Estimating invisible target speed from neuronal activity in monkey frontal eye field

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Working memory involves transient storage of information and the ability to manipulate that information for short-range planning and prediction. The computational aspect of working memory can be probed using dynamic sensorimotor behavior requiring complex stimulus–response mappings. Such a transformation occurs when extrapolating the future location of a moving target that is rendered temporarily invisible. Estimating the trajectory of an invisible moving target requires encoding and storing several target features, including the direction and speed of motion. We trained monkeys to make saccades to the estimated position of invisible targets moving at various speeds. The activity of neurons in the frontal eye field (FEF) was consistently modulated according to the speed of target motion. A reconstruction algorithm showed that estimates of target speed based on FEF activity were similar to behavioral speed estimates. FEF may therefore be involved in updating an internal representation of target trajectory for predictive saccades.

The frontal eye field (FEF) is a region of prefrontal cortex involved in transforming visual input into instructions for voluntary eye movements. Visual response fields of FEF neurons convey information about at least two, and possibly three, spatial dimensions[1,2]. FEF neurons respond in a spatially selective manner during saccade target selection[3]. The FEF receives afferent input from visual areas involved in motion processing[4,5], and its activity is modulated when a saccade target is cued by the direction of a moving stimulus[6]. A small FEF subdivision, the frontal pursuit area, has smooth-pursuit-related activity[7,8], but we know little about the influence of motion parameters such as direction and speed on visual, memory or saccade-related activity in the larger FEF.

One task that requires the integration of motion, working memory and saccade planning is predicting the path of an occluded moving target. Monkeys are able to perform such tasks[9]. To determine if FEF neurons are capable of representing target speed in the absence of a visual stimulus, we trained monkeys to make saccades to targets moving at different speeds that were rendered temporarily invisible before and during saccade execution (**Fig. 1a**). Monkeys tracked the target covertly while fixating on a small spot on the screen. The moving target was extinguished, as if it had passed behind an occluder, for a variable time interval. The task required that upon receiving a 'go' signal (extinction of the fixation spot), a voluntary saccade be initiated to the predicted target location while the target was still invisible. In addition to occlusion (Occ) trials, there were randomly interleaved control trials (**Fig. 1b**) in which the target appeared only near the end of the trial (Late trials).

A critical feature of the task was that the direction and amplitude of the saccade depended not only on the direction and speed of the target, but also on the time elapsed since its disappearance. By adjusting this time interval (the 'occlusion interval'), targets moving at different speeds could be mapped onto a fixed range of saccade amplitudes. Unlike an antisaccade task, where the stimulus–response mapping is one-to-one, the transformation in the occlusion task was many-to-many. Any given stimulus could evoke many different responses, and identical responses could be evoked by different stimuli. Our results suggest that FEF may be involved in the encoding and storage of motion parameters, as well as active updating of predicted target/saccade location based on that stored information.

Results

FEF neurons are known to signal saccade direction and amplitude, as well as whether and when to make the saccade[10–12]. We designed the task to separate the target speed and saccade parameters. To verify this, the latency and amplitude of the first saccade executed after the go signal on occlusion (Occ) trials were estimated from eye position and velocity recorded at the same time as neuronal recordings (**Fig. 2**). There were a total of 15,321 (monkey C) and 12,981 (monkey D) saccades in the analysis. The effect of target speed proved to be statistically significant (one-way ANOVA, $P < 0.0001$) for both metrics in both monkeys. However, the maximum difference in mean amplitude between speeds was relatively modest: 1.2° for monkey C (13% of overall mean, 8.9°) and 1.5° for monkey D (18.5% of overall mean, 8.1°). The difference in saccade amplitude between speed groups was comparable to the range of amplitudes within each group. The maximum differences in mean saccade latency were 50 ms (monkey C) and 44 ms (monkey D).

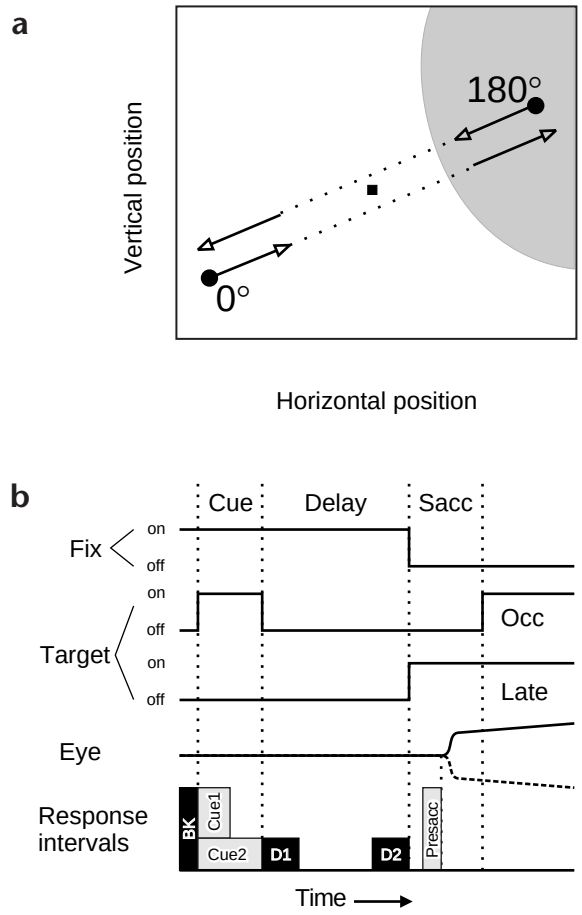

Fig. 1. Predictive saccade task. (**a**) Depiction of video display showing target trajectories. The target paths for the two directions of motion are shown with a slight separation for clarity. In the actual experiment, the paths overlapped. The solid lines indicate portions of the trajectory where the target was visible. Dashed lines indicate where the target was invisible. The small square in the middle of the display indicates the position of the fixation point. The gray patch in the upper right indicates the location of a hypothetical FEF neuron receptive/movement field. (**b**) Trial time structure with definition of the intervals over which neural responses were analyzed.

