Supplemental Material for "Saccades and drifts differentially modulate neuronal activity in V1: effects of retinal image motion, position, and extraretinal influences" by Kagan, Gur and Snodderly

Supplemental Methods, Supplemental Results, 3 Supplemental Tables, 14 Supplemental Figures, 3 Supplemental Movies

Supplemental figures are numbered from S1-S14 and supplemental tables are numbered from S1-S3. Figures S1-S5 are referred to in the main body of the paper. Other supplemental figures are discussed below.

Supplemental Methods

Sustained responses are not caused by undetected fixational saccades

Sustained position/drift responses to fixational eye movements (Snodderly et al., 2001) have been previously questioned on grounds of a potential failure to detect small saccades (Martinez-Conde et al., 2002). This is primarily an issue for a smaller subset of our data that was collected with a 100 Hz sampling rate. The suggestion that undetected saccades are the source of activity during drifts is implausible for several reasons:

1. A 100 Hz sampling rate is sufficient to detect most fixational saccades and map their end-points. A simple calculation shows that a 10°/s velocity threshold will allow detection of >6' (minarc) position shift within 1 sample interval (10 ms). The percentage of detectable small saccades depends on the saccade duration and approaches 100% for amplitudes >10' (Figure S6). Comparison of data with 100 Hz and 200 Hz sampling rates shows that *at the maximum 4%* of all saccades have amplitudes <6' and would be missed in 100 Hz recordings (Figure S7, *cf.* main sequences for M45 and M46). A real number for monkey M45 is probably even lower because she tended to make larger saccades than M46. The majority of the fixational saccades in our recordings (both with 100 Hz and 200 Hz) lasted at least 20 ms or more and had amplitudes >10' (Figure S7). The shortest 5 ms saccades, detected with 200 Hz rate (first red 5-ms bin in the duration distribution for M46), comprised only 2% of all saccades. But it does not mean that we failed to detect all <10 ms duration saccades with 100 Hz. Most fixational saccades are "step-like", with a net change in position (Figures S8, S9, S10), so even if we missed the exact onset of a short saccade, we would detect a position change in the next sample. Examples of raw eye position records of fixational saccades with 100 Hz and 200 Hz sampling are shown in Figure S9 and Figure S10, and metrics of fixational saccades and drifts are shown in Figure S7 and Figure S14.

2. Most data for the present paper was collected with a new experimental system, using an eye coil and sampling frequency of 200 Hz, which is adequate for studying small fixational eye movements.

A number of previous studies of fixational eye movements used a 200 Hz sampling rate (*e.g.* Horowitz et al., 2007; Leopold and Logothetis, 1998), 250 Hz (Horwitz and Albright, 2003) and many human studies used video-based eyetrackers with sampling rates close to 200 Hz, *e.g,* 250 Hz (Moller et al., 2002; Engbert and Kliegl 2003), 240 Hz (Hafed and Clark, 2002). Monkey M46 had a low frequency of only 0.4 saccades/s with eye position records sampled at 200 Hz, but exhibited strong sustained position/drift responses in completely saccade-free intervals, in both fixational (Figure S10) and voluntary (Figure 2) saccade trials.

3. The overall pattern of our findings clearly demonstrates that even if we missed some rare saccades, it still would not invalidate any of our results. First, there is a clear difference between neuronal classes in cells collected with same sampling rate. Saccade cells do not respond at all during drift periods, even when the CRF is clearly staying on the stimulus, while position/drift cells that exhibit sustained activation during drift periods do not respond at all to crossing saccades. If we missed some saccades, we would have missed them in both neuronal classes, and it would not explain why position-specific sustained responses occurred for some cells but not others. Second, for the potentially undetected tiny saccades to generate the observed levels of the sustained firing during "presumed" saccade-free drift periods, we would have to assume a completely unrealistic occurrence of saccades approximately every 150 ms.

These arguments show that undetected saccades are not the basis for activation during drift periods.

Estimation of neuronal response latency to saccades is not compromised by "insufficient" (100 Hz / 200 Hz) eye position sampling rate

A potentially important effect of a lower eye position sampling rate is a higher variation in estimation of the saccade onset time (up to 5 or 10 ms, Figure S6). This jitter could presumably result in a temporal blurring of post-saccadic response peaks determined by saccade-triggered averaging. Yet, one of our results is that we find very strong post-saccadic responses, almost equal to flash responses (where the onset is known with 1 ms precision), while another lab that used 1000 Hz sampling rate found 7-times weaker post-saccadic responses than flash responses (Martinez-Conde et al., 2002). Another study that employed an even lower, 60 Hz, sampling rate of eye position also reported near-equal response peaks for post-saccadic and flash responses (MacEvoy et al., 2008). These findings suggest that our temporal jitter in determining saccade onset is not sufficient to blur the post-saccadic response. We also report a high correlation (r=0.78) between response latencies to saccades and flashes, on a cell-by-cell basis, and a systematic relationship of post-saccadic and flash response latency to other independent characteristics, such as eye movement activation class, transiency and speed tuning. This additionally demonstrates the validity of our saccade response latency estimation. To summarize, the temporal jitter of the saccade onset times up to 5 or even 10 ms is small compared to the combined variations in saccade duration (Figures S7 and S12) and neuronal response latency (~40-70 ms, Table S1), and it does not introduce a systematic bias because positive and negative "shifts" average out (Figure S6).

Supplemental Results

Correspondence between results obtained from fixational and voluntary saccades during visual stimulation

In the subset of cells tested both with fixational and voluntary eye movements (n=33), there was a good correspondence between transiency index TI (r=0.82, p <0.01), SDD (r=0.88, p <0.01) and cross-covariance function estimates derived from the two conditions. When the classification of eye movement activation based on saccade-drift difference was performed independently for fixational and voluntary eye movements, only 5/33 cells received different assignments (pos<->mix, mix<->sac; there was never a confusion between saccade- and position/drift grouping. These 5 cells were recorded in monkey M46, which had a very low frequency of fixational saccades, so the number of fixational saccade events for these cells was smaller (7±2) than the number of voluntary landing saccades (10±3). Given the small number of fixational saccades and the more controlled conditions with voluntary saccades, we used assignments derived from the voluntary landing saccades for these 5 cells.

Correlation between receptive field size and eye movement activation

The correlation between SDD and CRF size was strong in one monkey where we collected most data within a relatively narrow range of eccentricities (r=0.48, p <0.001, all but one cell within 1.3-6.2°, mean±s.d. 5.3±1.4°, M45), but not significant in another monkey where we sampled a broader eccentricity range (0.6-10°, mean±s.d. 3.9±1.7°, M46).

condition/cells	pos	mix	sac
fixational increasing post-saccadic response latency	72±20 (31)	50±16 (33)	38±8 (21)
flash response latency in corresponding cells	62±16 (31)	59±12 (33)	49±8 (21)
voluntary landing post-saccadic response latency	74±15 (17)	54±16 (17)	54±14 (10)
flash response latency in corresponding cells	71±17 (17)	57±9 (17)	52±11 (10)

Supplemental Table S1. Neuronal response latency following saccades and flashes, mean±s.d. in ms (number of cells in parentheses).

Extraretinal effects

Statistics of fixational eye movements influences detection of extraretinal modulation

The lower incidence of extraretinal modulation in cells recorded from M42 compared to the other two monkeys ($p < 0.05$, Fisher's exact test) prevented detection of its presence in our previous study (Snodderly et al., 2001), because for each monkey we averaged data across all cells, thereby diluting the effect. Nevertheless, the question remains why the monkeys differ. To illustrate the differences among monkeys, the metrics of their fixational eye movements are summarized in Figure 8 and Table S2. M42 had a higher velocity of upward vertical drift that had to be compensated with frequent small downward saccades; whereas the drift velocity was lower and saccades less frequent in other two monkeys. It is unlikely that the saccade direction determined the occurrence of modulation, since most saccades in both M46 and M42 were downward, but they were more frequently accompanied by detectable extraretinal modulation in M46 than in M42. These results are consistent with the suggestion that saccade frequency and drift rate affect the detectability of the extraretinal modulation and are the likely determinants of the individual differences.

