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Area MT Neurons Respond to Visual Motion Distant From Their Receptive Fields

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Zaksas, Daniel and Tatiana Pasternak. Area MT neurons respond to visual motion distant from their receptive fields. *J Neurophysiol* 94: 4156–4167, 2005. First published August 24, 2005; doi:10.1152/jn.00505.2005. Neurons in cortical area MT have localized receptive fields (RF) representing the contralateral hemifield and play an important role in processing visual motion. We recorded the activity of these neurons during a behavioral task in which two monkeys were required to discriminate and remember visual motion presented in the ipsilateral hemifield. During the task, the monkeys viewed two stimuli, sample and test, separated by a brief delay and reported whether they contained motion in the same or in opposite directions. Fifty to 70% of MT neurons were activated by the motion stimuli presented in the ipsilateral hemifield at locations far removed from their classical receptive fields. These responses were in the form of excitation or suppression and were delayed relative to conventional MT responses. Both excitatory and suppressive responses were direction selective, but the nature and the time course of their directionality differed from the conventional excitatory responses recorded with stimuli in the RF. Direction selectivity of the excitatory remote response was transient and early, whereas the suppressive response developed later and persisted after stimulus offset. The presence or absence of these unusual responses on error trials, as well as their magnitude, was affected by the behavioral significance of stimuli used in the task. We hypothesize that these responses represent top-down signals from brain region(s) accessing information about stimuli in the entire visual field and about the behavioral state of the animal. The recruitment of neurons in the opposite hemisphere during processing of behaviorally relevant visual signals reveals a mechanism by which sensory processing can be affected by cognitive task demands.

INTRODUCTION

Representation of the world in visual cortex is highly topographic with neurons devoted to processing information from specific regions in the contralateral visual space. Early in processing, in primary visual cortex (V1), these retinotopic maps are very precise due to neurons having small, well-defined receptive fields (RFs). Although at several subsequent stages of processing (e.g., V2, V3, V4, or MT) the RFs become larger, they remain largely confined to the contralateral visual field, rarely extending into the ipsilateral hemifield by more than a few degrees (Gattass et al. 1985; Van Essen 1985). Cortical area MT, representing an important stage in the analysis of visual motion (Britten 2003; Pasternak et al. 2003), is one such area. RFs of these neurons are on the order of a few degrees near the fovea, and although they increase in size with distance from the fovea (Albright and Desimone 1987), they

are limited largely to the contralateral visual field (Maunsell and Van Essen 1987).

Despite this relatively precise topography, responses of MT neurons to motion appearing in the RF can be modulated by behaviorally relevant stimuli appearing in the ipsilateral hemifield and thus not represented by the recorded neuron (Martinez-Trujillo and Treue 2004; Treue and Martinez-Trujillo 1999). In this study, we report that even in the absence of direct stimulation of RFs, MT neurons respond to remotely presented behaviorally relevant motion stimuli. These responses were measured during a task requiring a comparison of two sequential motion stimuli, one or both of which were presented in the ipsilateral hemifield. This activity was often stimulus specific, had long latencies and took the form of excitation or suppression, each having a unique temporal dynamic. Because response magnitude during the comparison phase of the task was different from that during the sample, and because it was differentially affected during errors, this activity is likely to represent top-down influences from brain regions monitoring the entire visual field and task demands.

METHODS

Subjects

We recorded from two adult male macaque monkeys (*Macaca nemestrina*). Water was restricted for 22 h prior to each daily experiment, and the daily liquid rations were provided in the form of fruit drink during the testing sessions. At the end of each testing day, the monkeys were given fresh fruit and vitamins. No testing occurred on weekends, and the monkeys received 100 ml/kg allotments of water. Food was continually available in the home cage, and body weights were measured on a daily basis to monitor health and growth. Experiments were carried out in accordance with the guidelines published in the National Institutes of Health Guide for the Care and Use of Laboratory Animals (revised 1996) and were approved by the University of Rochester Committee for Animal Research.

Visual stimuli and behavioral procedures

The stimuli and the behavioral task were identical to those used in previous studies from this laboratory (e.g., Bisley and Pasternak 2000; Bisley et al. 2001, 2004).

VISUAL STIMULI. Stimuli were presented on a video monitor (17-in Nanao FlexScan T560i, 1,152 × 870 pixel resolution, 75-Hz refresh rate), placed 42 cm in front of the monkeys. They consisted of random dots placed in a circular aperture and having a constant translational

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step size (Δx) and temporal interval ($\Delta t = 13$ ms). The dots were 0.03 of visual angle in diameter with a luminance of 15 cd/m^2, shown on a dark background of 0.1 cd/m^2. Each dot persisted for the entire duration of the stimulus (500 ms) and, during each frame, had an independent direction chosen randomly from a specified distribution (Fig. 5A). Thus dots in a stimulus could move in a range of directions from 0 to 360°, and this parameter was termed the *direction range* of the stimulus.

BEHAVIORAL TASK. The monkeys performed a working memory task (Konorski 1959) in which they compared the directions of two moving stimuli separated by a delay and indicated whether those directions were same or different. During the experiment, their eye position was monitored by means of scleral search coils (Remmel 1984). The monkey initiated a trial by fixating for 1,000 ms a small spot within a 1.5° window. Successful fixation brought on the presentation of the first 500-ms long stimulus, the *sample*, followed by a 1,500-ms delay and subsequently the second stimulus, the *test*, also 500 ms in duration. Within 3 s of the test stimulus offset, the monkey had to indicate whether the two stimuli moved in the same or in opposite directions by pressing one of two buttons. Correct responses were rewarded with a drop of juice. On each trial, the direction range in the sample was selected at random and without replacement from a set of four (0, 150, 300, and 360°). The test stimulus always had 0° direction range. Responses on trials where the sample had 360° direction range were rewarded at random. Direction range thresholds, determined during each recording session, were on the order of 280–330° (Pasternak and Zaksas 2003).

Surgical procedures

For all surgical procedures, anesthesia was induced with ketamine hydrochloride (10 mg/kg) and diazepam (0.25 mg/kg) and maintained with 1.5–3% isoflurane. Monkeys were implanted with head-restraint devices and scleral search coils for monitoring eye position. MT was localized by examining brain scans of each monkey obtained by MR imaging (T2-weighted, 2 and 1.5-T GE magnets, small surface coil; TE/TR: 5,000/90 or 3,000/85; 1.5-mm-thick slices). The superior temporal sulcus (STS) was identified from coronal scans, and a craniotomy was placed at the location from which MT could be accessed. Recording chambers, 20 mm in diameters (Crist Instruments, Hagerstown, MD) were implanted over the craniotomies by means of bone cement and titanium screws.

Electrophysiological recordings

The recording procedures were identical to those used previously (Bisley et al. 2004). Tungsten microelectrodes (1.5–5 MΩ, FHC or 2–2.5 MΩ, FHC) were lowered into MT through a dura-penetrating guide tube positioned in a grid (Crist et al. 1988). Waveforms from single neurons were found and isolated using a dual window discriminator (BAK Electronics).

RF MAPPING. The borders of each neuron's RF were mapped initially by hand, using a joystick-controlled patch of dots while the monkey passively fixated a small cross on the screen. Once the RF was size was outlined, it was fitted with a stimulus of coherently moving dots. Speed and density of the moving dots were optimized by varying them systematically to obtain a maximal response. Speed varied from 3s to 35°/s, and dot densities varied from 2 to 5 dots/°^{2}. To determine the neuron's directional preference, responses were recorded to random-dot stimuli moving in each of eight directions, 45° apart. Each direction was presented at least five times, and a vector average was computed from mean firing rates in response to each direction. This computed direction was designated as *preferred*, and the opposite direction was termed *anti-preferred*. In ~3/4 of all behavioral sessions, the sample could move either in the preferred or in the anti-preferred direction, and in the remainder of the sessions,

the sample could also move in one of two orthogonal directions. Data from orthogonal directions are not presented in this paper.

