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Modulation of Visual Signals in Macaque MT and MST Neurons During Pursuit Eye Movement

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Chukoskie L, Movshon JA. Modulation of visual signals in macaque MT and MST neurons during pursuit eye movement. *J Neurophysiol* 102: 3225–3233, 2009. First published September 23, 2009; doi:10.1152/jn.90692.2008. Retinal image motion is produced with each eye movement, yet we usually do not perceive this self-produced "reafferent" motion, nor are motion judgments much impaired when the eyes move. To understand the neural mechanisms involved in processing reafferent motion and distinguishing it from the motion of objects in the world, we studied the visual responses of single cells in middle temporal (MT) and medial superior temporal (MST) areas during steady fixation and smooth-pursuit eye movements in awake, behaving macaques. We measured neuronal responses to random-dot patterns moving at different speeds in a stimulus window that moved with the pursuit target and the eyes. This allowed us to control retinal image motion at all eye velocities. We found the expected high proportion of cells selective for the direction of visual motion. Pursuit tracking changed both response amplitude and preferred retinal speed for some cells. The changes in preferred speed were on average weakly but systematically related to the speed of pursuit for area MST cells, as would be expected if the shifts in speed selectivity were compensating for reafferent input. In area MT, speed tuning did not change systematically during pursuit. Many cells in both areas also changed response amplitude during pursuit; the most common form of modulation was response suppression when pursuit was opposite in direction to the cell's preferred direction. These results suggest that some cells in area MST encode retinal image motion veridically during eye movements, whereas others in both MT and MST contribute to the suppression of visual responses to reafferent motion.

INTRODUCTION

Action has sensory consequences. For example, a rightward eye movement adds leftward motion to the retinal image. This self-produced motion—*reafference*—must be discounted to compute real-world motion. We usually do not perceive the reafferent motion generated during smooth-pursuit eye movements (de Graaf and Wertheim 1988; Turano and Heidenreich 1996; Wallach et al. 1985). Therefore some brain regions that combine signals related to visual motion and to smooth-pursuit eye movements must be involved in perceiving motion.

Cells in the middle temporal (MT) and medial superior temporal (MST) areas are closely linked to the perception of visual motion (Britten and van Wezel 1998; Britten et al. 1993; Celebrini and Newsome 1994; Duffy and Wurtz 1991; Graziano et al. 1994; Roy et al. 1992; Saito et al. 1986; Tanaka and Saito 1989; Tanaka et al. 1989). Extraretinal eye-position inputs have also been reported by many investigators in area MST (Erickson and Thier 1991; Komatsu and Wurtz 1988;

Nadler et al. 2008; Squatrito and Maioli 1997; Thier and Erickson 1992) and, less consistently, in area MT (Bremmer et al. 1997; Newsome et al. 1988; Squatrito and Maioli 1997). The coexistence of visual and pursuit eye-movement signals suggests that areas MT and MST might combine sensory and motor inputs to compute how objects move in the real world.

There are several ways in which visual responses could be modulated by eye-movement signals to compute real-world motion. Conceptually the simplest would be for cells' tuning to shift by a vector corresponding to the eye movement, thereby preserving neuronal selectivity in a real-world reference frame. Such a computation might be difficult to implement in neural circuitry, however, because it would require that cells switch among inputs representing many speeds and directions of retinal motion. An intermediate step could be achieved by analogy to the system of "gain fields" known to have a role in spatial-coordinate transformations in parietal cortex (Andersen et al. 1993; Salinas and Abbott 1995). In this system, neurons would change the amplitude of their response in association with eye movement, but not their stimulus selectivity. This response gain modulation could then be used by downstream neurons to infer the speed of objects in the world (Zipser and Andersen 1988). Area MST cell responses are different for retinal image motion presented during saccadic eye movements and during fixation (Erickson and Thier 1991). Some area MT and area MST cells also change their visual responses during both smooth-pursuit eye movements and saccades (Shenoy et al. 1999; Thiele et al. 2002). Recently, Inaba et al. (2007) reported changes in the speed tuning of neurons in area MST but not in area MT during smooth pursuit.

We studied the interaction of eye-velocity and stimulus-velocity signals in area MT and area MST cells by measuring responses to retinal stimuli of different speeds when the eyes were still and when they smoothly tracked a target. Some cells in both areas, but particularly in area MST, changed both response strength and speed selectivity during smooth eye movements. In area MST but not in area MT, the changes in preferred speed were on average consistent in sign but not necessarily in magnitude, with direct compensation for pursuit reafference. In addition, cells in area MST were often suppressed when retinal motion was opposite in direction to that of the pursuit movement. The results suggest that the process of compensation for reafferent motion may begin in area MT, but is more completely expressed in the responses of a subset of cells in area MST.

METHODS

We trained two rhesus macaques (*Macaca mulatta*) to perform the fixation and smooth-pursuit eye-movement tasks required for these ex-

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periments. All methods were designed in conjunction with and approved by the New York University Institutional Animal Care and Use Committee. The animals underwent a sterile head-restraint and scleral eye-coil implant surgery, modified from the methods of Wurtz and colleagues (Judge et al. 1980; Wurtz 1969). During the nearly 6 wk of osteointegration of the head-restraint implant, each animal was acclimated to his recording chair and the experimental surroundings. After this initial period, the animal was head-restrained and rewarded with juice or water for looking toward the fixation target while we monitored eye position with field coils. Fixation and pursuit training proceeded while we increased the demands of the tasks by lengthening each trial and increasing the positional accuracy required. Once these tasks were performed with minimal position error and high pursuit gain, we implanted a recording chamber over areas MT and MST.