Pre-saccadic suppression

On the population level, using averages across cells, we find little evidence of pre-saccadic suppression. The elevated baseline noticeable in the averaged data recorded in the light in M45 is most likely the artifact of overlapping influence from preceding saccades (Figure 7D). This monkey had a higher frequency of fixational saccades (Figure 8), therefore we re-did the analysis with more stringent conditions of no previous saccade in the 500 ms epoch prior to any selected saccade, and the pre-saccadic baseline became flat (data not shown). Very weak pre-saccadic suppression is also noticeable in monkey M46 for voluntary saccades. In general, some individual neurons did appear to show a weak suppression before the saccade onset, but this was not a consistent pattern across neurons (*cf.* Reppas et al., 2002). However, random fluctuations in the ongoing firing and low levels of ongoing activity in many cells could have contributed to the masking of this potential weak effect.

Effects of different saccade sizes on extraretinal modulation

We explored the possibility that saccade size influences the strength or the time course of the modulation. Fixational saccades were divided into three groups: amplitude <20', between 20' and 40', and >40'. Voluntary saccades were divided into four groups: <40', between 40' and 170', between 170' and 300', and >300'. In no case did we detect a statistically reliable distinction between modulation signals caused by various saccade sizes. This lack of dependence of extraretinal influences on saccade size is consistent with the results of Reppas et al. (2002) for LGN neurons. These results make it unlikely that that gaze shifts (Rosenbluth and Allman, 2002), rather than saccades *per se*, modulated the ongoing firing, since the effect was not dependent on saccade size and could be observed for movements less than 20'. Moreover, even after controlled voluntary saccades, when the gaze direction remains constant until the next saccade, the modulation signal returns to the baseline approximately in 300 ms, arguing against the possibility that gaze-dependent variations could account for the observed transient perisaccadic modulations.

monkey	mean saccade frequency (sac/s)	mean smoothed drift speed (°/s)	saccade amplitude mean (minarc)	saccade amplitude median (minarc)
M45	1.6	0.60	37	31
M46	0.4	0.35	24	20
M42	2.5	0.92	20	15

Supplemental Table S2. Metrics of fixational eye movements of three monkeys recorded while viewing a light screen (no stimulus present). Note that monkey M42 had a higher frequency of fixational saccades (corresponding to the mean drift duration 419 ms, median 330 ms) and higher drift speeds. Please refer to Figures S7 and S14 for more metrics of fixational eye movements in monkeys M45 and M46, and details of drift velocity calculations.

parameter	condition	mean	median	s.d.
saccade amplitude (minarc)	light	37	31	24
	dark	32	29	16
saccade velocity (°/s)	light	51	49	25
	dark	40	37	18

Supplemental Table S3. Light vs. dark condition, fixational saccade metrics, monkey M45.

Supplemental References (not listed in the main text)

Horwitz, G.D., and Albright, T.D. (2003). Short-latency fixational saccades induced by luminance increments. *Journal of Neurophysiology, 90,* 1333-1339. [PubMed]

Moller, F., Laursen, M. L., Tygesen, J., Sjolie, A. K. (2002). Binocular quantification and characterization of microsaccades. *Graefes Archive for Clinical and Experimental Ophthalmology, 240*, 765-770. [PubMed]

Rosenbluth, D. and Allman, J.M. (2002). The effect of gaze angle and fixation distance on the responses of neurons in V1, V2, and V4. *Neuron, 33,* 143-149. [PubMed]

Supplemental Movies

These movies (Flash *.swf format, please open in the browser) show a single behavioral trial recording (~5 s) for each of three eye movement activation classes: saccade (movie1), position/drift (movie2), and mixed (movie3) cells. In each movie, the dynamic display on the left shows the stationary stimulus (green bar), moving CRF (blue ellipse) and instantaneous firing rate in 100 ms time bins (color-coded vertical bar). Audio stream represents the neuronal firing – each "click" corresponding to a spike. The lower panel shows the corresponding trial record in the same format as used in Figures 1 and 2.

Supplemental figure legends

Figure S1. Relationship between transiency index (TI) and saccade-drift difference (SDD) for V1 neurons. Each point represents data from one cell averaged for 5-143 (mean 19±20) saccades. **(A)** Fixational saccades (118 cells). **(B)** Voluntary landing saccades (44 cells). Symbols' color denotes cell classification (black: "saccade-activated", gray: "mixed", white: "position/drift-activated"). Histograms on x and y axes show frequency distributions of SDD and TI, respectively. Vertical scale bars correspond to 20 cells in A and 8 cells in B.

Figure S2. Cross-covariance analysis. **(A)** Scatter plot of eye velocity – firing rate cross-covariance function peak vs. SDD, for fixational (n=118, circles) and voluntary (n=44, squares) eye movements. Symbol colors denote cell classification (black: "saccade-", gray: "mixed", white: "position/drift-activated" cells). The parameters derived from the cross-covariance analysis correlated well with the SDD: r=0.7, fixational; r=0.68, voluntary; p <0.01. The peak of the cross-covariance function did not reach p<0.05 significance in 40 position/drift and mixed cells, because of the strong firing in drift periods, which did not co-vary with eye velocity (*i.e.* saccades) but rather with retinal image position. **(B)** Means and s.d. of cross-covariance peak values, minimal latency (first significant lag), and peak latency (the lag corresponding to the peak of cross-covariance function) for sac, mix and pos cell classes derived from cross-covariance analysis.

Figure S3. Scatter plots for "peak" and "dip" minus pre-saccadic firing rates for light **(A)** and dark **(B)** "extraretinal" conditions. In the light, mean dip minus pre-saccadic rate for significantly modulated cells was -3.3±9.3 spikes/s, mean peak minus pre-saccadic rate 10.2±10.4 spikes/s; in the dark, -4.5±5.8 and 12.9±10.2 spikes/s, correspondingly.

Figure S4. Saccade-triggered averages from cells with ≤1 spikes/s ongoing activity that had a non-zero positive peak of extraretinal modulation. **(A)** 29 cells recorded in the light condition (mean ongoing firing 0.3±0.3 spikes/s; **(B)** 11 cells recorded in the dark (0.3±0.3 spikes/s). The shaded area indicates s.e.m.

Figure S5. Extraretinal modulation with no stimulus is much weaker than near-optimal stimulus-evoked responses. Scatter plots of post-saccadic mean "peak period" firing rates with and without a stationary stimulus for fixational saccades (**A,** n=27 significantly modulated cells out of 73 tested in both conditions, with and without stimulus; 25 in light, 10 in dark) and voluntary saccades (**B,** n=15/22 cells, 14 light, 3 dark). Each circle represents a datum from one cell with significant extraretinal modulation, either in the light (gray) or in the dark (black), or in both conditions. Two points are shown for cells with both light and dark conditions. Same cells as in Figure 9A, B.

Figure S6. Simulations of the effect of eye position sampling rate on estimation of saccade onset and detection of small saccades. (**A)** Examples of simulated "actual" eye position ("sampled" at 1000 Hz) and 100 Hz samples acquired at 9 different temporal offsets around the "saccade", and corresponding velocity profiles. Threshold for saccade detection 10°/s. Note the temporal jitter introduced by the 100 Hz sampling rate to the estimated saccade onsets (as compared to "actual" onsets for 1000 Hz traces). This jitter can be negative (saccade onset delayed) or positive (saccade onset advanced). The distribution of these shifts for the upper row example in A is shown in **B**. Since the shifts are both positive and negative, the net inaccuracy in the estimation of the saccade onset times across many saccades would be small. Note that depending on the temporal offset and the duration of the saccade and the sampling intervals, very small saccades can be detected or missed (**A**, rows 2 and 3). Missed instances are marked by solid orange threshold lines in the velocity panels. Panel **C** shows the percentage of detected saccades as a function of saccade amplitude, for 5-15 ms saccade durations and for 100 Hz and 200 Hz sampling rates. Mean detection curves calculated across all saccade durations as a function of amplitude are shown in gray (200 Hz) and black (100 Hz). All saccades >6' and >12' will be detected with 200 Hz and 100 Hz rates, respectively.