REMOTE STIMULUS LOCATIONS. Once a RF of a given neuron was mapped, an alternate location for stimulus presentation was chosen. This location was always placed in the opposite and noncorresponding quadrant of the visual field at equal eccentricity to the RF. Special care was taken to choose the remote location in a way that would eliminate any overlap with space corresponding to the horizontal reflection of the RF across the vertical meridian. In most cases, a remote location was simply a reflection of the RF across the fixation point. However, when a RF was close or on the horizontal meridian, the remote location was positioned as far as possible from the horizontal meridian while maintaining maximal distance from the RF and equal eccentricity. Four stimulus conditions, three of them illustrated in Fig. 1, A–C were used: sample and test in the RF; remote sample, test in RF; sample in the RF, remote test; remote sample and test. Each of the conditions was run in a separate block of 200–300 trials.

Data analysis

GENERAL METHODS. Analysis of spike data and statistical tests were performed using MATLAB (Mathworks) and Microsoft Excel. For the purposes of visual inspection, the activity of each neuron during each behavioral session was plotted as a spike density function (SDF) convolving the spike train with a skewed probability function kernel having a 1-ms growth phase time constant and a 20-ms decay phase time constant (Thompson et al. 1996). Unless otherwise noted, analyses were limited to correct trials, except when the sample contained 360° range, in which case all trials were used. For all statistical tests, the firing rates recorded during the trial were compared with the average baseline rates recorded on each trial during 500–800 ms of fixation, immediately preceding sample onset. The rate of activity at different stages of the task was analyzed by computing the mean number of action potentials over a given epoch in repeated presentations. Recorded data were used for analysis only if at least three trials for every sample direction and every range value were available. Generally, 8–30 trials were run at each direction and each range.

RESPONSES TO VISUAL STIMULATION. Responses to remote stimuli were detected by sliding a 100-ms bin across the duration of the stimulus in 50-ms steps and looking for at least one bin during which the activity is statistically different from baseline ($P < 0.0056$, unpaired *t*-test with Bonferroni correction). If the neuron showed such significant activity during the remote stimulus, it was classified as having responded to the stimulus.

RESPONSE LATENCY. Calculating the latencies of responses to remote stimuli by individual neurons was complicated by low firing rates as most conventional methods tended to produce overestimates. Therefore we examined the time at which the average response of the recorded population significantly deviated from baseline. For this purpose, the average activity of groups of neurons having either excitatory or suppressive responses was calculated for the duration of the stimulus in consecutive 25-ms bins. Latency was designated as the midpoint of the first of three consecutive significant bins, with significance determined as a deviation from baseline activity at the level of $P < 0.0025$. A bootstrap analysis was used to estimate the variance in the population latency (Efron and Tibshirani 1993). This analysis was performed separately on neurons with remote excitation and suppression as well as on their responses to stimuli in RF. It consisted of resampling without replacement the activity of individual neurons within each group and calculating the population latency from the resampled group. This procedure was repeated 4,000 times. The SDs of the bootstrap distributions provided a measure of the error in the population means. To determine whether the latencies of any two groups of responses were different, we performed a two-sample bootstrap hypothesis test (Efron and Tibshirani 1993). In this test, the
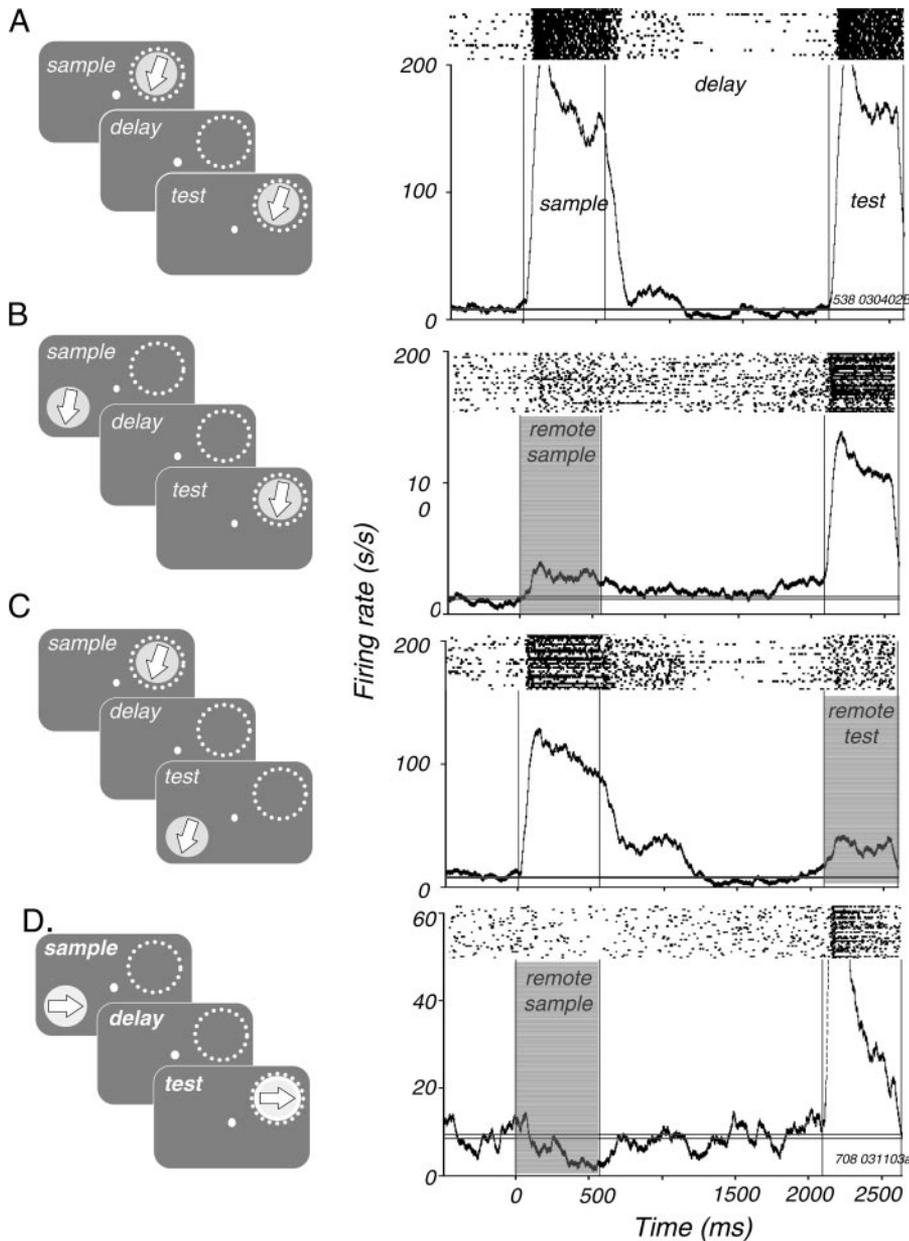
FIG. 1. Behavioral task and activity of example neurons during the task. The monkeys fixated a spot for 1,000 ms before being presented with 2 stimuli, sample and test, lasting 500 ms each and separated by a 1,500-ms delay. They indicated by pressing 1 of 2 push buttons whether the sample and test moved in the same or in different directions. All responses shown on the right are to stimuli that moved in the neuron's preferred direction. Neuronal activity was recorded until the offset of the test stimulus, at which point the monkey was no longer required to fixate. Average firing rate shown as a spike density functions (skewed kernel, 1-ms rising phase, 20-ms falling phase) and single trial rasters are shown above the plot. Onset and offset times of the stimuli are shown as light dotted vertical lines. Baseline activity, collected during the presample 500-ms fixation period, is shown as a light gray horizontal line with the thickness of ± SE. *A*: sample and test in the neuron's receptive field (RF). RF eccentricity: 6.7° from the fovea, in the upper right field. Both sample and test moved in the preferred direction. *B*: remote sample condition. The sample was presented in a noncorresponding location in the opposite hemifield, iso-eccentrically with the RF, 6.7° in the lower left field, while the test appeared in the RF. The neuron shows a weak but consistent excitatory response during the remote sample. Data are shown for trials in which a preferred sample was presented. In some of these trials, the test was also preferred, and in others the test was anti-preferred. As a result, the average test firing rate appears lower than in *A*, where all trials shown had a preferred test. *C*: remote test condition. Sample appeared in the RF, 6.7° in the upper right field, while the subsequent test was presented 6.7° in the lower left field. The neuron again responded to the remote stimulus moving in the preferred direction. Data are shown for trials in which a preferred test was presented. In some of these, the preceding sample was also preferred, and in others it was anti-preferred. As a result, the average sample firing rate appears lower than in *A*, where all trials shown had a preferred sample. *D*: remote sample condition. An example of suppression in response to the remote sample moving in the preferred direction, presented at 5.5° eccentricity, centered 11° diagonally across the fixation point from the center of the RF. As in *B*, all trials shown included a preferred sample, whereas the test could be either preferred or anti-preferred.

two bootstrap distributions of latencies are pooled. Two sets of latency values, equal in size to the real cell numbers, are then randomly selected without replacement and their means are compared. This procedure was repeated 1,000 times. The level of significance was calculated as a proportion of instances in which the difference between the randomly sampled means was greater than the difference between the real means.