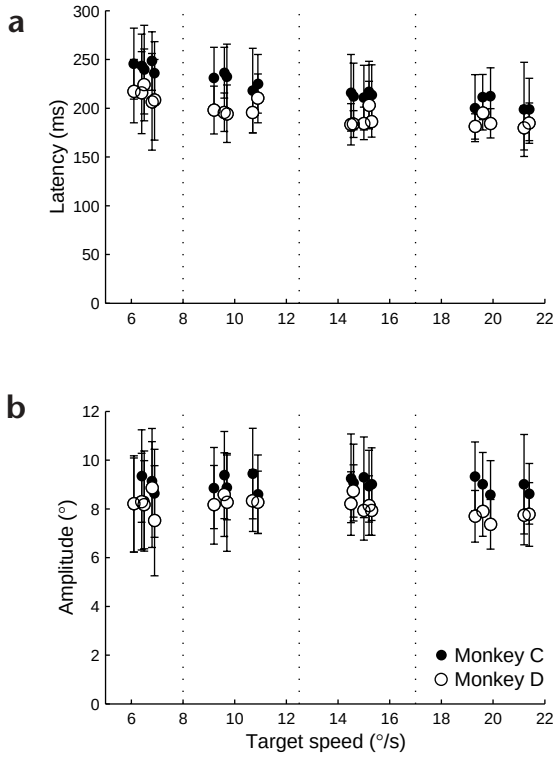

Fig. 2. Saccade latency (**a**) and amplitude (**b**) as a function of target speed. The precise target speeds vary slightly as a function of direction (due to CRT pixelation), but fall into four groups (dashed vertical lines). Error bars are ± s.d.

To estimate the internal representation of target speed, we took the saccade endpoint relative to the center of the display and divided by the time elapsed from when the invisible target trajectory crossed the center of the display to saccade onset. The timing of the go signal varied randomly to allow a range of saccade amplitudes sufficient to estimate the internal representation of target speed. We calculated the mean estimated target velocity (speed and direction) for both monkeys combined (**Fig. 3**). The monkeys tended to overestimate the speed of slow targets and underestimate fast targets. On average, the range of internal speeds spanned 10 °/s, which was two-thirds of the actual speed range. Of 64 estimates, there were no cases in which the ordering of internal target speed did not follow that of the actual target speeds. The probability that this ordering occurred by chance is $1/((4!)^{16}) < 10^{-22}$. This behavior strongly suggests that monkeys plan saccades using an internal estimate of invisible target speed.

To investigate the neural representation of target speed, a total of 292 neurons was recorded in 100 experimental sessions (monkey C, 167/55; monkey D, 125/45), covering most of the functionally-defined FEF[13]. The average firing rates were calculated for six time intervals (**Fig. 1b**): background (BK), cue (Cue1, constant duration; Cue2, constant path), delay (D1, early delay; D2, late delay) and presaccadic (100 ms before saccade onset). We first characterized the population of neurons by classifying them as visual, motor or visuomotor[14] using a sensorimotor index (SMI; Methods equation 3). We found that there was no significant difference between the SMI based on Cue1 versus Cue2 (*t*-test; $P = 0.77$). The SMIs formed a unimodal distribution with a mean not significantly different from zero (mean, –0.02; s.d. 0.39; min. –0.8, max. 1.0). Most cells were tonic-visual or visuomotor; there were few pure visual or pure motor cells.

To determine if FEF neurons carry speed-related signals that may be useful for predicting invisible target motion, we looked for evidence that target speed was encoded during the cue interval and maintained across the delay and presaccadic intervals. The activity of an FEF neuron that prefers fast target speeds is shown in **Fig. 4**. The cell's speed selectivity is carried through all trial intervals, regardless of target visibility. The activity of the same neuron during Late trials is also shown (dashed green lines). There is virtually no evidence of build-up activity when trials are aligned on saccade onset. Hence, this neuron has tonic visual activity, and the visual, delay and presaccadic firing rates all show a similar dependence on target speed. Saccade endpoints for the Occ trials are shown in **Fig. 4h**. There was no significant dependence of saccade amplitude on target direction or speed (two-way ANOVA, direction $P = 0.71$, speed $P = 0.64$).

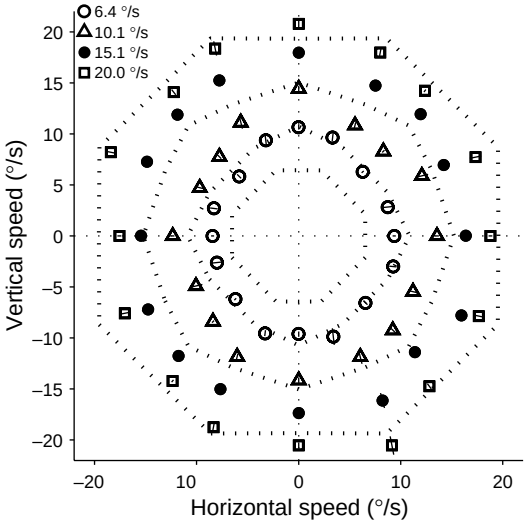

Fig. 3. Internal target velocity estimated from saccade vector and timing. Dotted lines indicate actual target speed. Symbols represent the animals' internal estimate of target speed. The numbers in the legend represent the mean target speed within each group averaged over direction. Error bars are ± s.e.m.