Figure S7. Eye position signals sampled at 100 Hz allow reliable detection of small fixational saccades of monkeys. Metrics of fixational saccades for eye position sampled at 100 Hz (M45; top two rows) or 200 Hz (M46; bottom two rows). Data in both cases were collected during presentation of a stationary bar. In both monkeys, saccade **directions** were distributed unevenly (bin size 10°, *cf.* Bair and O'Keefe 1998). The 10°/s velocity threshold for saccade detection resolves >6' saccades at 100 Hz and >3' saccades at 200 Hz. Thus even very small and short saccades, occurring within one sample (10 ms and 5 ms, red 5 ms bins in **duration** distribution histograms) were detected in both cases. The dense lines in the **main sequence** scatter plots (right column, rows 1 and 3) are the result of the sampling quantization – they represent the fixed relationship between the amplitude and the velocity for saccades whose duration was one sample. We did not use up-sampling of eye position traces as we wanted to present the original raw data for inspection. Note the similarity of main sequence slopes in both monkeys (see also Figure S13). The saccades in M46 were on average smaller than in M45 (see distributions of **overall and maximal amplitudes**, column 1, row 2 and row 4, bin size 2'); but smaller saccades are not the outcome of a faster 200 Hz sampling rate (*cf.* monkey M42 data at 100 Hz in Figure S13: mean amplitude 20'). Most saccades had equal overall (from start- to end-point of the trajectory) and maximal (from start- to farthest-point of the trajectory) amplitudes, indicating that circular or away-and-back saccades were rare (see also Figure S8). See Figures S9, S10, S11 for examples of raw eye position traces. Figure 8 shows a subset of similar saccade metrics for these monkeys in the experimental conditions when no stimulus was present on the screen (fixation in the light), used for the analysis of the ongoing activity.

Figure S8. Most fixational saccades in our study had a step-like trajectory, not circular or away-and-back spike-like waveforms. The histograms and cumulative plots in **(B)** show the distribution of the difference

between maximal 2D vector amplitude during the saccade and the overall 2D saccade amplitude measured at the end-points of the saccadic trajectory, expressed in % of the maximal amplitude. For an ideal step-like saccade **(A, top)**, the difference should be 0%, for an ideal circular or spike-like (away-and-back) saccade **(A, bottom)** – the difference should be 100%. In both monkeys, with both eye tracking systems (M45 – 100 Hz Purkinje eye tracker; M46 – 200 Hz eye coil) most saccades have 0% difference, and only a small fraction has values different from 0%, mostly within 10% to 50% (similar to **A, middle)**. These data show that at least 95% of saccades under our experimental conditions result in a substantial change in eye position that would be detected even if the onset of the saccade escaped detection.

Figure S9. Examples of raw eye position traces, velocity calculation and 2D trajectory during fixational saccades, in monkey M45 (100 Hz sampling rate) and in monkey M46 (200 Hz sampling rate). For each monkey, 4 saccades are shown. The first two columns illustrate very small saccades (<10'). Columns 3 and 4 illustrate larger straight and looping saccades, also shown in complete trial recordings in Figure S10. Time stamp 250 ms – saccade onset, ±100 ms epochs around the saccade onset are shown. Amplitude and maximal amplitude (in minarc) are shown above each 2D trajectory plot.

Figure S10. Examples of raw eye position traces and automatic saccade detection, in monkey M45 (100 Hz sampling rate) and in monkey M46 (200 Hz sampling rate). For each monkey, two complete 5-s fixational eye movement trials are shown, one for "position/drift-activated" and one for "saccade-activated" cells. A stationary bar was placed in the center of the CRF, and fixational eye movements moved the CRF over and around the bar. Green curves – horizontal eye position, magenta curves – vertical eye position. Orange inverted triangles denote "increasing" saccades (saccades that resulted in increased firing rate, see Methods), yellow – "decreasing", empty – "no effect" saccades. Long vertical dashed lines denote saccade onsets as found by the automatic saccade detection algorithm. Saccades denoted by *S9* labels are shown in Figure S9 on a more expanded scale. Drifts denoted by *S11* labels and light gray rectangles are shown in Figure S11 on an expanded scale. Short blue vertical lines along time-axis represent neuronal spikes. Note the contrasting neuronal firing patterns in the two cell types (*cf.* Figure 2A). In particular, note the sustained firing during slow drift periods, which is not associated with any saccade. In the example saccade cell in M46 (lower panel), the initial burst marked by **(*)** at the beginning of the trial is caused by the acquisition saccade (prior to trial onset, not shown), and the few spikes not associated with saccades are attributed to ongoing firing (5 spikes/s as assessed by separate recordings of spontaneous activity in the light without a visual stimulus).