DIRECTION SELECTIVITY. Responses were defined as being direction selective (DS) if firing rates during preferred and anti-preferred motion were statistically different for ≥100 ms of the stimulus ($P < 0.0056$, Bonferroni corrected unpaired *t*-test). The magnitude of directionality was calculated using a directionality index [DI = (preferred − anti-preferred)/(preferred + anti-preferred)]. To quantify the reliability of directional bias in the neuronal responses we used a receiver operator characteristic (ROC) measure (Bisley et al. 2004; Britten et al. 1992).

ROC ANALYSIS. This measure allows one to compute the probability with which, on the basis of firing rates, an ideal observer can reliably classify stimulus direction as preferred or anti-preferred. A value of 0.5 indicates that a given firing rate could have been elicited with equal probability by the preferred or anti-preferred stimulus. A value of 1.0 indicates that a response to the preferred stimulus was always greater than a response to the anti-preferred stimulus. Conversely, a value of 0 indicates that a response to an anti-preferred stimulus was always greater than to the preferred stimulus. The ROC values were calculated for a 100-ms bin slid in 25-ms increments throughout the duration of the stimulus. To test the significance of each ROC value, we used a permutation test. This was done by randomly redistributing firing rates for all the trials into preferred and anti-preferred groups, irrespective of the actual sample direction associated with each trial. An ROC value was then calculated from the redistributed groups, and the process was repeated 2,000 times, creating a distribution of ROC values. The real ROC value was deemed significant if it fell in the top or bottom 2.5% of the distribution (or $P < 0.05$, 2-tailed test).

CHOICE PROBABILITY. We used a virtually identical ROC-based method to calculate the choice probability (CP) of the MT responses (Britten et al. 1992, 1996). This measure relates firing rates to the

sample direction indicated by the monkey's decision rather than the actual sample direction. CP was evaluated in trials where the sample contained 360° range, having no net direction. In these trials, the monkey nevertheless had to indicate whether the coherent test was the same or different from the sample, thereby indicating what they perceived or remembered the sample direction to be. The significance of CP for individual neurons was evaluated with the permutation test described in the preceding text.

ERROR ANALYSIS. To compare responses during correct and error trials, the stimulus period was divided into five 100-ms epochs. Activity across all five epochs was compared with baseline by a two-way ANOVA. Firing rates in each epoch for correct and error trials were compared by a Bonferroni corrected t-test ($P < 0.01$ required for significance). This analysis was limited to neurons having at least two error trials for each sample direction.

RESULTS

We recorded from MT of two monkeys while they compared the motion of two random-dot stimuli, one or both of which appeared outside of the neuron's RF (see diagrams in Fig. 1, B–D).

The two comparison stimuli, sample and test, were separated by a 1.5-s delay, and the monkeys reported whether they moved in the same or different directions by pressing one of two response buttons. We used four test conditions in which the locations of sample and test were manipulated with respect to the position of the cell's RF. For each neuron, the location of remote stimulation was chosen to ensure the largest possible distance from the RF while remaining at the same eccentricity. Remote stimuli were always in the hemifield opposite from the RF and always in a horizontally and vertically noncorresponding location. No neurons used in the study had RFs that crossed the vertical meridian, and the average eccentricity for the population of 127 recorded (69 and 58 from the 2 monkeys, respectively) neurons was $7.3 \pm 0.33°$ (mean $\pm$ SE). Examples of neuronal activity for three of these conditions are shown in Fig. 1. When the sample and test, moving in the preferred direction, appeared in the RF (Fig. 1A), the cell responded strongly to both stimuli. Recordings from the same neuron when only the sample was presented outside of its RF, originally mapped in the upper right visual field, revealed a significant increase in the neuron's firing rate (Fig. 1B). In a separate block of trials, the same neuron was tested with sample in the RF and the test in a remote location (Fig. 1C). Under these conditions, the response of that neuron to the remote test was similar to its response to the remote sample shown in Fig. 1B. We also found neurons that suppressed their activity during the remote sample or test in a manner similar to that shown for an example neuron in Fig. 1D.

Remote responses: incidence and directionality

Responses to remote stimuli were recorded in blocks of trials, generally with only one of the stimuli, either sample or test, appearing outside of the RF. We classified each neuron as having been significantly excited or suppressed by sliding a 100-ms bin in 50-ms steps along the spike train throughout the stimulus duration and requiring at least one bin to significantly deviate from baseline ($P < 0.0056$; Bonferroni corrected unpaired t-test). This analysis revealed that among neurons tested with the remote sample ($n = 116$; see Fig. 1, B and D),

58% responded either with excitation (22%, $n = 25$) or suppression (36%; $n = 41$). A small subset of neurons (4%; $n = 5$) had periods of both excitation and suppression, whereas activity of the remaining 38% was not discernable from baseline. Among neurons examined with the remote test ($n = 88$; Fig. 1C), 71% showed significant responses. Among those, nearly 40% ($n = 35$) were excited, 31% ($n = 27$) were suppressed, and the rest ($n = 26$) remained at baseline. Of neurons with significant responses, ~60% ($n = 42$) were strongly affected by sample direction and the rest were nondirectional (Fig. 2A). During the remote test (Fig. 2D), this number was smaller, dropping to 30% ($n = 18$). Average responses of cells with directional (Fig. 2, B and E) and nondirectional (Fig. 2, C and F) excitatory (blue curves) and suppressive (red curves) responses are presented separately for the remote sample (Fig. 2, B and C) and the remote test (Fig. 2, E and F). Figure 2, B and C, shows the response to the sample. Note that both excitation and suppression persisted for ~200 ms into the delay. Responses to the test that occurred after its offset were not recorded since at this time fixation was no longer required (Fig. 2, E and F).

DIRECTIONAL EXCITATION. The activity in response to the direction determined as *preferred* with stimuli in the RF was *also preferred* when the stimuli were remote (compare solid and interrupted blue curves). However, this directional preference was transient and significant only during the 100- to 200-ms period of either remote stimulus ($P < 0.01$ for both stimuli, paired t-test). The excitatory response to the *anti-preferred* direction increased gradually with time and its magnitude in the final 300 ms of the response was not different from that elicited by the preferred direction ($P < 0.0056$, Bonferroni corrected paired t-test). About 80% of neurons (20/25) excited during the remote sample showed such directional responses. The relative number of directional neurons during the remote test was lower (Fig. 2, A and D).

We also found that the average directionality index (DI) for the response to remote sample was substantially lower than the average DI for the response to sample in the RF (0.30 ± 0.05 vs. 0.69 ± 0.02; means $\pm$ SE). We examined whether individual neurons with stronger directionality in the RF were more likely to have greater directionality of responses to the remote sample and found no correlation between the DIs for the two stimulus conditions ($r^2 < 0.1$, linear regression).

DIRECTIONAL SUPPRESSION. The average suppressive responses to the remote sample and test were also DS, being driven primarily by the direction determined as *preferred* under the standard mapping conditions. This suppressive response became maximal during the last 300 ms of the stimulus ($P \ll 0.01$ for both sample and test, unpaired t-test). The incidence of such responses was substantially higher during the remote sample than during the remote test (Fig. 2, A and D).