For discrete moving targets, it is not entirely possible to disambiguate speed from the spatial and temporal extent of the target trajectory. The approach taken here was to have the targets move over the same path (orientation and spatial extent) for all speeds. As a result, cue duration varied inversely with speed, in the range 350–1,400 ms (the path length was always 7°). Neuronal activity was then analyzed over both a constant time interval (Cue1) and constant path (Cue2).

A two-way ANOVA (factors: target direction and speed; $P < 0.05$) found 159/292 (54%) and 90/292 (31%) cells with significant effects of direction and speed, respectively, during the Cue1 interval. During the Cue2 interval, 157 (54%) and 139 (48%) neurons showed significant effects of direction and speed, respectively. It was expected that interval duration would affect the results for speed more than direction, as speed is correlated with duration, but direction is not.

The fact that 49 cells showed a speed effect for Cue2 (constant path) but not for Cue1 (constant duration) indicates that speed may be confounded with interval duration. As a control, we recorded activity on randomly interleaved Late trials during which the initial cue never appeared. Of 90 cells with a significant effect of speed during Cue1 on Occ trials, seven (8%) also had a significant speed effect during the same interval on Late trials. For Cue2, the number was 32 neurons out of 139 (23%). The latter is an estimate of the proportion of cells for which the speed effect might be confounded by interval duration, leaving 107 neurons (37% of the total) for which the speed effect was probably not attributable to duration.

If interval duration and target speed affect neuronal activity in a similar manner, then subtracting out the effect of duration should reduce the number of cells showing significant speed effects. To estimate the effect of duration, we calculated mean firing rate, sorted by target speed and direction, during the Cue1 and Cue2 intervals for Late trials. Then, for each Occ trial, mean firing rate was corrected by subtracting the mean activity for Late trials having the same speed, direction and interval duration. This correction was done for each cell. The corrected Occ trials were subjected again to a two-way ANOVA (direction and speed; $P < 0.05$). For Cue1, 136/292 (47%) neurons showed a significant direction effect and 107/292 (37%) showed a significant speed effect. For Cue2, the numbers were 133/292 (46%, direction) and 150/292 (51%, speed). Correcting for the effect of trial duration apparently increased the number of cells showing significant speed effects by about 19% (107 versus 90; 17/90) or 15% (150 versus 139; 21/139). There was almost no change in the proportion of cells with significant direction effects, as expected. The results suggest that temporal factors are not the cause of the speed effect and, in fact, serve only to degrade rather than enhance the underlying target speed signal.

To determine if speed information was sustained through the occlusion interval, we analyzed delay activity using a two-way ANOVA (direction and speed, $P < 0.05$). For Occ trials, there were 112 (38%) and 83 (28%) cells with significant direction and speed effects, respectively, during the early delay period (D1). For the late delay (D2), there were 105 (36%) cells with a significant direction effect and 62 (21%) with a significant speed effect. We also ran the statistical analysis on Occ trials that had been corrected by subtracting the activity recorded on appropriately matched Late trials. The number of cells showing significant effects was as follows: 112 (38%; early delay-direction), 170 (58%; early-speed), 105 (36%; late delay-direction), 161 (55%; late delay-speed). As was the case for visual responses during the cue interval, the correction had little impact on the numbers of cells showing direction effects, but dramatically increased the number of cells showing speed effects.

For presaccadic activity, the neuronal firing rate was averaged over a 100 ms interval terminating with saccade onset. The number of cells showing significant effects on Occ trials was 127/292 (43.5%) for direction and 41/292 (14%) for speed (two-way ANOVA; $P < 0.05$). The relative paucity (compared to cue and delay intervals) of cells showing a significant speed effect might be attributed to two factors. First, the shortness of the presaccadic interval increases the response variance. Second, signals related to saccade preparation peak during this time interval and might overwhelm other signals.

To show that presaccadic activity can encode speed independently of saccade amplitude, two example neurons are shown in **Fig. 5**. The upper row shows activity of a 'fast' cell. The same responses are plotted as a function of saccade amplitude (panel **a**) or target speed (panel **b**). The correlation coefficients (r) indicate that target speed accounts for much more of the variance in firing rate. Activity during the cue interval is also plotted to show the consistency of the speed preference across time (**Fig. 5b**). The same is shown for a 'slow' cell (**Fig. 5c** and **d**). To characterize the effects of saccade amplitude and latency across the entire population, one-way ANOVAs were computed with the factors target speed, saccade latency or amplitude (data were split by target direction). The latencies and amplitudes for each cell were discretized into four categories with equal numbers of observations in each. For latency, 50/292 (18%) cells showed a significant effect ($P < 0.05$) for at least one target direction, whereas for amplitude, 35/292 (12%) were significant and for speed, 55/292 (19%) were significant. Of the cells that showed a significant effect of target speed, 15/55 (27%) and 5/55 (9%) were also significant for saccade latency or amplitude, respectively. Generally, cells that were modulated by target speed were not modulated by saccade parameters.