Figure S11. Examples of raw eye position traces, velocity calculation and 2D trajectory during fixational drifts, in monkey M45 (100 Hz sampling rate) and in monkey M46 (200 Hz sampling rate). For each monkey, two drift periods are shown. Left column (panels 1) for each monkey illustrates drift periods during which strong sustained responses were recorded from "position/drift" cells – see Figure S10, light gray epochs. Right column (panels 2) shows additional drift examples. Three different drift velocity estimates are
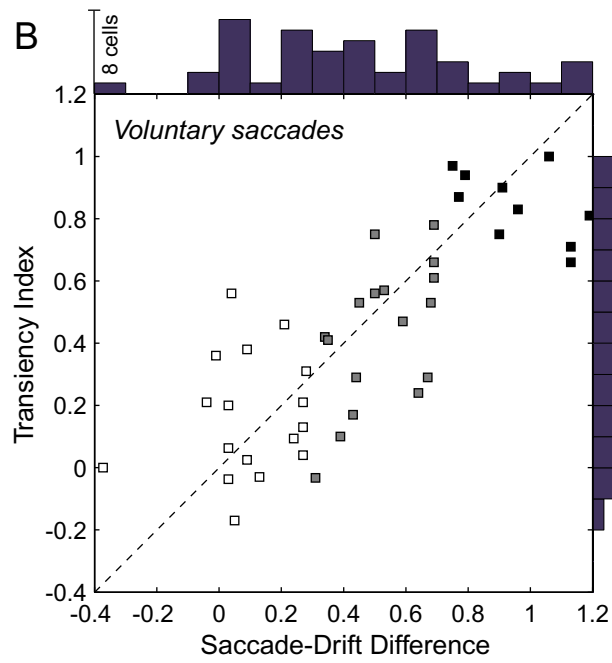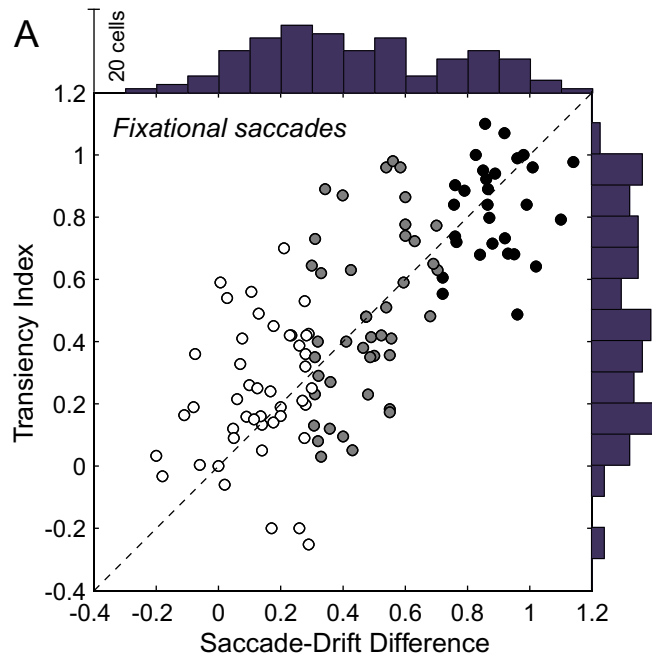
illustrated: "per sample" – using raw horizontal and vertical eye position records, "smoothed" - raw horizontal and vertical eye position records were linearly interpolated to 1 KHz and smoothed with a Gaussian filter of 10 ms σ before taking derivatives to obtain a smoothed velocity estimate, and "dir hor/ver" – per sample "directional" velocity calculated separately for horizontal and vertical eye position.
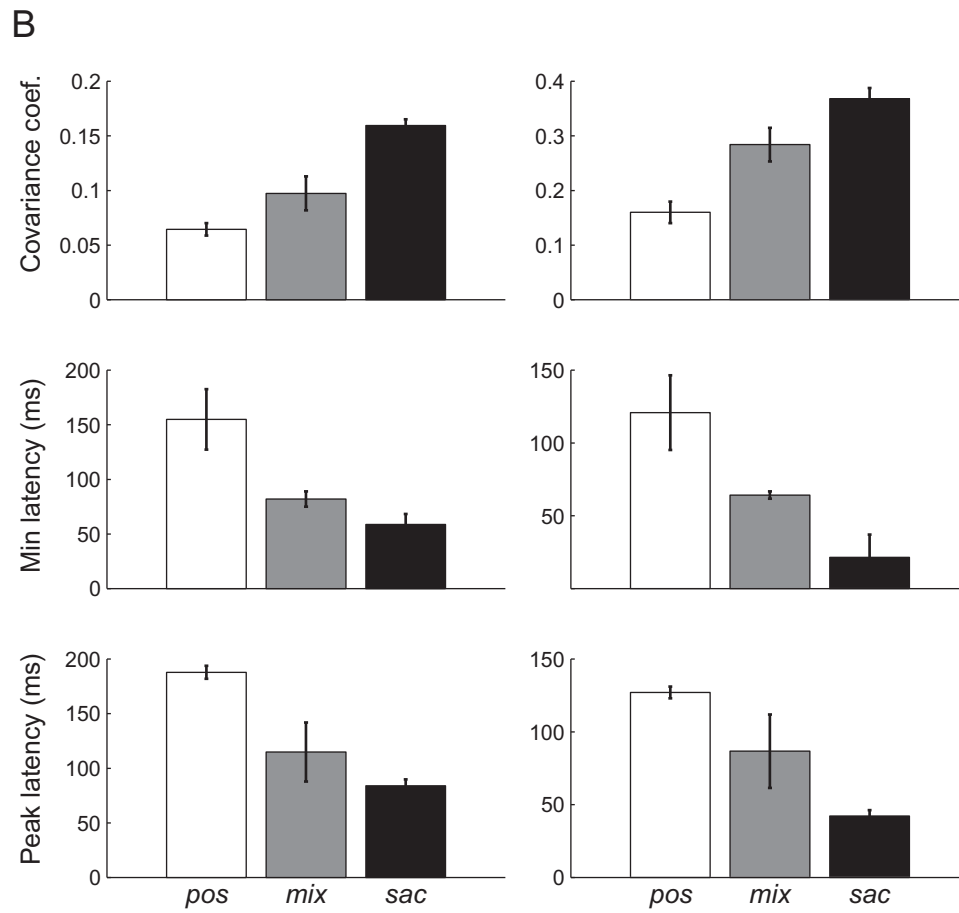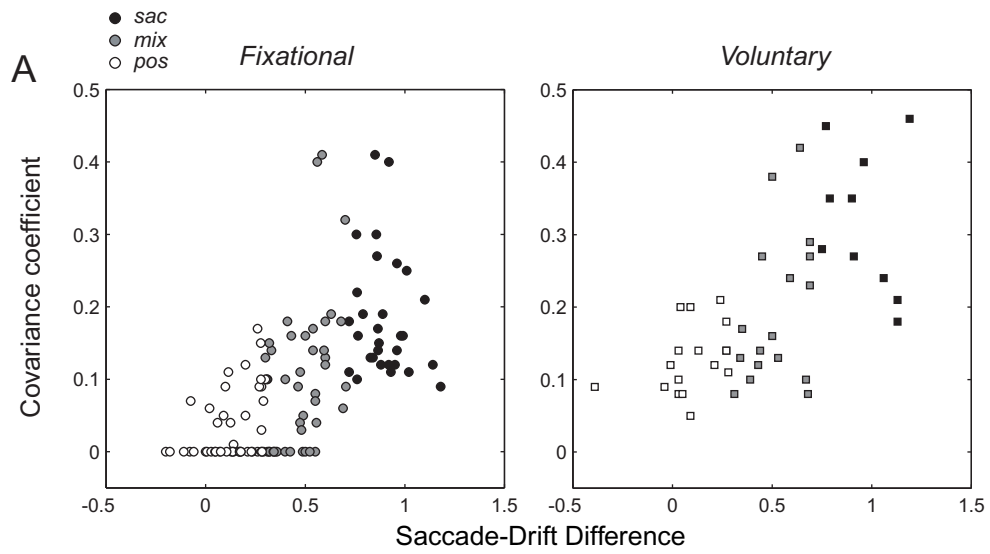
Figure S12. Voluntary saccade metrics collected with a 200 Hz eye position sampling rate (monkey M46). This figure shows the distribution of saccade directions (row 1, column 1 and 2; chosen to be orthogonal to the optimally oriented bar for each neuron), the main sequence (row 1, column 3), and the distributions of saccade amplitude, mean velocity, and duration (row 2, columns 1-3).
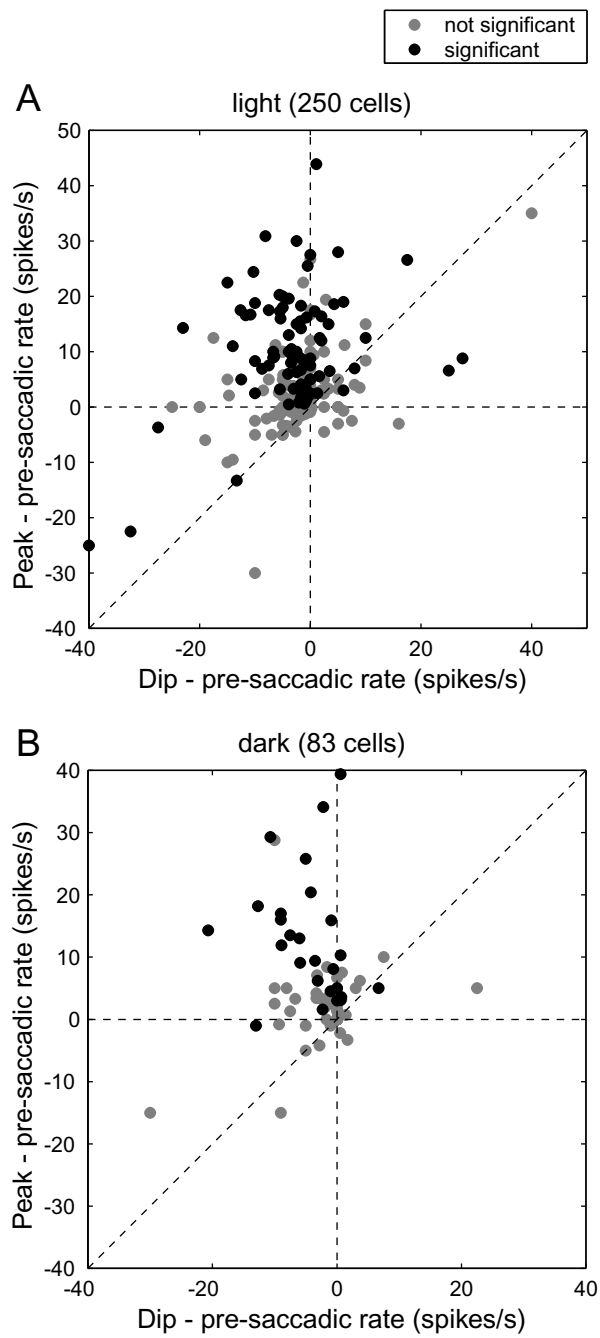
Figure S13. Saccadic main sequence (peak velocity as function of amplitude) for fixational and voluntary saccades for the 3 monkeys used in these experiments. Data from monkey M42 were collected at 100 Hz in the light without any stimulus present and used for the analysis of extraretinal effects (also used in Figure 8). Data from monkeys M45 and M46 are the same as in Figures S7 and S12. Note that fixational and voluntary saccades lie on a similar slope, and that amplitudes of larger fixational and smaller voluntary saccades overlap. See the legend to Figure S7 for explanation of sampling quantization effects manifested as dense lines of points with a fixed relationship between the amplitude and the velocity.
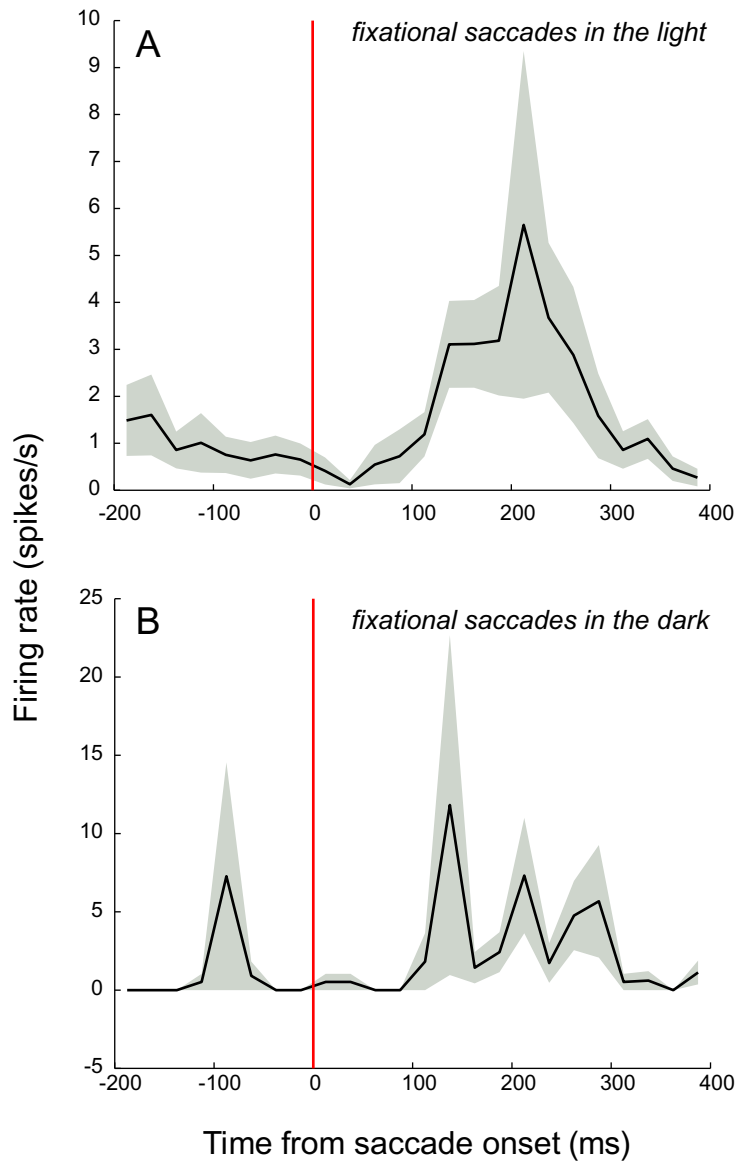
Figure S14. Fixational drift metrics in 2 monkeys acquired at 100 Hz eye position sampling rate (M45, top two rows) and 200 Hz sampling rate (M46, bottom two rows). The intersaccadic drift periods were recorded from the onset of a saccade until the next saccade. The 250 ms delay was imposed to ensure that all neuronal activity analyzed during drift periods was not attributed to modulations accompanying the preceding saccade. **Direction:** Overall drift direction was measured as the difference between eye position at the start- and end-points of the drift period (column 1, rows 1 and 3). Note the upward drifts in M46 (column 1, row 3), which were compensated