In exploratory recordings, we observed patterns of gray matter–white matter transitions and motion-selective cell responses characteristic of this part of the superior temporal sulcus (STS). We used these response properties and anatomical features to guide us during recording. We assigned cells to area MST if they were isolated on the upper bank of the STS and to area MT if they were isolated on the lower bank of the STS—all cells we recorded on the lower bank also had the smaller receptive fields and visual receptive field locations expected of MT on the basis of standard maps. We did not attempt to distinguish between the lateral–ventral and dorsal divisions of area MST because we found no anatomical distinction either during our recordings or in post hoc data analysis in terms of preferred stimulus size or relationship of pursuit direction to stimulus direction in the cells encountered on the upper bank of the STS. At the end of the recordings we recovered anatomical data from the animals and verified that our electrode tracks were localized to the correct regions of the STS. Cells of whose areal location we were uncertain were excluded.

The sample of recorded neurons included 62 cells from MST and 61 cells from MT. Of the MST cells, 28 were recorded from monkey 1 and 34 from monkey 2. Of the 61 MT cells, 36 were recorded from monkey 1 and 25 from monkey 2.

Visual stimulation

We generated visual stimuli with a Cambridge Research Systems VSG 2/3 display controller in a Pentium host computer, at a pixel resolution of $1,280 \times 1,024$ at a frame rate of 120 Hz (noninterleaved). Images were rear-projected onto a screen by a Barco 1208s projector. The screen subtended about $60 \times 50°$ at the monkey's viewing position (85 cm away from the screen center); there were thus nearly 12.5 pixels/deg at the monkey's eye. Stimuli were texture fields of white randomly positioned dots presented in circular apertures on a black background. Each dot was one pixel in size and was rendered using subpixel sampling to allow stimulus motion to occur in any direction, at any speed within a wide range, without aliasing caused by the pixel array. The location, size, direction, speed, and density of the dot textures were all optimized for the receptive field of each cell. Stimulus density was between 2 and 8 dots·deg^{-2}·s^{-1}. The fastest speeds generated motion steps of about 4°/frame, but most cells were tested with a top speed of about 2°/frame. In subsequent analyses we excluded any speeds in which a given dot moved more than halfway across the stimulus aperture in five frames (42 ms) because these displays could produce aliased motion in the opposite direction to the one intended. We first ran these speed-tuning blocks in the cell's preferred stimulus direction, followed by blocks in the null stimulus direction. Retinal stimulus speeds ranged from 1 to 256°/s.

Behavioral tasks

Monkeys fixated and pursued targets back-projected onto a large tangent screen. All trials were conducted in a dark room with background illumination of the cathode ray tube set as low as possible.

Under these conditions, the background was <0.001 cd/m^2, the lowest value we could measure. Fixation and pursuit targets were 0.4° red squares (luminance 9.2 cd/m^2), which could be positioned anywhere on the screen.

We first characterized the visual response of each neuron during fixation. A variable fixation interval (600–700 ms) began after the animal aligned his gaze with the target. At the end of this interval, a stimulus appeared in the receptive field of the cell as the animal maintained fixation for another roughly 2,200 ms. At the end of this interval, the stimulus and target were extinguished and the animal received a drop of preferred fluid as a reward for maintaining an eye position within 1–2° of the fixation target.

A typical pursuit trial began with the monkey fixating a small stationary target that appeared between 6 and 12° from the center of the screen on the horizontal or vertical midline, either right, left, above, or below the screen center. After a variable fixation interval (500–600 ms), the target stepped 1 to 3° away from the center of gaze and began moving smoothly toward the center of the screen at a constant velocity. We used this step-ramp paradigm (Rashbass 1961) to reduce the frequency of saccadic eye movements during the early phase of pursuit. Trials in the four cardinal directions were randomly interleaved. The speed of the pursuit target movement was 20°/s and the initial target eccentricity and step size were adjusted so that the main measurement interval for visual responses corresponded to the time during which the animal's gaze crossed the middle part of the screen. If time permitted, we sometimes also measured responses during pursuit at 10 and/or 30°/s. In subsequent population analyses, we included only one pursuit condition for each cell, the one that evoked the most reliable responses.

To characterize the visual response during smooth pursuit, we presented a stimulus in the receptive field during pursuit trials (Fig. 1). Moving texture stimuli appeared in a window placed over the receptive field, 100 ms after the onset of target movement; the window always moved with the fixation target and was therefore stationary on the retina so long as pursuit was accurate. The motions we presented within the window were thus set in retinal coordinates. Our monkeys were trained to pursue along cardinal axes. To present stimulus motion and pursuit targets along the same axes therefore required that the visual stimuli also move in cardinal directions. In 111 of 123 cases
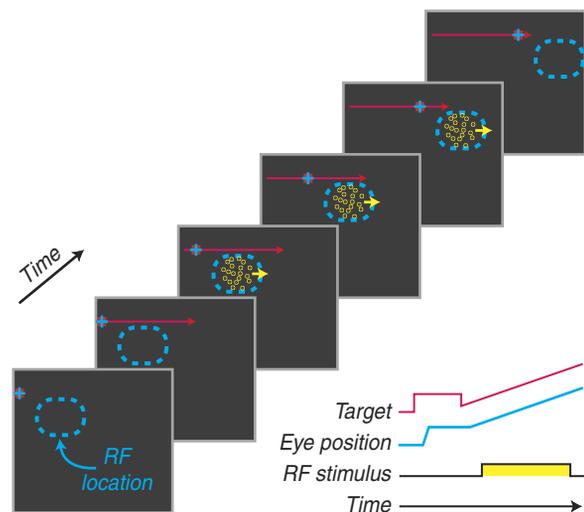

FIG. 1. The course of a single pursuit trial with a moving stimulus. The pursuit target moved across the screen in a step-ramp fashion (red). The stimulus window (yellow dots) remained centered on the receptive field (blue dashed lines) as long as the monkey pursued accurately; stimuli usually moved within the window along the axis of the pursuit movement. Fixation trials, trials in 2 pursuit directions, and the speed and direction of stimulus motion within the moving window varied in a randomly interleaved manner from trial to trial.

(90%), cardinal-direction stimuli evoked reliable visual responses, but in the remaining 12 cases in which visual responses were weak, we used a stimulus direction that was 45° away from the pursuit axis. We noticed no difference in the pattern of results for these 12 cases. We combined pursuit and visual stimulation to gather speed-tuning data in a randomized block design with seven to nine speeds and a "blank" (pursuit or fixation with no stimulus) presented either during fixation or at the chosen pursuit velocity in either the preferred or null direction. Our animals were rewarded with their favorite fluid for successfully maintaining gaze within 2–3° of the target for 1,200 ms of pursuit.