NONDIRECTIONAL RESPONSES. Many neurons with significant remote responses did not show directional bias. Such responses were particularly prevalent during the remote test, accounting for 63% (22/35) of excitatory and 81% (22/27) of the suppressive responses. These responses were somewhat less common during the remote sample, accounting for 20% (5/25) of excitatory and 49% (20/21) of the suppressive responses. As seen in Fig. 2, nondirectional responses tended to be at least a factor
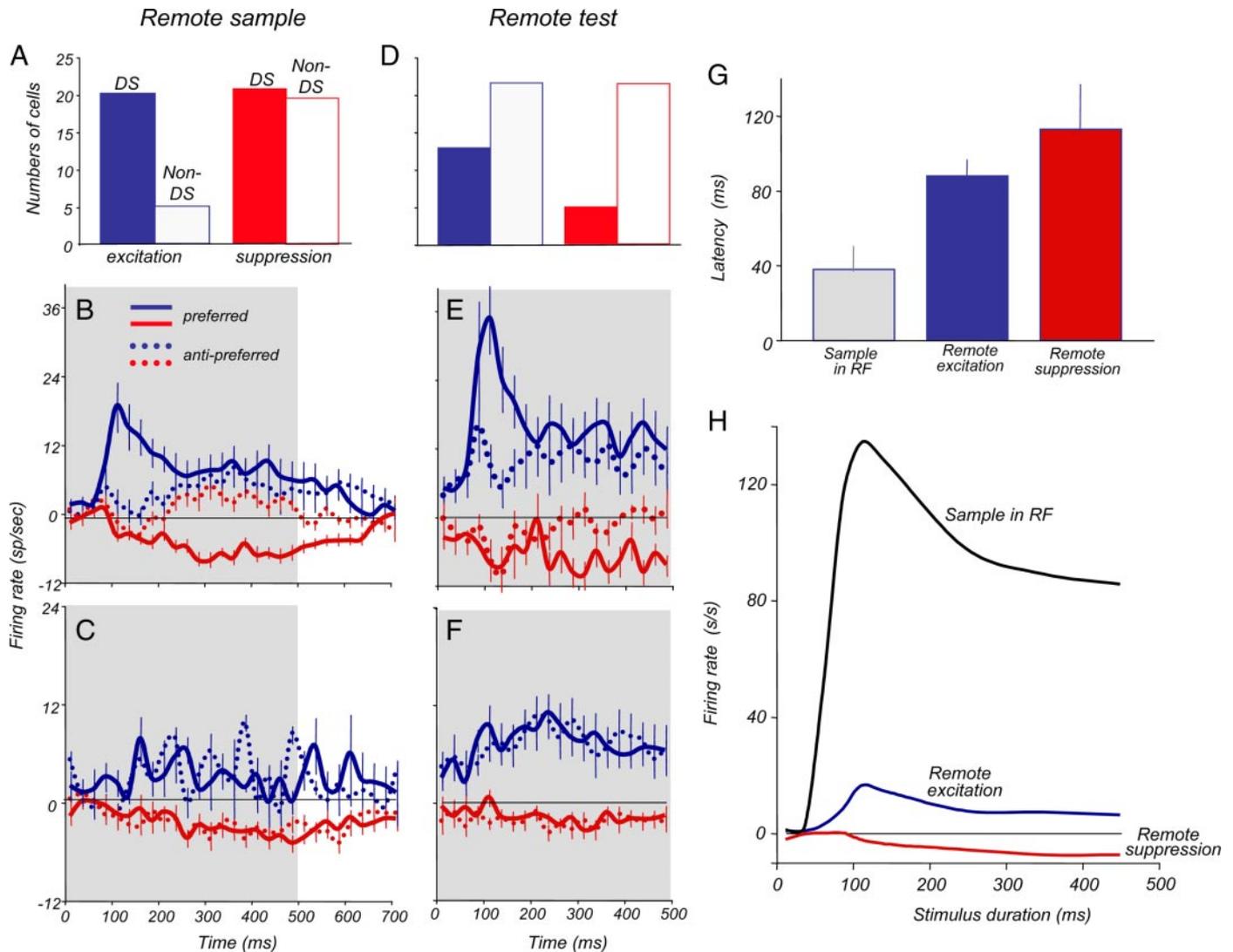
FIG. 2. Responses to remote sample or remote test. *A* and *D*: incidence of neurons with directional (DS, filled columns) and nondirectional (non-DS, unfilled columns) responses to remote sample and test. Cells with excitation (blue) or suppression (red) are shown separately. *B–F*: average responses during trials with stimuli moving in the preferred (solid line) and the anti-preferred directions (interrupted line) are shown for neurons responding with excitation (blue) and suppression (red). Responses are plotted separately for direction-selective (*B*) and nondirectional (*C*) responses to the sample as well as directional and nondirectional responses to the test (*E* and *F*). Directional responses, both excitatory and suppressive, were driven primarily by stimuli deemed preferred by the RF. All plots reflect firing rates calculated in consecutive 25-ms epochs after subtracting the baseline rate. Error bars: ±SE. The numbers of cells contributing to each pair of curves (preferred and anti-preferred) are shown in *A* and *D*. Shaded regions in *B, C, E,* and *F* indicate the presence and the duration of the stimulus. Only the 1st 200 ms of the delay, which began at 500 ms, is shown (*B* and *C*). *G*: average latencies of remote responses computed for neurons with direction-selective responses. Error bars represent bootstrap estimates of variance in the population latencies (see METHODS). Remote excitation, $n = 20$; remote suppression, $n = 21$; in RF, $n = 41$. *H*: relative magnitude of remote responses. Only responses to the preferred direction are shown. Excitation, $n = 20$, suppression, $n = 21$. The average response to stimuli in the RF is shown for neurons that contributed to the 2 remote response curves ($n = 41$).

of two weaker than the maximal directional responses. This difference may be indicative of the directional and nondirectional responses being supported by different mechanisms.

REMOTE TEST VERSUS REMOTE SAMPLE. In our task, identical stimuli could appear as a sample or as a test, but task demands during the presentation of these stimuli were different. During the sample, the monkey identified and retained its direction, whereas during the test, in addition to identifying test direction, it also had to compare it to the preceding sample. In the subset of neurons ($n = 12$) for which we had data for both remote sample and test conditions, the magnitude of the first 100 ms of the average test response was significantly greater than the average response to the sample ($P < 0.01$, paired *t*-test). This

difference was not detectable in neurons with suppression ($P > 0.5$, paired *t*-test, $n = 11$). It is likely that the difference in the strength of excitation is due to the difference in task demands during the sample and the test and could be related to the anticipation of the comparison process.

RESPONSE LATENCIES. The two types of remote responses also differed in their time course. To reliably determine the precise time at which these responses began, we measured the latency of the average population response to the preferred direction and estimated the variance using a bootstrap method (see METHODS). This was necessary because of the low firing rates of remote responses. With this approach, we determined that the average excitatory response to remote stimuli began 88 ± 9.4

(SD) ms after stimulus onset, while the suppressive response began 113 ± 24.8 ms after stimulus onset (Fig. 2*G*), significantly later than the excitatory response (*P* < 0.001, 2-sample bootstrap hypothesis test). There were no detectable differences between the latencies of directional and nondirectional responses. For comparison, the latency of the conventional response of the same group of neurons was 38 ± 13.2 ms, significantly shorter than either of the remote responses (*P* < 0.001, 2-sample bootstrap hypothesis test in each case). This value was similar to that recently reported by Bair et al. (2002) and earlier by Maunsell (1987) but shorter than the latencies reported by two other studies (Raiguel et al. 1999; Schmolesky et al. 1998). We verified the accuracy of our approach by determining individual response latencies for stimuli placed in the RF as the time at which activity of a given neuron exceeded the baseline by ≥2 SD. This measure provided the value of 44 ± 13 ms that corroborated the value derived from the population average. Thus the remote excitation and suppression were delayed 50 and 75 ms, respectively, relative to the conventional response to stimuli in the RF.

