to the second spot for the 11 neurons from the slopes of the amplitude of modulation versus retinal image-velocity plots. The majority (8/11, all gaze-velocity neurons) showed a linear relationship between amplitudes of modulation and peak retinal image velocity (Fig. 16D). Discharge modulation of many cells increased with retinal image velocity linearly beyond 100°/s. Correlation coefficients for the linear regressions for these neurons ranged from 0.59 to 0.98 with the mean of 0.86. Velocity sensitivity ranged from 0.06 to 0.58 with the mean of 0.20 ± 0.16 spikes/s per °/s (n = 8).

Retinal image-motion-related activity (Fig. 14) does not require actual retinal image-motion. In 7 of the 21 cells that responded to retinal image-motion (5 gaze velocity and 2 eye/head velocity), we briefly (200 ms) extinguished the second spot to examine how their activity was affected by the disappearance of this spot. About half of them (3/7) decreased activity during blanking as illustrated in our representative cell (Fig. 14B) then showed a visual response to reappearance of the second spot. We compared mean activity during the last 100 ms of the blanking period with the mean rates for an equivalent portion of the cycle without blanking. The mean activity decreased by 42% (range 33–58%). However, the remaining cells (4/7) maintained their discharge without showing any consistent change in their activity during the blanking period, indicating that pericruciate pursuit-related neurons are capable of maintaining the retinal image-motion response. In 9 of the 21 responding neurons (8 gaze-velocity and 1 eye/head-velocity), we also examined the effects of target blanking (for 200 ms) during smooth pursuit (see preceding text); 6 showed no change in their activity during blanking, whereas 3 decreased activity during blanking.
Activity during saccades

Previous studies showed that periarcuate pursuit-related neurons do not respond during saccades (Gottlieb et al. 1993; MacAvoy et al. 1991; Tanaka and Fukushima 1998). We examined the response of 56 cells during visually guided saccades (35 gaze-velocity, 21 eye/head-velocity). Nearly half \( (n = 26, 46\%) \) showed some changes in their activity associated with saccades (14/35 gaze-velocity, 12/21 eye/head-velocity neurons). Gaze- and eye/head-velocity neurons showed similar responses, the most common of which \( (n = 16) \) was a weak burst with peak activity occurring at the onset of or during the saccade that sometimes was accompanied by a preceding gradual increase of discharge rate. Representative responses are shown in Fig. 17 (A and B). Many had preferred directions. For example, the cell shown in Fig. 17A responded to leftward VOR suppression (Fig. 17A) and leftward pursuit (not shown) and also had a weak burst that preceded saccades toward rightward or upward directions (Fig. 17A2) but not toward leftward or downward (Fig. 17A3). In contrast, the cell shown in Fig. 17B increased activity during VOR suppression left and up (Fig. 17B1, inset). This cell discharged a burst of activity irrespective of saccade directions (Fig. 17B2 and 3). Such weak bursts occasionally were followed or preceded by suppression of activity \( (n = 3) \). Pauses without bursts also were observed \( (n = 2) \).

FIG. 14. Retinal image-velocity response of 2 representative gaze-velocity neurons (A, 1–4, and B, 1 and 2) recorded in the left periarcuate area during the fixation-with-2nd-target task. A1: horizontal pursuit. A, 2–4: fixation-with-2nd-target task at different stimulus frequencies. B, 1 and 2, fixation-with-2nd-target task with and without extinguishing the 2nd target (blanking). Traces as in Fig. 12. Insets (A2 and B1): illustrates the test target (large dot) moving horizontally while the monkey fixated the stationary target (small dot). For further explanation, see text.
Figure 17C is an example whose response might have been induced by the visual input of presenting the target. This cell responded best to down and right smooth pursuit. During visually induced saccades, it gradually increased activity before saccades as is evident when cell activity is aligned with saccade onset (Fig. 17C2). When aligned with target onset (Fig. 17C3), the first activity showed a clear burst with a latency of ~100 ms, suggesting a visual response to the target onset. Similar visual responses were observed in a total of five cells during the visually induced saccade task (latency 100–110 ms). Eye-position-related activity following saccades also was observed in some cells (n = 6) as previously reported (Tanaka and Fukushima 1998). Although many pursuit-related neurons showed various degrees of burst activity during visually induced saccades, virtually none of them showed burst activity associated with corrective saccades during VOR suppression or smooth pursuit (e.g., Fig. 17A1, B1, and C1, also Fig. 12) when the target was continuously presented. Of eight pursuit-related neurons that showed burst activity associated with visually induced saccades, only one also showed bursts associated with quick phases of vestibular nystagmus in complete darkness.