Using the fixation and pursuit paradigms described earlier, we measured speed and direction tuning for cells in areas MT and MST. First, we qualitatively estimated the best stimulus size, speed, and direction for each isolated cell. We then used this stimulus and its smaller variants to map the receptive field borders. We then tested stimulus direction and speed tuning. If the stimulus speed tuning differed from our original estimates, we ran the direction tuning series again. During these experiments, the stimulus patch was always placed in the most sensitive region, or "hot spot," of a cell's visual receptive field. The hot spot was typically smaller than the entire receptive field, particularly for area MST cells. Stimulus sizes for areas MT and MST were somewhat different, mostly because the best stimulus sizes of the more peripheral MST receptive fields were often ≥20° (mean area MT stimulus size = 5.8°; mean area MST stimulus size = 13.3°).

Cells with receptive fields that are close enough to the fovea to contain the fixation or pursuit target could respond to the appearance or movement of the fixation target alone. Of 77 area MT cells, 2 had receptive fields that included the fovea. For some regions of area MST, the receptive fields commonly crossed into the ipsilateral field (34/97). We examined responses from these cells to see whether there was an appreciable response to the acquisition of fixation, when the fixation target would have initially appeared in the receptive field. We found no increase in firing associated with the acquisition of fixation. Also, the appearance of the fixation or pursuit target did not elicit a reliable response from the cells, particularly when compared with the response elicited from optimal stimulus motion. Last, the cells with receptive fields that crossed into the ipsilateral field did not differ significantly from the rest of the population in terms of the response properties we studied. We conclude that the neuronal responses presented here result from stimuli presented to the receptive field or to pursuit eye movement and not from the appearance of or acquisition of the fixation or tracking target.

Eye-movement recording

Eye movements were monitored using a scleral search coil system (CNC Engineering). Signals induced by movements of the eye coil were low-pass filtered, digitized, and stored by the computer with 12-bit resolution at 500 Hz. Eye-position calibrations were done daily to ensure accurate measurements. We fit the horizontal and vertical calibration data with a sinusoid at the start of each experiment session to estimate and remove fixed nonlinearities in our system. By compensating for coil nonlinearities, we maintained an accuracy of about 0.1° to horizontal and vertical eccentricities of 50°.

Our experiments depended on the diligence of the animals in maintaining accurate pursuit in all directions, so we analyzed pursuit gain for all 25,634 included trials by measuring eye velocity (corrected for saccadic intrusions as described in the following text and in Fig. 2) and dividing it by pursuit target velocity. A figure showing the gain distributions for eight combinations of target and stimulus direction (up, down, left, and right; same and opposed) is in Supplemental Fig. S1.[1] Summarizing the results, the grand mean pursuit gain for all conditions was 0.939, meaning that the retinal slip due to imperfect pursuit was, on average, about 1.2°/s, much slower than the preferred speeds of our cells. This slip was of course somewhat

variable due to variations in pursuit speed during each trial but, on average, this variation was much smaller than the mean slip and therefore of little visual consequence. There were no systematic differences in pursuit gain in the four different directions we used and no differences between conditions in which the visual stimulus moved in the same or the opposite direction from the pursuit target.

Another potential issue arises from oscillations in pursuit velocity that are occasionally discernible in the eye-movement data (e.g., Fig. 2*A*, *bottom right traces*). These oscillations, although infrequent, do cause a modulation of retinal speed during pursuit. Because the amplitude of these velocity oscillations was always <2°/s, the effects would primarily be expressed in responses to slow stimulus speeds and would affect measurements of cells tuned for slow speeds. We did several analyses to determine whether our data showed different effects either for cells preferring low speeds or for stimuli presented at low speeds (Supplemental Figs. S3 and S4). The answers were uniformly negative and we conclude that these variations in pursuit speed did not have measurable effects on our results.

Electrophysiological recording

Once areas MST and MT were identified using physiological criteria in preliminary mapping experiments, we located regions in which neurons that had visual receptive fields centered between 5 and 20° of the center of gaze. A tungsten-in-glass microelectrode (Merrill and Ainsworth 1972) was advanced hydraulically into the cortex through a 23-gauge guide needle. Signals from the electrode were conventionally amplified, filtered, and displayed on an oscilloscope; action potentials from single neurons were isolated with a dual time–amplitude window discriminator (Bak Electronics). Pulses triggered by each action potential were acquired, time-stamped with 0.1-ms precision, and stored by the host computer.

Data analysis

We analyzed data only from correctly completed trials. However, the 3° position criterion did allow for occasional small catch-up saccades during smooth-pursuit eye movements. To remove intervals with these velocity transients, we set conservative thresholds for detecting saccades from eye-velocity and acceleration measurements. We removed trials from analysis that did not allow adequate contiguous intervals for analysis. For other trials, we excluded time intervals affected by saccadic eye-velocity excursions, allowing 50 ms for visual latency. Figure 2 shows example trials including the rejected intervals around saccades during pursuit and fixation trials. Having established for each trial the periods of suitable smooth-pursuit tracking, we then analyzed responses within these periods. From the spikes and interval times we calculated firing rates for each trial and combined repeats from multiple stimuli to obtain an average firing rate, with an estimated SE of the mean over the whole stimulus epoch.

Preferred directions and direction biases were calculated using a vector-combination method for both stimulus and pursuit direction data. We permuted the spike counts on each trial with respect to the stimulus or pursuit directions that originally evoked the response and recalculated direction bias to assess the significance of the bias for each cell. We repeated this permutation 1,000 times to obtain the 75% confidence criterion for each cell. If the direction bias from the measured (nonpermuted) data was higher than the 75% confidence criterion then the cell was taken to have a significant direction bias (O'Keefe and Movshon 1998).