DISTANCE OF REMOTE STIMULATION FROM CLASSICAL RF. Our study uncovered two major types of remote responses, excitation and suppression. These two distinct patterns of activity did not depend on the RF size, eccentricity, or the distance of remote stimulation from the cell's RF. The data in Fig. 3*A* show the distribution of RF sizes as a function of eccentricity for subsets of neurons color coded to indicate whether they showed excitation, suppression, or no activity in response to a remote stimulus. The linear fit to the data yielded a slope of 0.43 and a *y* intercept of 1.8 ($r^2 = 0.51$), a result that is consistent with previously published accounts of RF properties in MT (Albright and Desimone 1987; Desimone and Ungerleider 1986). The mean RF size for all recorded neurons was 5.0 ± 2.3° and the mean eccentricity was 7.3 ± 3.3°. The size or eccentricity of the neuron's RF was not related to the presence or nature of responses to remote stimuli (*P* > 0.6, ANOVA). Figure 3*B* shows how the distance between the RF and remote stimulus centers varied as a function of RF size. The linear fit yielded a slope of 2.09 and a *y* intercept of 3.5 ($r^2 = 0.51$), indicating that the edges of RF and remote stimuli were, on average, >3.5° apart. Figure 3*C* shows the distribution of center-to-center distances between the neurons' RF and site of remote stimulation. For neurons responding with excitation, the average distance from RFs was 13.8 ± 6.2°, for neurons showing suppression, it was 13.1 ± 5.9°, and for neurons that did not respond to remotely placed sample, the average separation from RFs was 15 ± 7.8°. The plot demonstrates that the distance of RFs from remote stimuli in the ipsilateral visual field had no bearing on the presence or the nature of remote responses (*P* > 0.4, ANOVA).

TEMPORAL DYNAMICS OF REMOTE DIRECTIONAL RESPONSES. The time course of the directional response differed in excitatory and suppressive responses. During the excitatory response, its direction selectivity was transient, occurring relatively early in the response. On the other hand, the directional response during the suppression developed relatively late and persisted for several hundred milliseconds. To directly compare the dynamics of these directional signals, we computed ROC values (see METHODS) for the two types of responses. The data, shown in Fig. 4, illustrate the presence and complementary
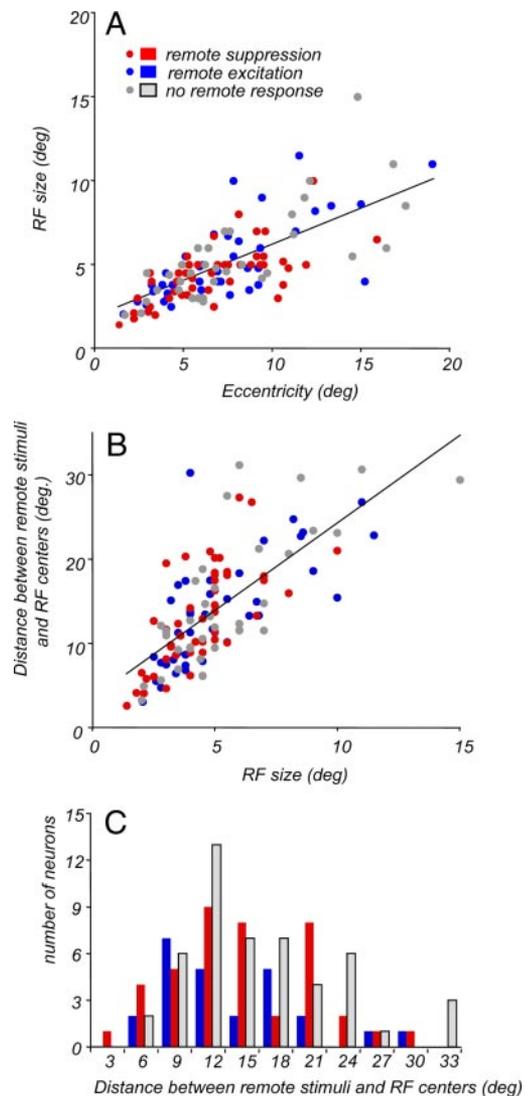

FIG. 3. RF sizes and locations of remote stimulation in MT. *A*: RF sizes and their eccentricities for all recorded neurons. The data are grouped by the nature of response to remote stimuli. The plot shows that remote excitation and suppression do not depend on the size of the receptive field or its eccentricity. The result of a linear fit ($r^2 = 0.51$; $y = 0.43x + 1.84$) is consistent with other estimates of the relationship between MT RF sizes and eccentricity (Albright and Desimone 1987; Desimone and Ungerleider 1986). *B*: relationship between RF sizes and the distance between the remote stimuli and RF centers. A linear fit ($r^2 = 0.51$; $y = 2.1x + 3.5$) shows that the edge of a remote stimulus was generally >3.5° removed from the edge of the corresponding RF. *C*: separations between remote locations and RFs of individual neurons. The data are grouped as in *A*. The plot demonstrates that the distance of RFs from remote stimuli in the ipsilateral visual field had no bearing on the presence or the nature of remote responses. The distributions of distances for neurons that did not respond to remote stimulation (gray) as well as those with excitatory (blue) or suppressive (red) responses were statistically inseparable (*P* > 0.25, ANOVA).

nature of a relatively constant reliable directional signal throughout the duration of the remote stimulus. Although the directionality of remote responses was weaker than that of responses to stimuli in the RF (see preceding text), these directional signals were highly significant for both excitation (during 75–225 ms, *P* ≪ 0.001 at each time point, Bonferroni corrected *t*-test) and suppression (during 225–450 ms, *P* ≪ 0.001, Bonferroni corrected *t*-test).
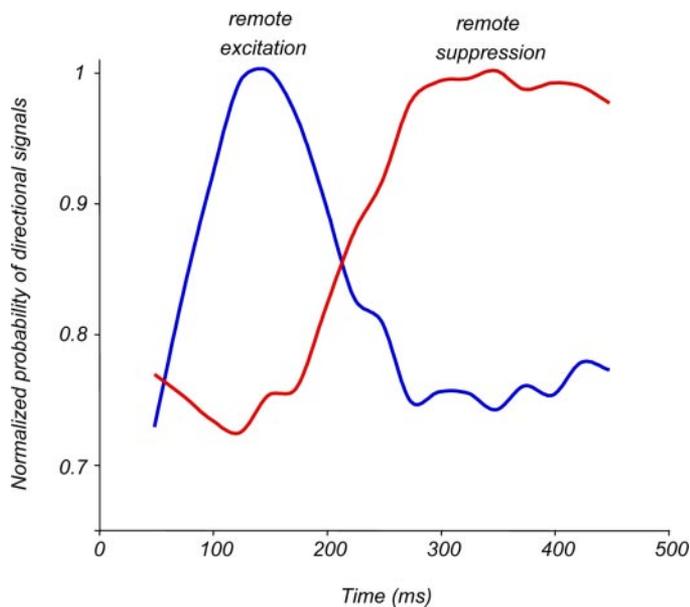
FIG. 4. Time course of direction selective signals in remote responses. Normalized average direction selectivity computed with ROC analysis for neurons with excitatory (blue curve) and suppressive (red curve) responses to remote stimulation. ROC analysis was performed by sliding a 100-ms time bin along the spike train in 25-ms steps and is shown only for neurons with significant directional responses, seen in Fig. 3, *B* and *E*. Stronger suppression for the preferred direction resulted in ROC values <0.5, and the curve has been inverted for visualization purposes. Each curve was normalized to its maximal ROC value.

Trials with remotely presented sample and test

To determine whether the remotely driven activity is also present when no stimuli used in the task appear in the RF, we tested a subset of neurons with both sample and test presented remotely (*n* = 49). The results were nearly identical to those observed when only one stimulus was remote. During the sample, 24% (*n* = 12) of these neurons responded with significant excitation, the majority of which (*n* = 9) were DS, whereas 43% (*n* = 21) were suppressed, of which seven had significant directional bias. During the test, 41% (*n* = 20) were excited and 18% (*n* = 9) were suppressed. Among these, 12 excited and 3 suppressed neurons showed significant directional bias. We also found that under these conditions, the initial 100 ms of the excitatory test response was greater than the same period of the sample response (*P* < 0.05, paired *t*-test). In summary, the pattern of these results was similar to those obtained with only one of the stimuli presented remotely, suggesting that the remotely driven activity does not require the involvement of the classical RF.

Remote responses reflect motion coherence

MT neurons have been shown to perform integration of local motion signals (e.g., Movshon et al. 1985). This property has been recently demonstrated with random-dot stimuli containing a range of local directions (Bisley et al. 2004). We examined whether remote responses carry motion integration signals similar to those observed in conventional MT responses (Bisley et al. 2004). During each testing session, the sample stimuli consisted of local motion vectors with narrow or broad distributions of directions (Fig. 5*A*). Responses to such stimuli

presented in the RF and during remote stimulation are shown in Fig. 5.