We analyzed the shape of the speed selectivity functions using a template-matching algorithm that classified the speed

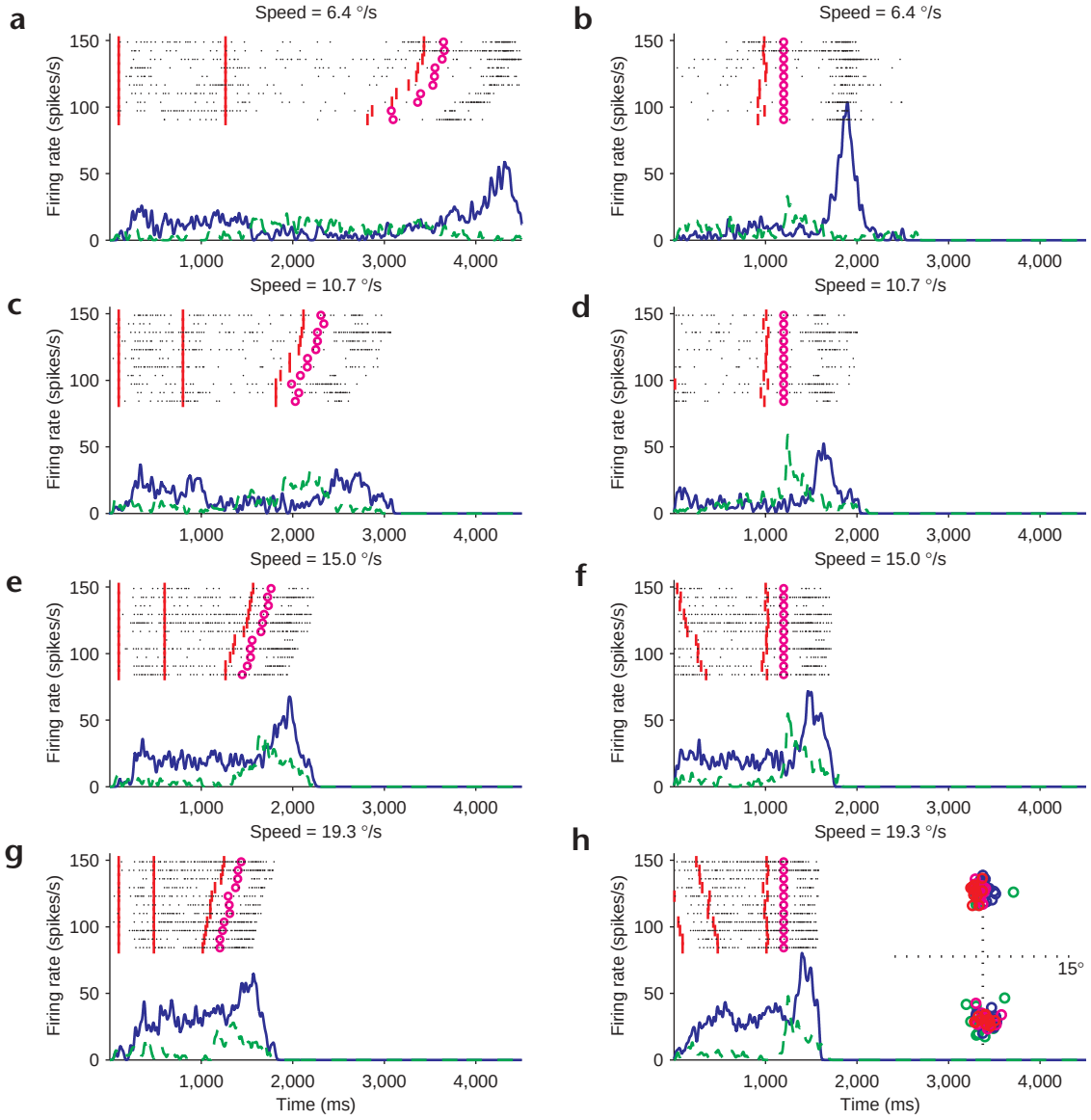

Fig. 4. Trial rasters and spike histograms for a 'fast' neuron. Only trials in the preferred direction are shown. Each subplot shows spike rasters for individual Occ trials (black dots) with trial intervals (background, cue, delay, saccade) indicated by event markers (red ticks). Saccade onset is indicated with a magenta circle. Trials are sorted in descending order of overall duration. Left column, trials aligned on cue onset. Right column, trials aligned on saccade onset. Thick solid blue lines are spike density plots smoothed with a Gaussian (σ = 12 ms) for Occ trials. Dashed green lines are spike density plots for Late trials (rasters not shown). In (**h**), saccade endpoints for all Occ trials are shown, sorted by target speed (green 6.4, blue 10.7, magenta 15.0, red 19.3 °/s). Two-way ANOVA showed that the effects of target direction and speed on saccade amplitude were not significant (dir, $P = 0.71$; speed, $P = 0.64$).

dependence as lowpass, highpass, U-shaped, inverted-U, N-shaped or inverted-N. Most neurons were lowpass (25–36%, depending on time interval) or highpass (27–36%). U-shaped and inverted-U comprised 11–13% and 9–12%, respectively. The remaining cells were evenly divided between N-shaped and inverted-N. The classification was consistent across trial epochs.

If delay activity during Occ trials encodes a memory of target speed, then the speed preference established during the cue interval should be sustained throughout the delay and presaccadic intervals. **Fig. 6a** shows the response to the best and worst speeds for each cell averaged across the entire population. The averaging was done by adding the mean trial-by-trial firing rates for the selected interval, and then dividing by the total number of trials. The best and worst speeds were selected based on activity during the cue interval and fixed for subsequent intervals. To obtain a conservative estimate, responses to both directions of target motion were included. For the population as a whole, there is a small but statistically robust difference between best and worst speeds (unpaired t-test, $P < 0.001$) for all intervals. This difference respects the speed preference established during the cue interval. **Fig. 6b** and **c** show the average response of slow (best speed < 8 °/s) and fast (best speed > 17 °/s) neurons to their best and worst stimuli. There was a third class of intermediate cells (8 °/s < best speed < 17 °/s;