Following Nover et al. (2005), we fit speed-tuning data for each cell with the probability density function of the gamma distribution

$$R = as^{k-1}e^{-s/\sigma}/\Gamma(k)\sigma^k$$

where R is the firing rate and s is the retinal speed of the stimulus in the neuron's preferred direction. This function captured the important

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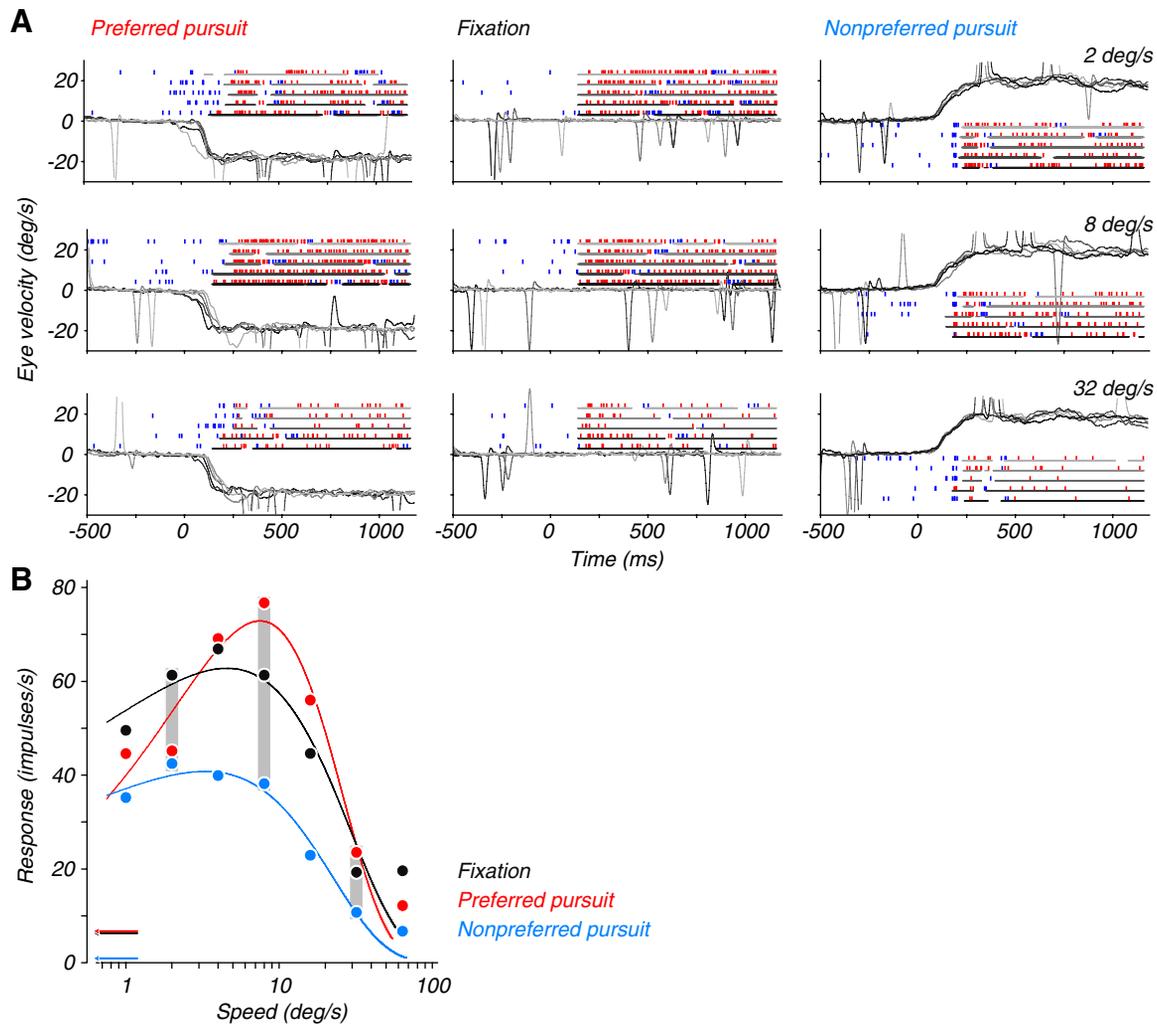[1] The online version of this article contains supplemental data.

FIG. 2. Sample data from a neuron recorded in the medial superior temporal (MST) area. *A*: each of the 9 panels shows eye-velocity and spiking data from 5 trials, each represented by a different shade of gray. In each trial, saccadic eye-velocity excursions were detected and used to define exclusion windows, indicated by breaks in the lines under each raster line. Allowing for a 50-ms visual latency (Bair and O'Keefe 1998), spikes associated with those excursions (shown in blue) were identified and removed from the analysis. Spikes indicated in red were counted over the period of each trial when eye velocity was close to target velocity to compute a firing rate. The 3 columns represent trials of pursuit in the preferred stimulus direction (*left*), fixation (*middle*), and pursuit in the null direction (*right*). The rows show trials with retinal speeds of 2, 8, and 32°/s. *B*: averaged firing rates for all tested speeds in the 3 pursuit conditions for this cell. The speeds for which data are shown are marked with gray bands. The smooth curves show fits to the data of the probability density function of the gamma distribution, as described in the text.

aspects of our data with three parameters: *a* to set the speed range and *k* and σ to determine the curve shape. We used the preferred speed values drawn from these fits for all comparisons. Not all cells had peaks that were well defined within the range of speeds tested, so we used a resampling technique to obtain confidence intervals (CIs) for the parameters derived from the fits to the data. We resampled and refit the speed-tuning data with replacement 1,000 times and used these to obtain the range of both the peak speeds and the fraction of variance accounted for each cell. To restrict speed analyses to only those cells where the fits were robust and reliable, we included cells whose peak speeds were accurately captured by the fits (as established by verifying that the 80% CIs spanned a narrow range of speeds, <2:1) or that the mean of fractional variance accounted for by the fits was >50%.