Recording location

Figure 18 summarizes reconstructed recording locations for the two monkeys. Recordings in one monkey (U) were performed mostly in the fundus and posterior bank of the right arcuate sulcus (Fig. 18, C and D) as in previous studies (Gottlieb et al. 1993; MacAvoy et al. 1991; Tanaka and Fukushima 1998). Recordings in the other monkey (N) were performed slightly more rostrally and medially in the superior ramus of the left arcuate sulcus (Fig. 18, A and B). Thirty of 66 gaze-velocity neurons and 19 of 34 eye/head-velocity neurons were recorded in the monkey U (Fig. 18, C and D). The remaining 36 gaze-velocity and 15 eye/head-velocity neurons were recorded in the monkey N (Fig. 18, A and B). We often observed saccade-related bursts of activity in the same record-

FIG. 15. Preferred directions of periarcuate gaze-velocity neurons during smooth pursuit, VOR suppression and retinal image-motion of the 2nd test target. A: directional tuning of a representative gaze-velocity neuron for the 3 task conditions (1–3). Traces as in Fig. 3. B and C: comparison between retinal image-motion-direction and smooth pursuit direction (B), and between retinal image-motion-direction and VOR suppression direction (C) for gaze-velocity neurons (●) and eye/head-velocity neurons (□). Linear regression and correlation coefficients were calculated for all cells.
D I S C U S S I O N

The main findings from this study are the following. 1) The great majority of pursuit-related neurons in and near the FEF (>92%, n = 100) responded during VOR suppression (Figs. 5A, 6B, and 10B), and the activity of the majority (66/100) was related to gaze velocity (Figs. 6A and 7) with preferred directions of individual cells distributed almost equally for all directions (Fig. 4, A–D). 2) The majority (28/43; 65%) responded to chair rotation in complete darkness, suggesting vestibular input (Fig. 11). 3) During smooth gaze tracking regardless of chair rotation, these neurons maintained their discharge even when the tracking target was briefly extinguished (Fig. 12). And 4) more than half of them tested (21/40; 53%) responded to retinal image velocity of the second laser spot (Fig. 16D) with preferred directions of individual cells similar to those during smooth pursuit and VOR suppression (Fig. 15). Moreover, these responsive cells maintained retinal image-motion response even when the second target was briefly extinguished (Fig. 14B).

From the mean eye-velocity, head-velocity and retinal image-motion-velocity sensitivity, we can estimate their discharge (R) during slow gaze tracking as

\[ R = 0.58E + 0.53H + 0.21I + \text{resting discharge} \]

where \( E, H, \) and \( I \) are eye velocity, head velocity and retinal image velocity, respectively, and resting discharge is typically 19 spikes/s per °/s. About half (≈47%) of our pursuit-related neurons did not receive retinal image-motion response, indicating that discharge of these cells is modulated by the first two terms.

Smooth-gaze-tracking areas in and near the FEF

Smooth-pursuit-related areas near the FEF have been identified in macaques as the posterior bank and fundus of the arcuate sulcus (Gottlieb et al. 1994; MacAvoy et al. 1991; Tanaka and Fukushima 1998; cf. Tian and Lynch 1996a,b). In Cebus monkeys, smooth-pursuit-related areas also were found in the superior arcuate sulcus near its medial tip (Fig. 5 of Tian...
Gaze-velocity neurons were found in both of the periarcuate areas (Fig. 18), suggesting that pursuit-related areas may be more widespread in and near the FEF including the surrounding area 6 (Tian and Lynch 1996a,b).