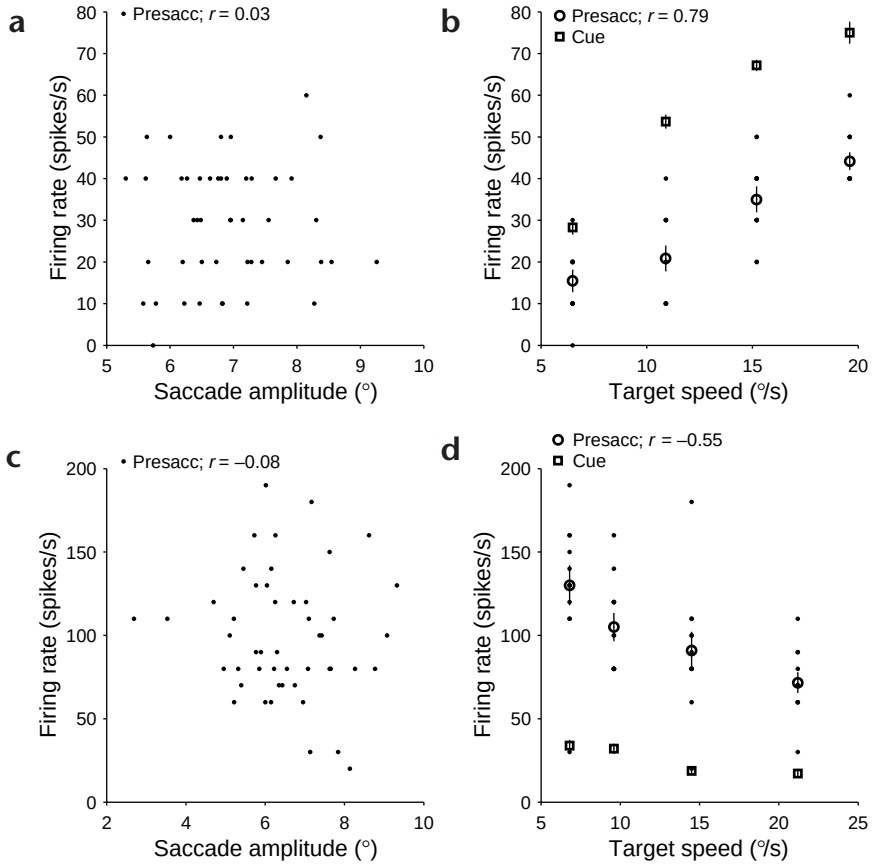

Fig. 5. Presaccade firing rate for two neurons plotted as a function of saccade amplitude and target speed. (**a**) Activity of a fast cell 100 ms before saccade onset versus saccade amplitude; *r* is correlation coefficient. (**b**) Small filled circles are same data as in (**a**) plotted against target speed. Large open circles are mean firing rate for each speed. Open squares are mean firing rate during cue (equal path) interval. Error bars are ± s.e.m. (**c**, **d**) Same comparison for a slow cell.

$n = 88$) that showed a consistent speed preference, but the differences in mean response were smaller and not statistically significant ($P > 0.05$).

One might ask how consistent the speed preference is for each cell. One way to test this is to find the number of cells that had the same best speed across the four time intervals used in **Fig. 6**. By chance, one expects a proportion of $4 \times (0.25)^4 = 1.56\%$, or 4.6/292 cells. The actual number was 32/292 = 11%, which is seven times greater than expected. If one relaxes the criteria and asks how many cells preferred the slowest two speeds or fastest two speeds across all intervals, then the expected proportion is $2 \times (0.5)^4 = 12.5\%$, or 36.5/292 cells. The actual number was 69/292 = 24%, or 1.9 times greater than chance. There were an additional 11 cells that preferred one of the two intermediate speeds across all intervals and did not overlap with the 69 slow and fast cells.

As a further test for the consistency and reliability of speed-related activity, we performed a receiver-operating characteristic (ROC) analysis of the response of each neuron to its best and worst speed. The best and worst speeds were based on responses during the cue interval. The analysis was done only for the target direction that gave the best response averaged over all intervals for each cell. **Fig. 7** shows the distribution of ROC areas for the entire population of cells. The same best and worst speeds were used to sort responses during the early delay (D1; **Fig. 7a**), late delay (D2; **Fig. 7b**) and presaccade (**Fig. 7c**) intervals. Open circles in **Fig. 7** show the ROC area distributions for trials without a cue (Late trials). The filled circles are the distributions for cue present (Occ) trials. The downward pointing arrows indicate the medians of the distributions. The differences between the means and medians of the cue-absent and cue-present distributions were evaluated using unpaired *t*-tests and Mann-Whitney rank-sum tests. The resulting *P*-values were all less than 0.0001.

Based on the average firing rates of the entire population, the target speed can be estimated using a simple reconstruction algorithm. First, we calculated the mean firing rate during each trial interval for each cell as a function of target speed and direction. Then we assigned each cell a label based on a weighted combination of the best and worst speed (S^{pref}, S^{null}) for that cell:

$$L_i = w_p \cdot S_i^{pref} + w_n \cdot S_i^{null} \quad (1)$$

The best and worst speeds were chosen based on activity during the cue interval and remained the same for all subsequent intervals. The weights, w_p and w_n (1.25 and –0.25, respectively), were the same for all cells and time intervals. They were chosen so that the estimated slowest and fastest speeds during the cue interval were close to veridical (**Fig. 8**, open circles). For each target