RESULTS

We recorded direction-biased cells with similar receptive field locations in both areas MT and MST. The stimulus location that elicited the best response was generally near the center of the receptive field. The ratio of receptive field size to receptive field eccentricity was greater in area MST than that in area MT in our population, in agreement with published data (Tanaka et al. 1993; Ungerleider and Desimone 1986). Responses to dot motion were similar in areas MT and MST. There were similar proportions of directionally biased cells in the two areas (MT: 81.8%; MST: 80.4%). The most striking difference between the areas lay in the bias for radial stimulus direction preferences in area MT, as reported previously (Albright 1989). Area MT cells tended to prefer stimuli directed away from the fovea ($\chi^2 = 29.701$, df 7, $P < 0.001$), whereas the distribution of preferred directions relative to the fovea in area MST was statistically indistinguishable from uniform.

Responses to visual motion during pursuit

What happens to neuronal responses in area MT and area MST when visual motion is presented during pursuit? We

recorded speed-tuning data during both fixation and pursuit from 62 cells from area MST and 61 cells from area MT. We chose the pursuit axis to be the cardinal axis closest to that which was best for visual stimulation. Eye-velocity traces aligned with spike rasters for a typical MST cell are shown in Fig. 2*A* and Fig. 2*B* shows the resulting speed-tuning curves. Pursuit in the preferred stimulus direction slightly enhanced the peak response and shifted the preferred speed up, whereas pursuit in the null direction suppressed visual activation at all speeds.

Figure 3 shows example data obtained during fixation and pursuit. Speed-tuning data measured during fixation are shown in black, speed-tuning data from pursuit in the preferred stimulus direction are shown in red, and speed-tuning data from pursuit in the null stimulus direction are shown in blue. The four examples represent the diversity of responses we encountered in area MT and area MST. Some cells, such as *MT 2*, showed little change in the response to image motion during smooth pursuit. However, many cells in area MST and some in area MT showed changes in response amplitude during pursuit, as in examples *MT 1* and *MST 1*. In some cells we observed combinations of increases for one pursuit direction and decreases for the other pursuit direction (e.g., *MST 2*).

We also observed changes in the preferred speeds of cells, such as *MST 2*. This example shows the pattern one would expect for a cell that compensated exactly for pursuit—a shift in tuning (cf. Inaba et al. 2007). The tuning curve for pursuit in the preferred stimulus direction is shifted toward higher retinal speeds in the null direction, whereas tuning for pursuit in the null stimulus direction shifted toward higher retinal speeds in the preferred direction. Other cells, such as *MST 1*, showed smaller shifts in speed tuning and sometimes for only one pursuit direction. These shifts were quite variable from cell to cell, in some cases being too small to compensate for the eye movement and in others too large to seem useful. Note that our analysis of preferred speed was confined to the preferred retinal direction and so might have underestimated speed shifts for unusual cells, such as *MT 2* in Fig. 3, which showed changes in response to stimuli moving in the nonpreferred retinal direction.

How often and how well do changes in preferred speed compensate for reafferent motion during pursuit? The changes in speed tuning in our area MT and area MST populations were quite variable. To explore the relationship between these tuning changes and pursuit, in Fig. 4 we plot the observed shift in preferred speed against the pursuit speed, which is the shift that would be expected if the cell were perfectly compensating for the pursuit eye movement. The dashed diagonal marks the identity line. For this analysis we included only cells in our population for which we could reliably estimate peak speed (46 MST cells and 34 MT cells, each contributing two data points, for preferred- and null-direction pursuit). In both areas, shifts in preferred speed were scattered. However, in area MST, but not in area MT, the shifts in preferred speed were correlated with the shift expected due to reafferent motion (area MST: $r = 0.35$, $n = 48$; $P = 0.007$; area MT: $r = 0.13$, $n = 34$, $P = 0.231$). Although the trend for the area MST population was in the correct direction to compensate for the ongoing smooth eye movement, the slope of the best-fit line passing through the origin ($m = -0.56$) was shallower than the ideal of -1. Thus the observed speed-tuning shifts in the area MST population provide only a partial compensation for pursuit velocity; no reliable compensation was observed in the area MT population.

Note that our analysis considered only speed in the preferred stimulus direction. In principle, a cell preferring low speeds that compensated for eye velocity might have reversed its direction preference and developed a preference for the opposite direction when pursuit was in the neuron's preferred direction. We never observed this behavior for any of our neurons and it appears that although reafference can modify preferred speeds for some cells, it cannot reverse their preferred directions.

As shown by the examples in Fig. 3, pursuit movements were often associated with changes not only in response amplitude but also in preferred retinal speed. To further examine changes in speed tuning independently of response amplitude changes, we used a correlation analysis to compare the speed-tuning curves of cells under fixation and pursuit conditions. We compared the observed speed tuning during pursuit with two specific predictions: a retinal speed model, in which a cell's tuning for stimulus speed should have the same shape and position on the speed axis, and a world speed model, in which tuning for world speed (i.e., retinal speed minus eye speed) should be the same. We computed correlations between the tuning measurements made during fixation with the data obtained during pursuit. Because our speed-tuning measure-
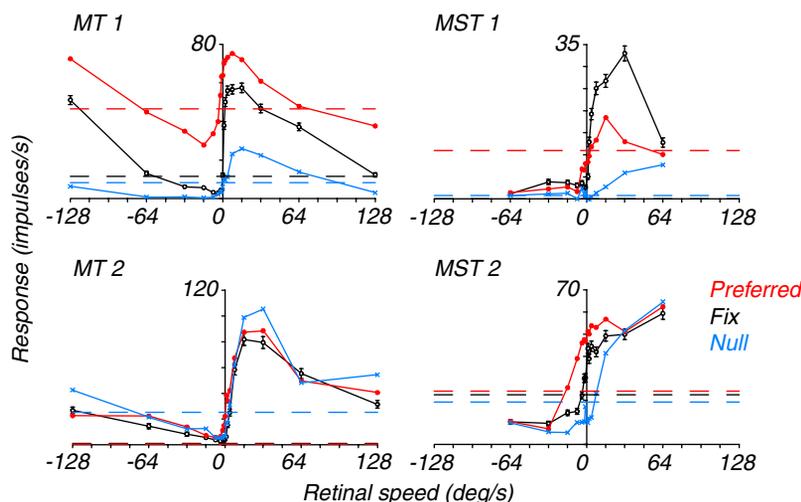