by infrequent, predominantly downward, fixational saccades whose distribution was shown in Figure 8 and in Figure S7. **Duration:** Since we used 250 ms delay after each saccade for collecting neuronal data during drifts, and used exactly the same data epochs for calculating drift metrics, the distributions and the numbers shown in column 2, rows 1 and 3 should be increased by 250 ms to represent the full intersaccadic drift interval. **Position:** Eye position during most drift periods was relatively stable, with s.d. <5' (column 3, rows 1 and 3). **Amplitude:** Amplitude was estimated in three ways (column 1, rows 2 and 4): 1) *Overall amplitude*, the 2D displacement from start- to end-point of drift period. 2) *Max from onset*, the 2D displacement from start- to the farthest point of the trajectory (this was done to account for potential looping or oscillating curved trajectories). 3) *Max per sample*, the maximal 2D displacement from one sample to the next (5 or 10 ms). The similarity between "overall" and "max from onset" distributions shows that most drifts were directionally monotonic. **Velocity:** We report the following measures of velocity during drift periods (columns 2 and 3, rows 2 and 4): 1) Mean velocity from one sample to the next (*i.e.* per sample). 2) Peak velocity per sample. To a large degree these velocities are caused by the noise in the experimental system (2-3' for Purkinje eyetracker, 1-2' for
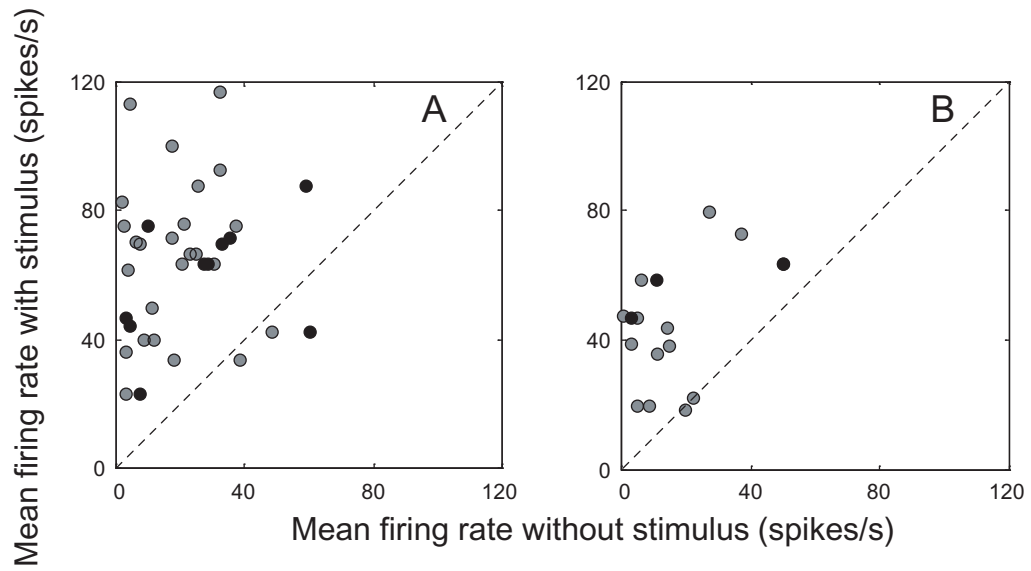
eye coil). For example, a displacement of 1' will have 1.7°/s speed, 2' – 3.3°/s, 3' - 5°/s at 100 Hz. Importantly, this noise is random and uniformly fluctuates around the mean signal, therefore it does not cause any significant change in the position (see Figures S10, S11). These calculations are shown primarily to illustrate that the criterion used to detect saccades (*i.e.* velocity <10°/s) is outside the velocities calculated in the same way during the drift periods. We used two additional approaches to get a more realistic estimate of drift velocities. 3) *Mean directional velocity* was calculated separately for horizontal and vertical eye position, from start- to the farthest point of the trajectory. This procedure averages random positive and negative per-sample fluctuations of the position signal, but retains any consistent directional component of the drift. Again, averaging until the farthest point of the trajectory was chosen to ensure that the velocity was not underestimated in looping trajectories. Most of the directional velocity estimates fell below 1°/s (largely overlapping green and magenta curves, bin size 0.25°/s). 4) *Mean and peak smoothed drift velocity* was calculated by linearly interpolating eye position records to 1 KHz and then smoothing them with a Gaussian filter of σ=10 ms (see Figure S11). This procedure eliminated most of the instrumental noise from the records but kept the position fluctuations intact.