Two types of periarcuate pursuit-related neurons and vestibular input

The present results indicate that periarcuate pursuit-related neurons can be separated into two types on the basis of their response properties during pursuit-vestibular interaction conditions (Figs. 1A, 2–4): gaze-velocity and eye/head-velocity neurons (Figs. 5 and 6). These two types of neurons showed similar discharge characteristics during smooth pursuit and VOR suppression (Figs. 8–10) and retinal image motion of the second target (Figs. 15 and 16), although the number of eye/head-velocity neurons examined was small in the latter two conditions. In contrast to gaze-velocity neurons that had similar preferred directions for eye and vestibular sensitivity (Fig. 4D), eye/head-velocity neurons include cells that showed oppositely directed eye and vestibular sensitivity (Fig. 4E). Moreover, vestibular responses of these two types of neurons were different during chair rotation in complete darkness (Fig. 11, A and B, Table 1). These results indicate that the main difference in their activity during pursuit-vestibular interactions (Fig. 1A, 2–4) can be attributed to their vestibular input.

Previous studies reported vestibular responses in the motor cortex (areas 4 and 6) but not in the FEF in anesthetized cats (Boisacq-Schepens and Hanus 1972; Frederickson et al. 1974; Mergner 1979) or alert monkeys (White and Brinkman 1988) after electrical stimulation of the vestibular nerve (see Fukushima 1997 for review). The present results indicate that vestibular related signals are widely distributed in the FEF and nearby area 6 not only for cells related to smooth pursuit but also for cells that are unrelated to eye movement (Figs. 11, A and B, and 18).

Discharge characteristics of periarcuate pursuit-related neurons seem similar to those found in the posterior parietal cortex, particularly the MST (Komatsu and Wurtz 1988; Newsome et al. 1988), as well as in the cerebellar vermis (Büttner et al. 1991; Kase et al. 1979; Sato and Noda 1992; Suzuki and Keller 1988). Both areas contain cells carrying gaze-velocity and retinal image-velocity signals. For example, visual tracking neurons in the MST (Kawano et al. 1984, 1994; Sakata et al. 1983; Thier and Erickson 1992) carry gaze-velocity related signals (Thier and Erickson 1992) although others do not (e.g., type C neurons of Kawano et al. 1984). The periarcuate eye/head-velocity neurons that have oppositely directed eye and vestibular sensitivity resemble type C neurons in the MST (Kawano et al. 1984). Reciprocal connections between the periarcuate pursuit-related areas and MST (Stanton et al. 1993, 1995; Tian and Lynch 1996a,b; Tusa and Ungerleider 1988).
may contribute to the similarity in the discharge characteristics of these two areas.

**Maintenance of gaze velocity-related discharge and retinal image-velocity response of periarcuate pursuit-related neurons**

This study shows that activity of periarcuate pursuit-related neurons is maintained during a brief period without a tracking target not only during pursuit as previously reported (Tanaka and Fukushima 1998) but also during VOR suppression (Fig. 12B1). Decreased discharge during blanking of the target tended to be much less during VOR suppression than during pursuit, possibly reflecting the vestibular input in part during VOR suppression. Periarcuate neurons also responded during smooth gaze-tracking direction-changes even without the tracking target (Fig. 12, A3 and B2). This task condition (Fig. 12, A3 and B2) requires processing of the preceding retinal image-velocity-information to estimate the appropriate smooth-gaze-tracking response at the time an invisible target would have changed directions. Appropriate discharge of our cells during such direction changes even without the tracking target suggests an involvement of these cells in initiation of such eye/gaze movement.

This study further shows that the retinal image-velocity response of some of our cells to the second target spot was maintained even when it was invisible (Fig. 14), suggesting that their activity is not a simple reflection of retinal image-motion response. It is possible that it may partly reflect reconstructed components of the second target motion in our task condition.

**Possible role of the periarcuate cortical areas for visually guided behavior**

To track a moving object accurately during whole-body rotation, gaze-velocity signals must be calculated to match the velocity of the eyes in space to target velocity (Robinson 1981). Target-velocity-in-space can be calculated by retinal image velocity of the target and gaze velocity. As this study shows, single pursuit-related neurons in the periarcuate areas carry both signals. FEF lesions or chemical inactivation of these areas severely impairs smooth pursuit (Keating 1991, 1993; Shi et al. 1998). After muscimol infusion into the periarcuate pursuit-related areas our monkeys were unable, in many trials, to generate smooth gaze movement when the tracking target was extinguished before changing direction in an identical tracking condition to that in Fig. 12A3 (Fukushima et al. 1999b). These results together suggest that the periarcuate cortical areas are necessary for calculation of target velocity in space and/or gaze-velocity command signals, although how this is accomplished is still unknown.