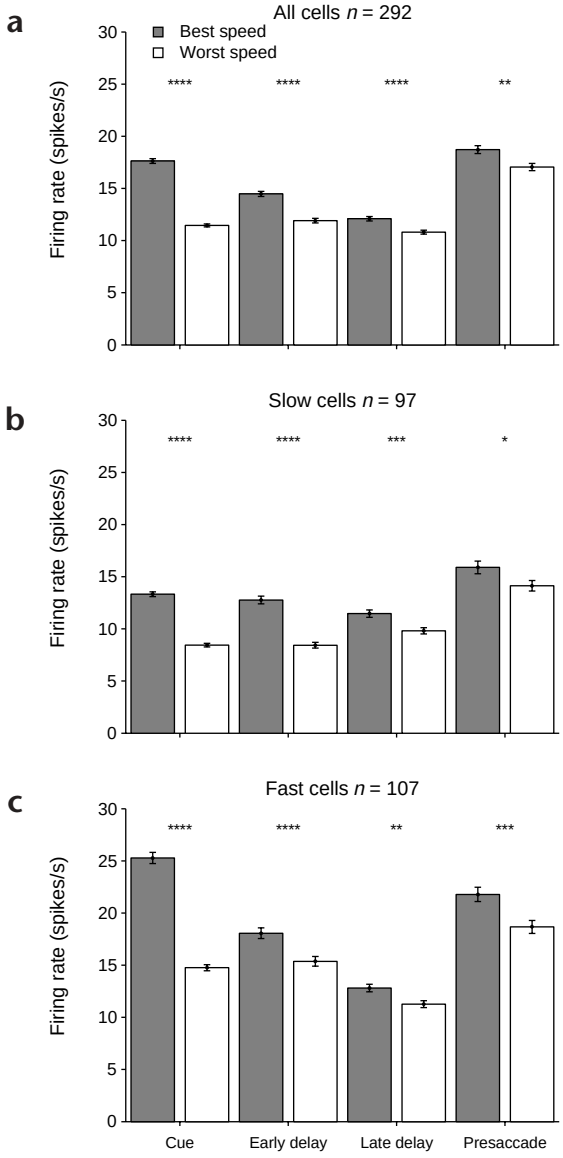

Fig. 6. Average firing rates for Cue2, D1, D2 and presaccade intervals, sorted by best versus worst speed. Best and worst speeds were determined based on activity during Cue2 interval and used to classify the cells as slow or fast. (**a**) All cells. (**b**) Slow cells (best speed < 8 °/s). (**c**) Fast cells (best speed > 17 °/s). Asterisks correspond to *P*-values from unpaired *t*-tests.

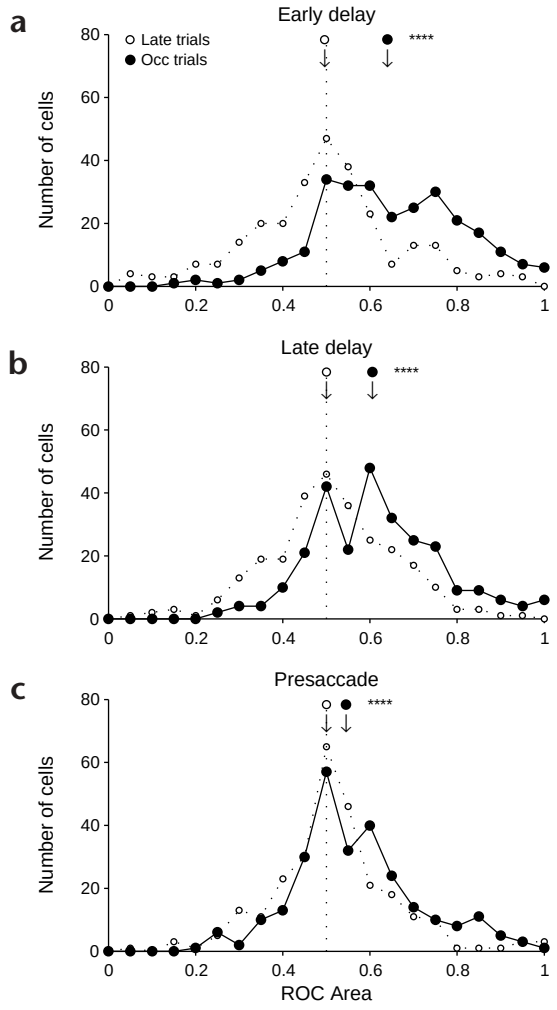

Fig. 7. ROC analysis of responses to the best and worst speeds for each cell. The best and worst speeds were determined from activity during the Cue2 interval. Downward pointing arrows indicate the medians of the cue-absent and cue-present distributions. Asterisks indicate *P*-values resulting from unpaired t-tests comparing the cue-absent and cue-present distributions.

speed, the estimated speed, S_k^{est}, was calculated as the weighted sum of the responses of all neurons:

$$S_k^{est} = \frac{\sum_{i=1}^{N} R_{i,k} \cdot L_i}{\sum_{i=1}^{N} R_{i,k}} \qquad (2)$$

The speed estimates for the delay and presaccade intervals are shown in **Fig. 8a** and **b**. An estimate of the bias inherent in this procedure was obtained by shuffling the labels among cells (**Fig. 8**, dashed lines). The results for Cue1 and Cue2 were similar, providing further evidence that the FEF responses encode speed independently of stimulus duration or path length. The range of estimated speeds during the delay and presaccade intervals is compressed, similar to the behavioral data (**Fig. 3**). Nevertheless, the ordering of the estimated speeds is veridical in 23/24 cases. Hence, a simple intuitive estimator produced reasonable results with a small set of free parameters (only two free parameters, w_p and w_n, for 32 experimental estimates).