FIG. 3. Speed tuning under different pursuit and fixation conditions for 2 cells recorded from the middle temporal (MT) area (*left*) and 2 recorded from area MST (*right*). The plots represent speeds in the preferred and the null stimulus direction as positive and negative values, respectively. Three speed-tuning curves are shown in each plot: responses during pursuit in the preferred stimulus direction in red, during fixation in black, and during pursuit in the null stimulus direction in blue. Responses to fixation or pursuit with no receptive field stimuli are shown with dashed lines. The SEs for the 3 eye-movement conditions were similar, so we show SE bars only for the fixation curve to reduce clutter.
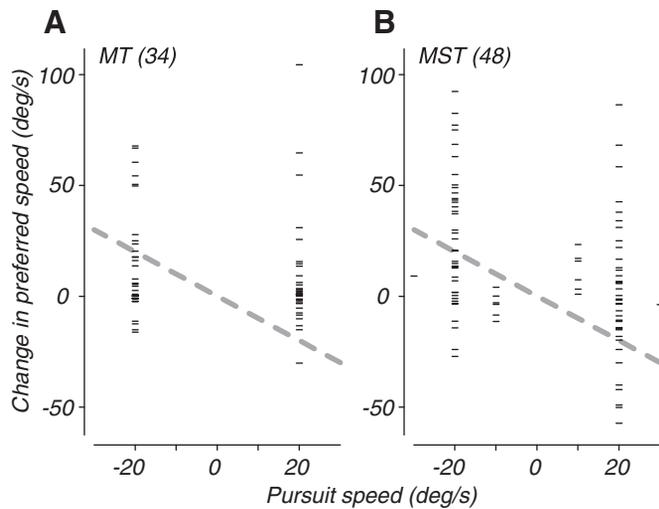
FIG. 4. A comparison of the observed shift in preferred speed of neurons with the pursuit speed (i.e., the shift expected from the reafference of the pursuit movement) for cells from areas MT and MST. The negative diagonal indicates the prediction shift if velocity compensation were perfect. Cells for which the preferred speed in at least once condition was not well constrained by the data are omitted.

orange), had high correlations for both predictions (both; *top right*, gray), or had low correlations for both predictions (neither; *bottom left*, gray). Because the number of data contributing to each point depended on the number of conditions tested, there is no fixed threshold for significance, although the white shading on the background indicates cells whose correlations with either prediction were not significant (central square), or cells whose correlations with one or the other prediction were not significant (horizontal and vertical arms). Note that in contrast to some previous applications of this statistic (e.g., Smith et al. 2005), we are not attempting to establish classification boundaries but are asking more simply how well different models describe our data.

The tuning behavior of most cells in area MT (*left panel*) was better explained by the retinal speed prediction and only a few cells (5/34, 15%) were well correlated with the world speed prediction and not the retinal speed prediction. On the other hand, a more substantial minority of area MST cells showed this tuning pattern (11/46, 24%). Because the tuning curves of many cells were broad (e.g., Fig. 3), a substantial fraction of the data for both areas lay in the ambiguous top right quadrant (MT: 8/34, 24%; MST 9/46, 20%); only three cells from either area fell into the lower left quadrant (4%). Like the analysis of speed tuning in Fig. 4, this pattern of correlation suggests that some part of the population signal in area MST can usefully be thought of as representing object speed during eye movements in world-centered coordinates, but that it is only a minority of cells that provide this representation (cf. Inaba et al. 2007).

We frequently observed changes in response amplitude during pursuit (Fig. 3). We compared the response measured during fixation with the response measured during pursuit, separately for preferred and null directions. We also measured

ments were done at fixed retinal speeds, we did not have measurements of response at the same world speeds for this analysis. We therefore used values taken from the fitted speed-tuning curves, with the speed values shifted by subtracting the pursuit speed. We used partial correlations to remove the effects of correlations between the two predictions and in Fig. 5 we plot the values for the retinal speed model against the world speed model. We divided the space into quadrants to observe whether cells largely correlated with the retinal speed prediction (*bottom right*, pistachio), the world speed prediction (*top left*,
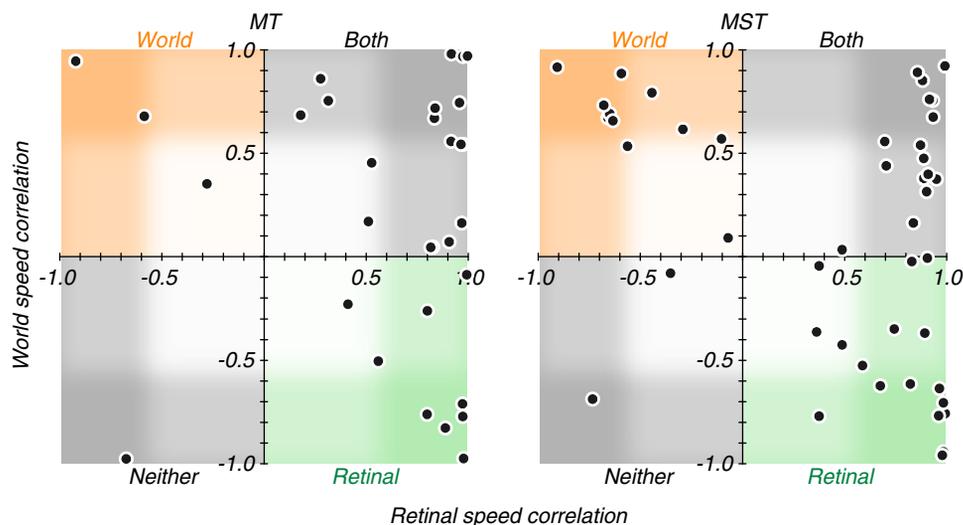