Gaze-movement- and/or retinal image-velocity-related signals are found in many areas in the brain (i.e., MST, pontine nuclei, the cerebellar vermis and the central thalamus) (e.g., Schlag and Schlag-Rey 1986; see Keller and Heinen 1991 for review) in addition to the periarcuate cortical areas. It has been suggested that MST forms an internal positive feedback circuit in the pursuit system that provides signals for the maintenance of pursuit (Newsome et al. 1988). It is possible that similar positive feedback circuits include periarcuate pursuit-related neurons for calculation of target-velocity-in-space and/or gaze-velocity command signals (Fukushima 1997; Tanaka and Fukushima 1998), thus enabling those neurons to maintain discharge during the blanking in response to the second target movement (Fig. 14) or during maintenance of gaze tracking (Fig. 12).

Although periarcuate pursuit-related neurons seem to be positioned to issue gaze-velocity commands, they remain much more central than the cerebellar floccular lobe (Fukushima et al. 1999a; Krauzlis and Lisberger 1996; Lisberger and Fuchs 1978; Miles and Fuller 1975; Miles et al. 1980, Shidara and Kawano 1993; Stone and Lisberger 1990). Preferred directions of gaze-velocity signals for the periarcuate neurons are uniformly distributed, whereas those for floccular gaze-velocity Purkinje cells are sorted into roughly horizontal and vertical components (Fukushima et al. 1999a; Krauzlis and Lisberger 1996; Miles et al. 1980, Shidara and Kawano 1993; Stone and Lisberger 1990). The majority of periarcuate pursuit-related neurons discharge before the initiation of pursuit using a step-ramp pursuit task with the median latency of −19 to −12 ms (Gottlieb et al. 1994; Tanaka and Fukushima 1998), whereas many of floccular gaze-velocity Purkinje cells are reported to discharge at or after the initiation of pursuit (Stone and Lisberger 1990; cf. Shidara and Kawano 1993).

Gaze-velocity responses of our periarcuate gaze-velocity neurons seem specific to the task conditions because most lose their gaze-velocity-related response during chair rotation in complete darkness in which the animals were not required to perform any task. This difference between periarcuate neurons and floccular or brain stem neurons (e.g., Lisberger and Fuchs 1978; Scudder and Fuchs 1992) may be due to the more direct connection of the latter to their afferents.

Nearly half of our pursuit-related neurons (46%), that include gaze-velocity and eye/head-velocity neurons, showed activity changes associated with visually induced saccades. In particular, their various degrees of burst activity (Fig. 17, A and B) resemble the well-known activity of saccade-related FEF neurons (Bruce and Goldberg 1985). Although we did not examine further the nature of saccade-related activity of our neurons, our results suggest the possibility that some pursuit-related neurons in the periarcuate areas carry saccade-related signals as well. Neurons that respond both to saccades and pursuit have been reported in the cerebellar vermis (e.g., Suzuki and Keller 1988) and fastigial nucleus (e.g., Fuchs et al. 1993). Gaze-related activity is also evident in neurons related to arm-reaching.
tasks in the premotor cortex near the posterior arcuate area
(Mushiake et al. 1997; cf. Boussaoud et al. 1993). These
results substantiate the importance of gaze-related activity
in the periaarcuate areas for visually guided behavior that
involves not only the eyes and but also the extremities.

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Present addresses: J. Fukushima, College of Medical Technology, Hokkaido
University, Sapporo 060-8012; Y. Shimine, Dept. of Ophthalmology, Hok-
kaido University School of Medicine, Sapporo 060-8638, Japan.
Address for reprint requests: K. Fukushima, Dept. of Physiology, Hokkaido
University School of Medicine, West 7, North 15, Sapporo 060-8638, Japan.

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