A   Fixational   Voluntary
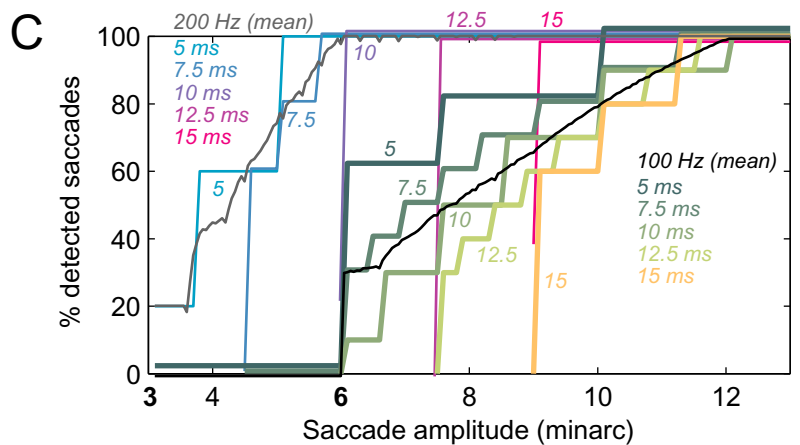
Covariance coefficient

Saccade-Drift Difference

B

Covariance coef.

Min latency (ms)

Peak latency (ms)

pos   mix   sac

pos   mix   sac

Supplementary Figure S2
Kagan, Gur and Snodderly

Eye movements and neuronal firing in macaque V1

A

light (250 cells)

B

dark (83 cells)

not significant
significant

Supplementary Figure S3
Kagan, Gur and Snodderly

Eye movements and neuronal firing in macaque V1

A — fixational saccades in the light

B — fixational saccades in the dark

Firing rate (spikes/s)

Time from saccade onset (ms)

Supplementary Figure S4

Kagan, Gur and Snodderly

Eye movements and neuronal firing in macaque V1

A

(1) saccade amplitude 12.1 minarc, duration 10 ms, 100 Hz eye position sampling rate - 100% detection

Eye position (minarc)

Velocity (deg/s)

-shift

+shift

- sampled at 100 Hz
- "actual" (1000 Hz)

(2) saccade amplitude 6.1 minarc, duration 5 ms, 100 Hz eye position sampling rate - 60% detection

Eye position (minarc)

Velocity (deg/s)

(3) saccade amplitude 8.1 minarc, duration 10 ms, 100 Hz eye position sampling rate - 50% detection

Eye position (minarc)

Velocity (deg/s)

Saccade onset relative to sampling (ms)

B

data from panel A(1)

Onset estimation shift (ms)

+shift

-shift

Saccade onset relative to sampling (ms)

C

200 Hz (mean)
5 ms
7.5 ms
10 ms
12.5 ms
15 ms

% detected saccades

12.5   15

10

7.5

5

100 Hz (mean)
5 ms
7.5 ms
10 ms
12.5 ms
15 ms

5

7.5

10

12.5

15

Saccade amplitude (minarc)