When the sample was presented in the RF (Fig. 5*B*), the response to the preferred net direction decreased with increased direction range, whereas the response to the anti-preferred direction increased, and the directionality of this response was preserved even at 300° range (*P* ≪ 0.001, paired *t*-test). When
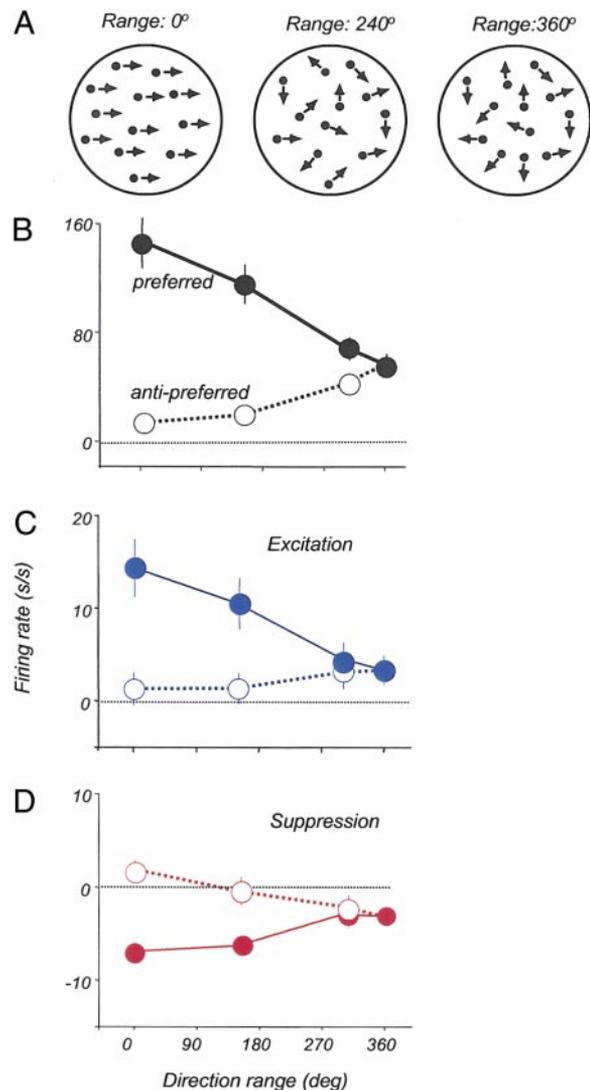

FIG. 5. Effect of motion coherence on responses to remote sample. *A*: direction range stimuli used during the task. At 0° range, all dots in the stimulus moved in the same direction; at 240° range, individual dots moved in any direction within ±120° around the mean. At 360° range, direction of individual dots was unconstrained (random local motion). During each recording session direction range thresholds were measured with stimuli containing 0, 150, 300, and 360° range presented at random using the method of constant stimuli. *B*: effect of direction range on average response to sample presented in the receptive field. Each data point represents the activity recorded during the epoch of 100–200 ms after stimulus onset, the period of maximal excitatory response to the remote sample (see Fig. 2*B*); *n* = 41. The direction range was strongly reflected in firing rates during either a preferred (—, ●) or an anti-preferred (· · · , ○) sample. *C*: effect of direction range on average excitatory response to a remote sample of neurons shown in *B*. As in *B*, each data point represents activity during the 100–200 ms epoch; *n* = 20. *D*: effect of direction range on average suppressive remote response of neurons shown in *B*. Each data point represents activity recorded during the 400–500 ms epoch, the period of maximal suppression (see Fig. 2*B*); *n* = 21. Baseline was subtracted from firing rates in all plots. Error bars: ±SE.

the sample was remote, the directional bias of the excitatory response (Fig. 5*C*) was preserved at a broader 150° range ($P <$ 0.01, paired *t*-test), and there was a significant difference in firing rates in response to 0 and 360° range ($P < 0.01$, paired *t*-test), although the neurons could not distinguish between net directions when the range reached 300° ($P > 0.2$, paired *t*-test). Suppressed remote responses also showed the dependence on the direction range (Fig. 5*D*), decreasing with increased direction range, and the response to random motion (360° range) was significantly lower than that to a 0° range ($P < 0.001$, paired *t*-test). Furthermore, the directionality was preserved at a 150° range ($P < 0.01$, paired *t*-test) but not at 300° range ($P > 0.5$, paired *t*-test). The nature of the relationship between the direction range and neural activity demonstrate that motion integration signals, commonly observed in conventional MT responses, are also characteristic of responses to stimuli appearing in the ipsilateral hemifield.

While the dependence of neural activity on direction range was similar for both remote and conventional responses, the relationship between these responses and behavioral performance was not. Although the monkeys made errors with 300° range sample, their performance remained at a relatively high level, averaging nearly 80% correct. With this stimulus in the RF, MT neurons also reliably discriminated between the preferred and anti-preferred directions (Fig. 5*B*; $P \ll 0.001$, paired *t*-test). However, when the same sample was remote, MT responses failed to distinguish between the two directions. This dissociation between neural activity and behavioral performance suggests that remote responses were unlikely to contribute to the behavioral choice made by the monkeys. This hypothesis is supported by the analysis of choice probability described in the next section.

Choice probability

The relationship between the neural activity and the monkeys' behavior was examined by calculating choice probability (CP, see METHODS for details) during trials with an ambiguous sample containing 360° range. For neurons with direction-selective remote responses, CP was calculated both for the remote and in RF responses. For blocks of trials with sample in the RF, the average CP was 0.54, a value significantly above chance ($P < 0.01$, *t*-test) and consistent with previously published MT data (Britten et al. 1992, 1996). For the remote responses, CP values averaged at 0.49 and were not significantly different from chance ($P > 0.5$, *t*-test). The lack of significant CP in the remote responses suggests that the monkeys may not directly use this activity for perceiving sample direction, supporting the dissociation between behavioral performance and neural activity on trials with 300° sample.

Activity on error trials

Although the firing rates during remote responses were not predictive of the monkeys' choice of direction, their presence appeared to be related to the animals' behavioral state. This relationship was revealed by the analysis of neuronal activity on error trials. As errors were almost never made when the sample motion was coherent (0° range), the data for this analysis came from more challenging trials in which the sample contained direction range of 300°. Under these condi-

tions, remote sample responses were weaker but still detectable (Fig. 5, *C* and *D*). Because no differences were found in error effects for either stimulus or sign of response between DS and non-DS neurons ($P > 0.3$ in each case, ANOVA), their responses were evaluated together. As average firing rates were higher for responses to the remote test and substantially higher for responses in the RF, the rates of individual neurons in each group were normalized to their strongest response during correct trials.

RESPONSES TO REMOTE SAMPLE. Fig. 6*A* compares the normalized activity of neurons with excitatory and suppressive responses to the sample moving in the preferred direction on correct and error trials. It shows that on error trials, both types of responses were largely absent. While on correct trials the average excitatory activity during the 100- to 300-ms period was significantly different from baseline ($P < 0.01$, *t*-test with Bonferroni correction), on error trials it was significantly lower ($P < 0.01$, paired *t*-test with Bonferroni correction) and did not deviate from baseline ($P > 0.85$, ANOVA). Similarly, on correct trials significant suppression was present during the last three epochs ($P < 0.01$, *t*-test) but absent on error trials ($P > 0.6$, *t*-test). Furthermore, responses to the preferred and the anti-preferred sample did not differ at any time, whether on correct (see Fig. 5, *C* and *D*, 300° range) or error trials, excitation or suppression ($P > 0.3$ in all cases, ANOVA). Thus the association of remote responses with behavior of the monkey was not direction specific, confirming the choice probability analysis.

It is noteworthy that the responses of the same neurons on correct and error trials recorded with sample presented in the RF (Fig. 6*C*) showed no detectable differences at any time during the stimulus ($P > 0.9$, ANOVA).

RESPONSES TO REMOTE TEST. We also performed a comparison of remote test responses on correct and error trials in which the sample contained 300° direction range (Fig. 6*B*). In contrast to the activity during the remote sample, both excitatory and suppressive responses were still significant on error trials ($P < 0.05$ in each case, ANOVA). There were no differences between responses during correct and error trials either in the case of excitation or suppression ($P = 0.86$ and $P = 0.13$, respectively, ANOVA) The difference in the effects during sample and test complements the observation of the difference between responses to the remote sample and the remote test and further strengthens the association between remote responses and the behavioral state of the animal.