FIG. 5. Partial correlation analysis of the speed tuning of cells recorded from MT (*left*) and MST (*right*) during pursuit and fixation. We computed the correlation of speed tuning during pursuit with the predictions of 2 models: *1*) a retinal speed model (abscissa), in which reafferent motion and visual motion are processed together; and *2*) a world speed model (ordinate), in which reafferent motion is subtracted from retinal motion to yield a tuning curve defined in world coordinates. The quadrants of each plot indicate whether correlations between speed-tuning curves measured during pursuit and fixation are well explained by the world speed model, the retinal speed model, neither model, or both. The white square in the middle indicates regions of the space in which neither correlation is significant at the level of $P < 0.1$; the light bands above, below, and to the sides of the square indicate regions in which one correlation was significant but not the other. See text for details.

baseline (unstimulated) responses during pursuit and during fixation. Figure 6A shows the difference in peak evoked firing rates for the optimal stimuli during preferred pursuit (red) and null pursuit (blue) for cells recorded in MT (*top*) and MST (*bottom*); on the *right* are marginal distributions for these differences. Pursuit in the preferred direction (red) did not significantly change peak response levels in either area, but pursuit in the null direction (blue) significantly reduced the response amplitude of cells recorded in area MST (*bottom*, blue asterisk, *t*-test, $P = 0.004$). This difference could in principle have arisen from responses to the pursuit alone, measured without visual stimulation, which act as baseline responses in this design. Figure 6B shows the distributions of change of these baseline responses for cells recorded in areas MT and MST, rendered as in Fig. 6A. There was no difference in the baseline response for the null pursuit conditions, but the population of MST cells showed a significant increase in firing during preferred pursuit (*bottom*, red; *t*-test, $P = 0.01$). We conclude that the suppression of response during null pursuit in area MST was due to an interaction between visual and eye-movement signals and not to a response related purely to the pursuit eye movement. In additional analysis (presented in Supplemental Fig. S2), we show that this suppression is due to a change in response gain, whereas the enhanced response during preferred direction pursuit is due to an increase in the baseline firing.

In principle, the modulation of response amplitude we observed might include a contribution from gaze-related modulations of the kind described by Andersen et al. (1985). This cannot account for much of our effect, since the range of gaze positions in the two directions of pursuit was similar. If there were gaze-dependent response modulation, we reasoned that one would expect gaze field modulation to either increase or decrease the activity over the course of a trial. We measured the number of spikes in 100-ms bins and fit a regression line to the binned data to obtain a slope associated with the response to each pursuit condition in each cell. None of the cells analyzed showed the pattern expected from eye-position modulation—slopes of opposite sign for opposite pursuit directions. Instead, most of the slope values were near zero, indicating that the response was steady throughout the pursuit movement.
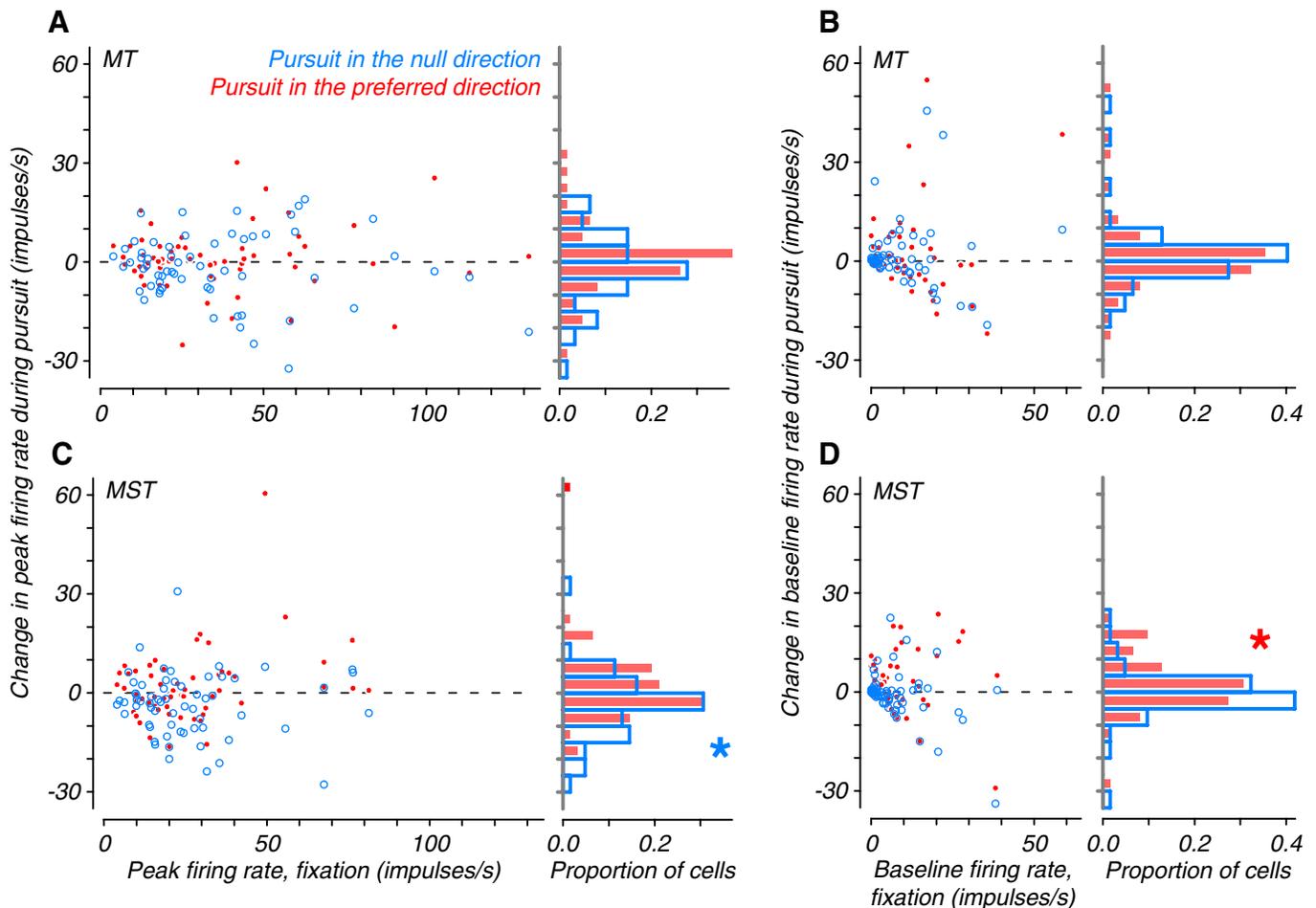