Discussion

A role for prefrontal cortex in forming an internal representation of moving targets is suggested by evidence that schizophrenia patients are impaired on motion prediction tasks[15] and that frontal eye field lesions can impair certain kinds of oculomotor predictions[16]. Our results show that monkeys use an internal estimate of target speed when programming predictive saccades and that

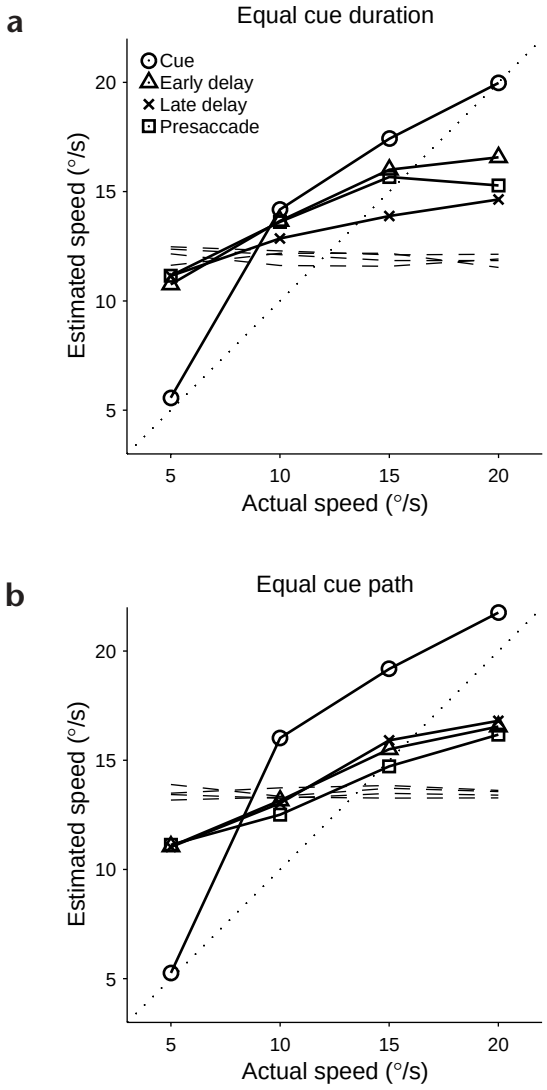

Fig. 8. Reconstruction of target speed. The weighted responses of all 292 neurons were used to estimate target speed. The estimator was designed to provide a veridical estimate of the fastest and slowest target speeds based on activity during the cue interval (open circles). The same estimator was then applied to activity during the early delay, late delay and presaccade intervals. The dashed lines are speed estimates obtained using a random estimator. (**a**) Estimator (*L*) based on best and worst speeds during equal duration cue interval (Cue1). (**b**) Estimator based on best and worst speeds during equal path cue interval (Cue2).

FEF neurons have stimulus- and memory-related activity that vary with target speed. The responses of FEF neurons could be used to estimate target speed, even when the target was invisible.

We were concerned that apparent speed selectivity during the occlusion interval might have been an artifact of time-varying activity related to saccade preparation. There are at least two aspects of saccade preparation that need to be considered: one is the anticipation that any movement will be required and the other is the probability of a movement to a particular spatial location. A common observation in oculomotor structures is a 'build-up' of activity before saccade initiation (for example, ref. 17). In FEF, build-up activity distinguishes between pro- and anti-saccades[18] and is sensitive to uncertainty about target location[6]. One would expect build-up cells to be misclassified as 'slow' cells in our experiment. A similar account for 'fast' cells would require a complementary population of neurons that have high baseline activity and 'build-down' before saccades. Such neurons were rarely observed perhaps due to generally low baseline firing rates. To control for some of the confounding effects of anticipation, we included trials that had a similar time-structure as occluded-motion trials, but with no visual stimulus during the cue interval. The anticipation hypothesis predicts that the apparent effect of target speed should vanish when the activity on 'cue-present' (Occ) trials is corrected by subtracting the activity on 'cue-absent' (Late) trials. In fact, when this procedure was used, the effect of target speed was enhanced substantially, suggesting that anticipation and target speed have different effects on activity in FEF.

The Occ and Late trials also differed with respect to uncertainty about the particular response required. In cue-absent trials, the monkey knew neither the direction nor amplitude of the required saccade until the target appeared (which was coincident with the go signal). In cue-present trials, the monkey was given the direction of the saccade when the cue appeared, but the amplitude was not specified until the go signal. Hence, there was less uncertainty on cue-present than cue-absent trials. Based on the work of others[6,19,20], reduced uncertainty should lead to a more rapid build-up of preparatory activity. But this does not fully account for speed selectivity, as the uncertainty was the same for all speeds. One might further posit that preparatory activity builds up at a rate proportional to response urgency[21]. This could explain fast cells, but it is not clear how it would account for slow cells. Also, some models require that preparatory activity plateau at the same level prior to the saccade[12,22], which should eliminate any speed dependence from activity immediately preceding the saccade. Finally, any explanation based on either anticipation or uncertainty would require that the apparent speed-dependence found in the first 350 ms of the visual response be correlated with preparatory activity, such that build-up cells prefer slow targets, and build-down cells prefer fast targets. This would be a remarkable coincidence.

The strongest evidence for speed coding is the reconstruction of target speed using labels derived from the activity in the first 350 ms of the cue responses (**Fig. 8a**). This interval was the same for all speeds, so these labels should not in any way depend on stimulus duration. Nevertheless, when these labels were applied to activity in later trial epochs, they give estimates of target speed that were correlated with actual target speed. This could not have happened if the later activity did not have similar speed-dependence as the response in the first 350 ms. There must have been true speed information in the late delay and presaccade activity; otherwise, those speed estimates would have been identical to the noise (indicated by the dashed lines in **Fig. 8a**).

A more problematical issue is whether speed-dependent activity modulation reflects a native sensory signal or, alternatively, is an artifact of training. It is known that FEF neurons can be 'trained' to respond selectively to stimuli to which an animal responds preferentially[23]. We tried to avoid this type of learning by using a non-unique, many-to-many stimulus–response mapping, such that, within the limited set of stimuli and responses, all stimuli, responses, and stimulus–response pairings were equally likely. Specifically, we tried to ensure that all stimulus speeds were mapped to the same set of motor responses. Also, due to delay-interval variability, the exact saccade amplitude was not specified until the go signal was received. Hence the saccade could not have been programmed based on target speed alone, but required a combination of target speed and elapsed time. For

these reasons, we feel that speed-dependent activity was far more likely to reflect stable afferent input than learned stimulus–response associations, but we would not necessarily argue that it had a fundamentally sensory nature[24] or that it was independent of the particular task we chose.