DISCUSSION

We have shown that during the delayed direction discrimination task, many MT neurons responded to visual motion far removed from their classical RFs. These responses took the form of either excitation or suppression and were affected by the direction and the level of coherence of the remote stimuli. The two types of responses were characterized by different and complementary temporal dynamics and had long latencies when compared with conventional responses of MT neurons. They were absent on error trials during the sample and thus likely reflected the behavioral state of the animal. Finally, the magnitude of these responses and their presence on error trials depended on whether the remote stimulus appeared as a sample or a test, suggesting modulation by task demands.
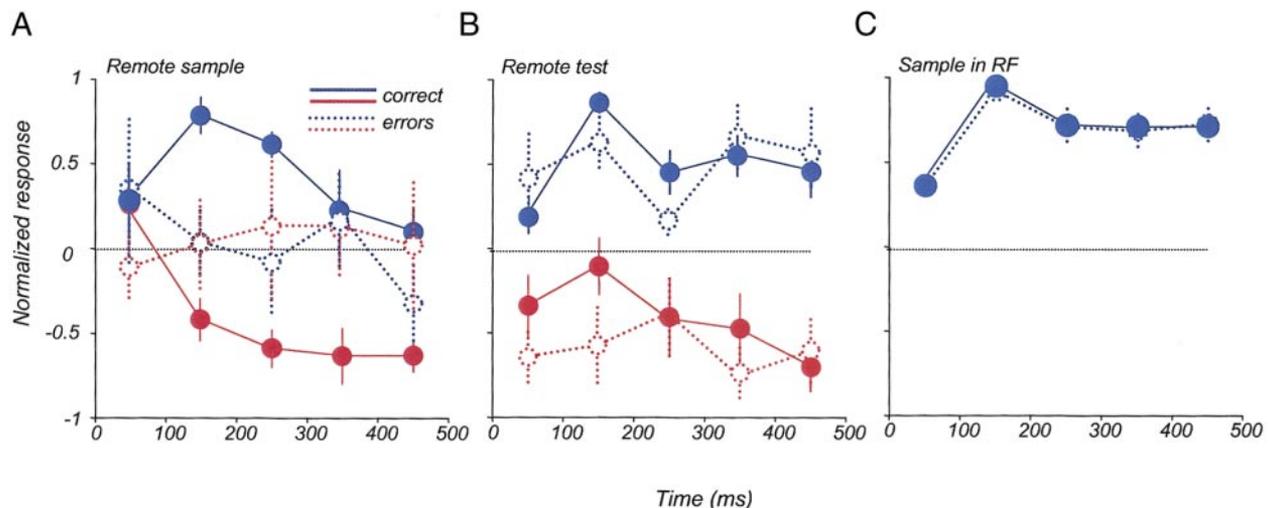
FIG. 6. Remote responses on correct and error trials. *A*: average normalized excitatory (blue curves) and suppressive (red curves) responses to the remote sample on trials with direction range set to 300°. Only neurons with sufficient number of errors were used (on average ≥4 error trials). On correct trials, remote excitation during the 100- to 300-ms period was significantly different from baseline ($P < 0.01$, t-test, Bonferroni correction) and from the activity on error trials (filled blue symbols, solid blue curves; $P < 0.01$, paired t-test, Bonferroni correction). On error trials, the average activity was not significantly different from baseline at any time ($P > 0.85$, ANOVA). Suppression, present during the last 3 epochs ($P < 0.01$, t-test with Bonferroni correction) on correct trials, was absent on error trials ($P > 0.6$, t-test, Bonferroni correction); $n = 25$ (10 excited; 15 suppressed). *B*: average normalized activity of responses to the remote test, recorded on trials with 300° of range in the sample. Both correct and error responses, for both excitation and suppression, are significantly different from baseline ($P < 0.05$, ANOVA). The magnitude of excitation did not significantly differ between correct and error trials ($P = 0.86$, ANOVA). Likewise, the magnitude of suppression did not differ between correct and error trials ($P = 0.13$, ANOVA). $n = 22$ (12 with excitation; 10 with suppression). *C*: average normalized activity of responses to the sample in the RF, calculated for neurons with remote excitation shown in *A*. Responses during correct and error trials were indistinguishable ($P > 0.9$, ANOVA). Error bars: ±SE.

Origin of remote responses

Robust responses to stimuli distant from the classical RF have not been reported previously and present a challenge to the concept of a RF. Before discussing the nature and implications of these unusual responses, we should consider a possibility that they were due to inadvertent stimulation of the classical RF by extraneous stimuli, such as the display having nonuniformities or small eye movements across the monitor. This is unlikely for several reasons. First, during each trial the monkey's fixation was tightly constrained and remained well within a 1.5° window (see METHODS). Second, the stimuli were displayed on a large, uniformly dark monitor covering about 40° area containing no visible features, other than the stimuli used in the task, that would stimulate a neuron's classical RF. Furthermore, although small saccades have been shown to elicit transient activity in MT, they last no longer than 40 ms (Bair and O'Keefe 1998), a period too short to account for remote responses lasting several hundred milliseconds and highly selective for both the direction and coherence of motion. Such responses could have been elicited by a series of small saccades only if these saccades were all taken in the same direction, which was not possible within the constraint of a small fixation window.

It is also unlikely that these responses arose as a consequence of either the interhemispheric connectivity within MT or the activation of large surround components of the RFs. During each recording session, remote stimulation was limited to the location contralateral and opposite to that of the RF to take advantage of the nature of interconnections between MTs in the two hemispheres. While there are prominent connections between the spatially matched RF locations in MT in the two hemispheres, sometimes at some distance from the representation of the vertical meridian (Krubitzer and Kaas 1990;

Maunsell and Van Essen 1987), there are no known connections between the representations of the upper and lower fields in the opposite hemifields (L. G. Ungerleider, personal communication). Furthermore, because RFs in MT are limited in size and rarely extend into the ipsilateral hemifield by more than a few degrees (Albright and Desimone 1987; Bisley et al. 2004; Desimone and Ungerleider 1986; Maunsell and Van Essen 1987), stimuli placed in the ipsilateral hemifield as far as 10–15° away would be unlikely to fall within the neuron's classical RF.

MT neurons do possess large suppressive or enhancing surrounds (Allman et al. 1985; Tanaka et al. 1986; Xiao et al. 1995, 1997), and it is conceivable that the remote responses could be a result of stimulation of these surrounds. However, this is unlikely because stimulation of the surround has generally been shown to modulate responses, usually in the form of attenuation (e.g., Tanaka et al. 1986; Xiao et al. 1997). It should be noted, however, that these studies have not examined the surrounds in the absence of a visual stimulus in the RF. There was one report of weak excitatory responses to disparity stimuli placed in the surround of MT RFs (Bradley and Andersen 1998). However, because of the stimulus proximity to the RF center, the authors concluded that these responses were due to slight overlap with the central RF. Thus although we cannot rule out the possibility that the remote responses are a reflection of surround stimulation, the existing studies of MT surrounds and the nature of remote responses make this possibility highly unlikely.

Nevertheless, the directionality (weaker as it may be) of the remote responses and the nature of their dependence on stimulus coherence strongly suggest the involvement of contralateral DS neurons. One likely scenario is that these signals are generated in the contralateral MT and are passed on to a

cortical region with access to information from the entire visual field and the information about task demands, which in turn sends these signals down to the MT located in the opposite hemisphere. Indeed, the latencies of the excitatory and suppressive remote activity exceeded the latencies of conventional responses in MT by some 50 and 75 ms, respectively, a lag time long enough for the information processed in the contralateral MT to be passed through a multi-synaptic circuit. Similar delays were reported in a study that investigated the top-down contribution of PFC to task-related activity in inferotemporal cortex (Tomita et al. 1999). Precisely which cortical area(s) may contribute to the circuitry underlying the observed effects is unclear. One possibility is that remote responses represent top-down influences coming down from an area like the PFC, which, in addition to sensory signals, carries information about the behavioral state of the animal (Miller 2000). A number of studies have shown that feedback from dPFC plays an important role in enhancing selectivity during cue and memory delay periods in several cortical areas, including inferotemporal and parietal cortices (Chafee and Goldman-Rakic 2000; Fuster et al. 1985; Tomita et al. 1999). The property of exerting executive control over task performance makes dPFC a more likely candidate as the source of top-down signals than other cortical areas, such as MST, which has strong connectivity with MT and spatially extensive visual response fields (Desimone and Ungerleider 1986). Although currently there is no direct evidence that PFC neurons are involved, they are interconnected with MT (Barbas 1988; Schall et al. 1995), respond to visual motion (Kim and Shadlen 1999; LaMendola et al. 2004), and are strongly modulated by task demands and the behavioral state of the animal (Miller 2000).