Supplementary Figure S6

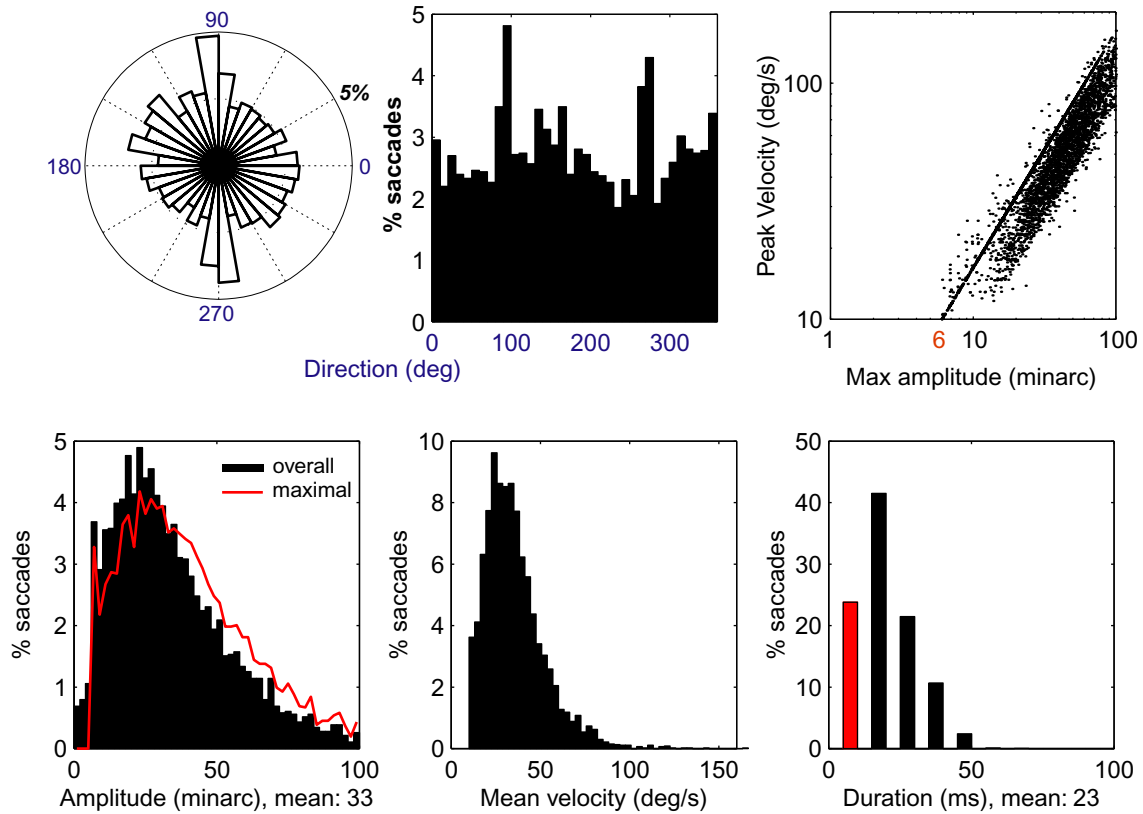*Kagan, Gur and Snodderly*

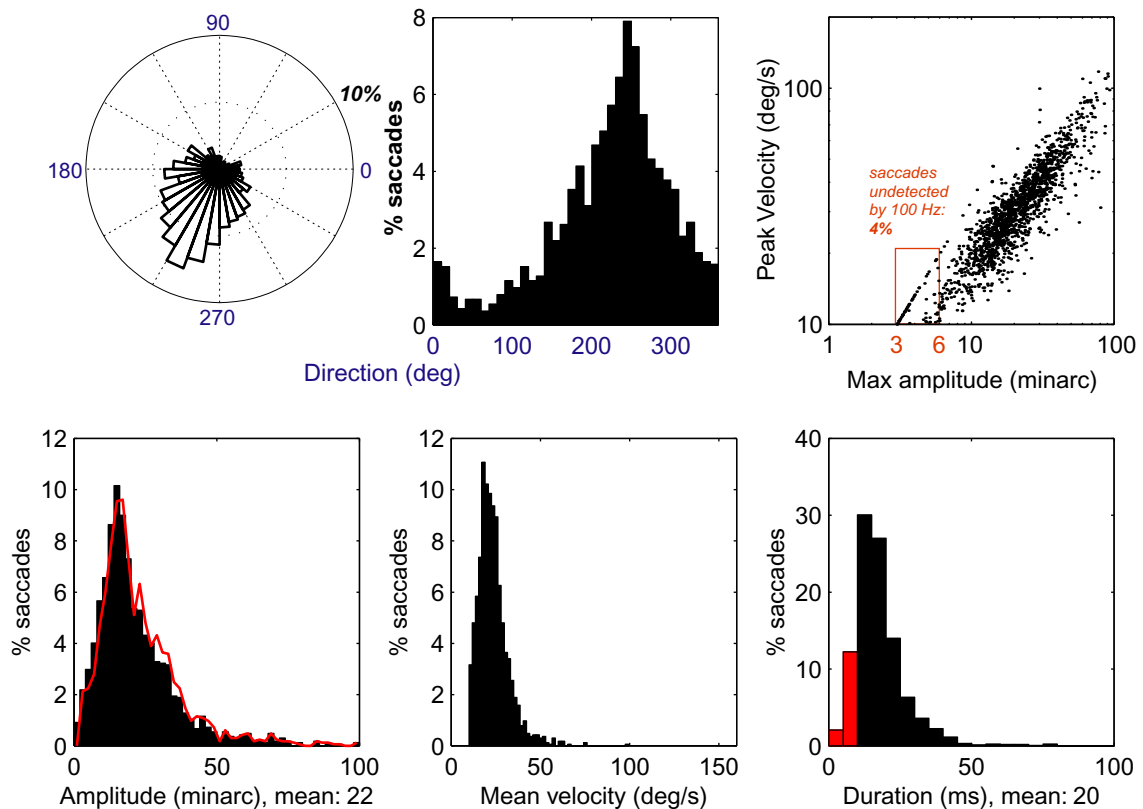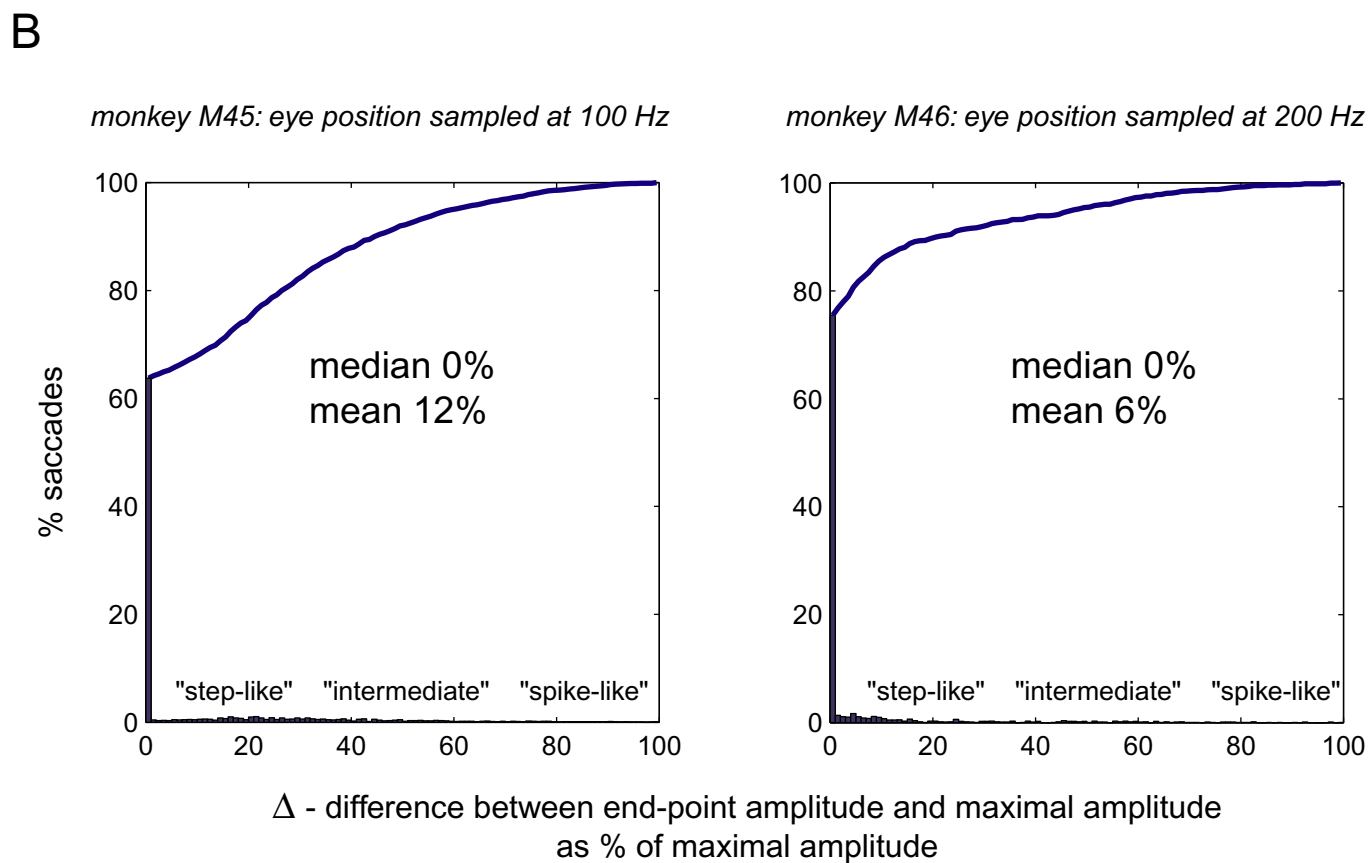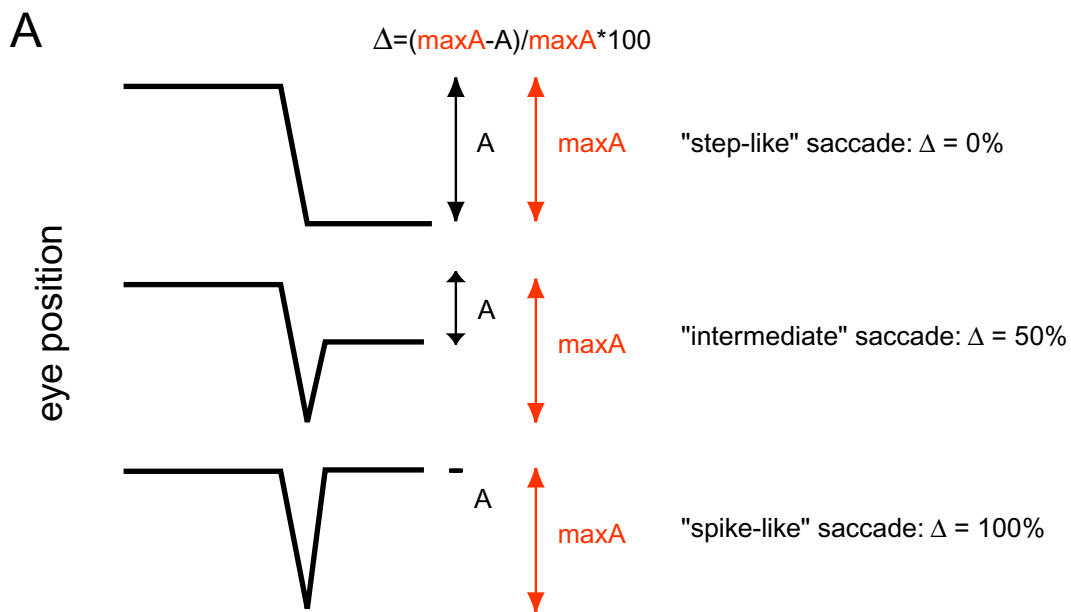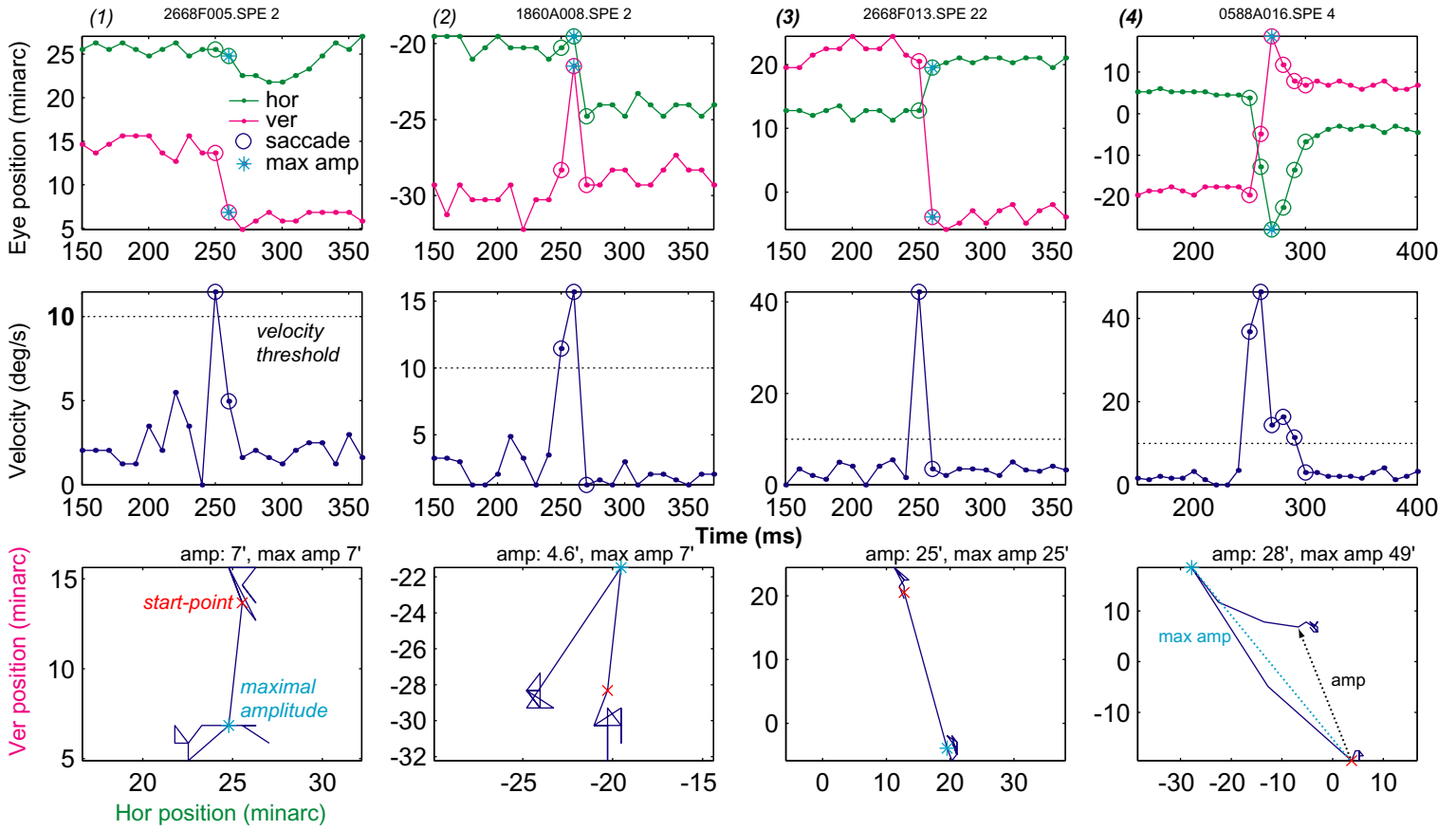Eye movements and neuronal firing in macaque V1