Target speed appears to modulate the sensory, delay and presaccadic activity of FEF neurons in a manner consistent with feature-based working memory[24]. This modulation was observed even though average saccade latency and amplitude were by task design more or less constant across speed. Hence, speed-dependent activity was not easily related to the programming of a saccade vector or saccade timing. It is possible that the activity modulation is related to storage of target speed in working memory during the occlusion interval and may be used to provide an internal representation of the moving target that is continuously updated during saccade planning.

Methods

Experiments were performed on two juvenile male rhesus monkeys (*Macaca mulatta*). All methods were approved by the Institutional Animal Care and Use Committee at Columbia University and the New York State Psychiatric Institute. Monkeys were prepared for experiments by surgical implantation of a post used for head restraint and a recording chamber to give access to the cortex. A monocular scleral search coil was implanted for eye-position recording[25].

Neuronal recording and stimulation. Recording chambers were implanted at stereotaxic coordinates 15–18L, 20–25A, following previous FEF studies[26]. Neuronal activity was recorded using platinum-tungsten 8-trode multiwire microelectrodes (typical impedance 0.5 MΩ). A digital signal processor-based multichannel time-amplitude window discriminator separated action potentials from background noise. Using the multi-electrode and multichannel discriminator, we were able to record up to eight neurons simultaneously. The time of each action potential was recorded with a resolution of 0.02 ms. Electrical microstimulation was used to determine if recording sites were located within the physiologically defined FEF[13]. Trains of biphasic pulses (67 ms trains, 0.2 ms/phase, 350 Hz) were delivered while monkeys fixated a central target, which was turned off for 200 ms before the electrical stimulus was delivered[27]. Pulse amplitude was varied between 0 and 100 μA to ascertain the threshold for electrically evoked saccades. Recording sites were assigned to the FEF if the stimulation threshold was ≤50 μA (ref. 13).

Eye movement recording. Eye position was monitored using a search coil system. Separate horizontal and vertical eye position signals were fed through an analog differentiator (low pass, –3 dB at 25 Hz) to yield horizontal and vertical eye velocity. The eye position and eye velocity signals were then digitally sampled by computer at 1 kHz/channel and stored on disk for offline analysis. Eye position and velocity records were used to estimate saccade latency and amplitude. Saccade onsets and endpoints were computed using an acceleration criterion.

Behavioral task. We trained monkeys to perform a motion-prediction task in which they were shown a small moving target (**Fig. 1**). Visual targets were displayed on a 94 cm calibrated color monitor. Targets were small (0.5 or 1.0°) white squares of 65.0 cd/m^2 luminance presented on a uniform dark background. The target was visible during an initial cue interval, disappeared during a variable delay interval, and then reappeared moving along the same linear trajectory. Target speed was constant throughout its trajectory for a given trial, but was randomized from trial to trial. The monkeys' task was to fixate a stationary spot in the center of the display during the initial target motion and approximately the first three-quarters of the delay interval. The fixation spot then disappeared at a random time and this was the go signal for the monkey to initiate a saccade. The monkey was rewarded for making a saccade to the predicted location of the invisible moving target before it re-appeared. If the saccade was initiated after the target had re-appeared, the trial was aborted, and the monkey was not rewarded.

On any given trial, the target moved in one of two directions, either toward or away from the receptive/movement field (RF/MF) of the neuron(s) under study. For each cell, we chose one of 16 different axes of motion, spaced at 22.5° intervals around the clockface, to align the target trajectory with the receptive/movement field. A complete experiment always comprised two directions (toward and away from the RF/MF) and four speeds (approximately 5, 10, 15, 20 °/s). The randomization of target direction, speed and occlusion duration deterred the monkeys from performing a stereotyped 'default' oculomotor response.

The range of speeds was dictated by exigencies of the experimental design, primarily the desire to have a minimum delay duration of 500 ms, and to maintain a constant average saccade amplitude for all speeds. These constraints prevented the use of speeds greater than 25 °/s. As FEF receives anatomical input from visual areas MT and V4, one might expect FEF neurons to respond to a similar range of speeds tuning, which can be up to 120 °/s (ref. 28). Such high speeds cannot be rendered smoothly on most video displays; therefore we cannot claim to have covered the whole range of speeds expected to yield a response in FEF neurons.

In addition to trials where the target disappeared momentarily (referred to as Occ trials), control trials were randomly interleaved. On control trials, no cue was given, but the monkey was required to fixate for a variable time and then make a reaction-time saccade to an eccentric target moving away from the center of the display. These were referred to as Late trials because the target appeared only near the end of the trial. Late trials were equivalent to Occ trials with the target turned off during the cue interval and on during the saccade interval. Late trials otherwise had the same time structure and reward contingencies as Occ trials.

Sensorimotor index. We characterized each neuron using a sensorimotor index based on mean firing rate (FR) during the Cue1 or Cue2 and Presaccade intervals (**Fig. 1b**) using data from Occ trials:

$$\mathrm{SMI} = \frac{[\mathrm{FR\ (cue)} - \mathrm{FR\ (presacc)}]}{[\mathrm{FR\ (cue)} + \mathrm{FR\ (presacc)}]} \quad (3)$$

This index varied from –1.0 (pure motor) to +1.0 (pure visual).

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Competing interests statement

The authors declare that they have no competing financial interests.

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