Possible mechanisms

The phenomenon we observed is likely to be related to recent reports that the activity of MT neurons can be modulated by attention and task demands. Several of these studies have shown that allocating attention to a neuron's RF can have profound effects on its responses to visual motion (Cook and Maunsell 2002; Recanzone and Wurtz 2000; Seidemann and Newsome 1999; Treue and Maunsell 1996, 1999). Furthermore, Treue and Martinez-Trujillo (Martinez-Trujillo and Treue 2004; Treue and Martinez Trujillo 1999) reported that when attention is directed to a given direction of motion appearing in the hemifield opposite to the neuron's RF, responses to the same direction presented in the RF are enhanced while responses to the opposite direction are suppressed. A similar phenomenon has also been observed in an fMRI study (Saenz et al. 2002). Treue and Martinez-Trujillo termed this phenomenon feature-based attention and proposed that attention may be acting on MT neurons in a nonspatial, feature-based fashion, enabling cognitive control over the ability to enhance the processing of behaviorally relevant motion information.

Our data also demonstrate that MT neurons are strongly affected by stimuli appearing at distant locations. Indeed, it is possible that the remote responses reported here and feature-based attentional modulation characterized by both excitatory and suppressive effects (Martinez-Trujillo and Treue 2004) may depend on the same top-down mechanisms. This idea is supported by some of the properties of the remote signals, including its stimulus specificity, and their opponent nature. Long response latencies are consistent with the signal having traveled up through the sensory pathways in the contralateral hemifield and subsequently descended ipsilaterally by way of neurons that monitor the entire visual field (Tomita et al. 1999). Furthermore, presence of both excitatory and suppressive responses is consistent with previous reports of the nature of top-down signals from PFC, and mechanistically accounted for by the presence of corticocortical projections that in a confined region can target both excitatory glutamatergic pyramidal neurons and inhibitory GABAergic interneurons (Chafee and Goldman-Rakic 2000; Fuster et al. 1985; Somogyi et al. 1998). Additional experiments are needed to ascertain whether signals observed here are indeed mechanistically linked with feature-based attention. Without confirmation of a modulatory role for these signals, one may speculate on alternative interpretations of their existence. For example, it is conceivable that the top-down signals result from a more passive associative link between spatial locations. Because the locations of stimuli within any block of trials were predictable, the consistent behavioral pairing of the locations could have enabled signals from contralateral MT neurons to be functionally linked to the relevant ipsilateral MT neurons through top-down gating.

We found that the remote responses were characterized by the different temporal dynamics of excitatory and suppressive activity. Suppressive responses began later and developed slower, becoming most pronounced and most directional 200–300 ms later than the excitatory responses. The timing of the directional signal carried by excitation and suppression was particularly interesting. Directionality in the two response types was similar in magnitude and reliability, occurring early in excitation and late in suppression. The relative importance of these two types of signals is difficult to establish without a better understanding of the circuitry. However, the complementary nature of temporal dynamics and the opposite sign of activity of the two groups of neurons is suggestive of a direct push-pull mechanism and allows for the existence of a consistent directionality throughout the remote response. The differences in the nature and the time course of remote responses may be a result of disparate temporal dynamics associated with excitatory and inhibitory circuits, placing important constraints on modeling the individual contributions of both signal types to top-down influences on activity in visual cortex (Abbott et al. 1997).

Behavioral relevance

Over the past few decades, numerous laboratories recorded from MT under passive viewing in untrained or anesthetized monkeys, and none reported the existence of MT activation by remote stimuli (e.g., Albright and Desimone 1987; Desimone and Ungerleider 1986; Maunsell and Van Essen 1983). Nevertheless, it is conceivable that this activation is a common feature of MT neurons that also exists outside of the behavioral context and has been missed by others because it is relatively weak. Several approaches could be used to address this question. One would require recording activity during the presentation of remote stimuli in passively fixating monkey. Other approaches include determining whether firing rates during ambiguous stimuli predict the behavioral choice (choice prob-

ability, CP), the comparison of behavioral and neural performance under the same stimulus conditions, and the comparison of remote activity on correct and error trials as well as the comparison of neural responses to the same stimuli with different behavioral roles. In this study, we could not assure that under passive fixation condition, our trained monkeys would ignore the remote stimuli. For that reason, we examined the evidence for behavioral relevance of these responses with the alternative approaches listed in the preceding text.

The comparison of remote activity and the monkeys' performance during 300° sample revealed a dissociation between behavior and neuronal responses. Although the neurons failed to distinguish between the preferred and the anti-preferred directions (see Fig. 5, *C* and *D*), the monkeys performed at a relatively high level, averaging 79% correct. Indeed, CPs computed for remote responses to the 360° ambiguous stimulus revealed that they were not predictive of the behavioral choice. This dissociation was in stark contrast to the correlation between neural activity and behavioral performance observed with the same stimuli inside the RF because both the monkeys and MT neurons reliably discriminated between the two directions of 300° sample (see Fig. 5*B*) and showed significant CP for 360° stimuli. Thus our data suggest that in contrast to conventional responses to stimuli appearing in the RF, remote responses are unlikely to be used to form perceptual decisions about stimulus direction.

The absence of the contribution of remote responses to perceptual decisions does not rule out their association with the behavioral state of the animal. The analysis of errors committed during the 300° sample provided insights into this question. It showed that on error trials responses were absent during the remote sample but not during the remote test. There are several possible explanations for this differential effect. First, responses to the 300° sample were weaker than the responses to the coherently moving test, potentially making the effect more difficult to detect. The low variability of responses within each group of neurons, supported by the statistical reliability of the observed effects argues against this possibility. Second, the relatively small number of error trials could have been responsible for our failure to detect remote responses during the sample. This is also unlikely because the numbers of error trials contributing to the analysis of responses to sample and test were similar (on average ≥4 trials). Thus the selective loss of remote responses to the sample and not to the test was most likely related to the difference in the behavioral roles of the two stimuli.

There are many potential sources of errors during our task. For example, the monkey may have failed to identify the sample direction, forgotten it during the delay, or missed either stimulus due to inattention. Given the complexity of the task, it is not possible to identify the source of errors with any certainty. However, the absence of remote responses during the sample and their preservation during the test suggest that errors could have resulted either from a failure of sensory encoding and/or from inattention during of the sample. The nondirectional nature of the error effect and the absence of significant choice probabilities argue against remote responses being utilized in forming the perceptual decision required by our task. Thus the absence of remote responses on error trials is more likely to be associated with the animal's attentional state during the sample.

The evidence in support of the behavioral relevance of these responses also comes from the difference in the strength of the response to the remotely presented sample and test. Specifically, the early epoch of the excitatory response to the remote test was substantially stronger than the corresponding part of the remote response to the preceding sample. Because the appearance, timing, and spatial location of both sample and test were similar and equally predictable, it is likely that higher firing rates in response to the remote test were related to the difference in the unique behavioral roles of the two identical stimuli appearing as the sample or the test. Thus the higher firing rates may be associated with the anticipation of the comparison process, which takes place during the test period.

In summary, we found that 50–70% of MT neurons responded to remotely presented visual motion in the absence of direct stimulation of their RFs. These responses were characterized by high degree of stimulus specificity and opponency in both sign and temporal dynamics. Because of their specificity, it is likely that they originated in MT or another DS cortical area in the opposite hemisphere. We hypothesize that these responses were carried to the recording site by top-down signals from a cortical region monitoring the entire visual field and the behavioral state of the animal. The existence of these signals places constraints on models of cognitive modulation of sensory responses. Future studies will determine the precise source of these unusual responses and their functional implications.

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