FIG. 6. Changes in response magnitude between pursuit and fixation conditions. *A*: changes in peak firing rate during pursuit for cells recorded in MT (*top*) and MST (*bottom*). Red points and marginal distributions are for pursuit in the cell's preferred direction; blue points and marginal distributions are for pursuit in the nonpreferred direction. The mean changes (means ± SE, in impulses/s) in evoked firing rate for preferred pursuit for MT were 0.99 ± 1.22 and for MST the changes were 1.74 ± 1.36 impulses/s; for the nonpreferred pursuit for MT the changes were −1.84 ± 1.36 and for MST the changes were −3.66 ± 1.22. *B*: changes in baseline firing rate during the same conditions shown in *A*. Baseline firing is taken as the response during pursuit or fixation in the absence of a visual stimulus to the receptive field. Conventions as in *A*. The mean changes (means ± SE, in impulses/s) in baseline firing rate for preferred pursuit for MT were 1.94 ± 1.49 and for MST the changes were 2.91 ± 1.10; for nonpreferred pursuit for MT the changes were 1.50 ± 1.27 and for MST the changes were −0.75 ± 0.93. The blue asterisk in *A* and the red asterisk in *B* indicate the 2 distributions whose means differ significantly from 0.

DISCUSSION

We observed a range of response patterns to retinal motion presented during smooth pursuit. Some cells did not change their response at all: speed tuning during pursuit resembled speed tuning during fixation; such cells encode motion in a retinal coordinate frame. We found more of these cells in area MT, where they were a clear majority of the sample, than in area MST. Some cells changed their preferred speed during pursuit. Cells that shift their speed preference by precisely the velocity of the pursuit eye movement effectively compensate for the retinal motion created by the eye movement itself. A few cells in area MT—but a substantial minority of cells in area MST—showed this specific response pattern. When considered as a population, cells recorded in area MST shifted their speed tuning in line with the predicted velocity compensation for the pursuit eye movement. Finally, we also observed cells whose response magnitude changed during pursuit. This type of change occurred in both areas MT and MST, although more frequently in area MST. This change was most often suppressive in nature and reflected a change in the gain of visually evoked responses.

Such changes are conceptually similar to the gain modulations reported in studies of coordinate transformations of spatial position by Andersen and colleagues (1985). Our effects, however, appear to be modulations of the response based on the velocity of the pursuit movement and not on the position of the eye. These eye-velocity–dependent gain changes suggest that the general phenomenon of gain-field modulation exists in domains other than visual spatial location. Models of this sort of gain change (Salinas and Abbott 1995) indicate that once the visual and the extraretinal signal combine in this nonlinear manner, downstream neurons can extract any linear combination of the signals. Our results suggest that a cell's response would be a joint function of the visual stimulus and the velocity of the pursuit eye movement. Cells that modulate the gain of their response carry signals from which information about both eye and stimulus motion may be derived.

Models of sensorimotor recalibration usually posit either that response properties change to compensate for the reafferent stimulation or that an intermediate representation is created that represents both the afferent and reafferent visual signal. Our results suggest that cells in MST, and to a lesser extent in MT, show signs of both kinds of transformation. In a related recent study, Inaba et al. (2007) measured speed tuning in MT and MST cells during pursuit, in an experiment related to ours. As we did, they found a fraction of cells in MST that shifted their speed tuning to compensate for the reafferent motion. In contrast to our results, they did not comment on gain changes. The difficulty with the experiments of Inaba and colleagues is that they apparently did not always test a sufficiently wide range of retinal velocities to distinguish a gain change from a change in preferred speed; some of their published curves appear to span only one side of the speed tuning of their neurons, leaving open the question of whether they fully characterized the position and amplitude of the tuning curve peak. Their data, as presented, are consistent with ours, but we suspect that had they tested a wider range of speeds they would have found the more heterogeneous pattern of tuning curve changes that we report here.

Cells in area MST frequently showed a suppression of response during pursuit in the null stimulus direction. Such a suppression effectively suppresses responses due to slip of the visual background over the receptive field—moving the eyes in the null direction of a cell causes retinal slip in its preferred direction, a stimulus whose visual effectiveness the animal might well seek to attenuate. The fact that this suppression is the most prominent response change in area MST cells is interesting because we only occasionally perceive the kind of background slip during smooth-pursuit movements that these area MST cells suppress (as in the Filehne illusion, which has recently been documented to occur in monkeys by Dash et al. 2009).

In a related study, Thiele and colleagues (2002) found a suppression of the visual response during saccades in some STS cells and suggest that this response suppression might be the physiological substrate for the perceptual phenomenon of saccadic suppression. We too have identified a prominent suppression of the visual response magnitude for many area MT and area MST cells, but during smooth pursuit. The amount of reafferent motion perceived during an eye movement depends on the type of eye movement and the particular arrangement of the visual scene. During experiments with stimulus arrangements much like ours, subjects perceive the stimulus well; for example, they can discriminate speed roughly as well during pursuit as during fixation (Turano and Heidenreich 1996). Perhaps our effects and those reported by Thiele and colleagues are similar, but reflect suppression of reafferent motion signals at different velocities.

In summary, we found that reafferent motion caused by a smooth eye movement changed the response to retinal stimulation in some area MT and many area MST cells. The changes we observed may represent movement and motion information to downstream neurons in a way that lets them compensate for the effects of self-produced motion. However, it is equally the case that such compensation seems not to be completely achieved in areas MT and MST, suggesting that further computations take place in areas downstream.

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