monkey M45: eye position sampled at **100 Hz**, 53 neurons - FIXATIONAL SACCADES

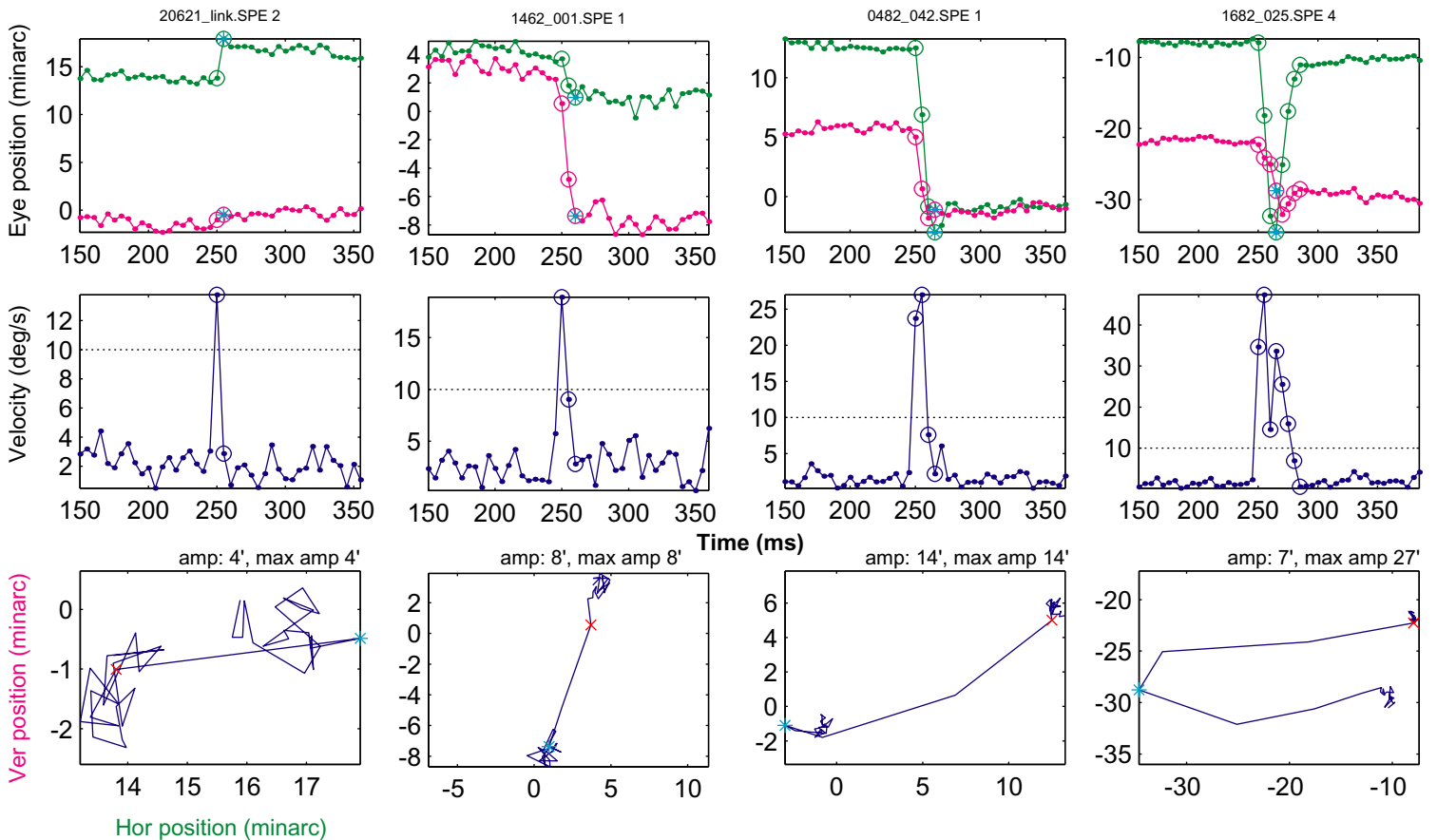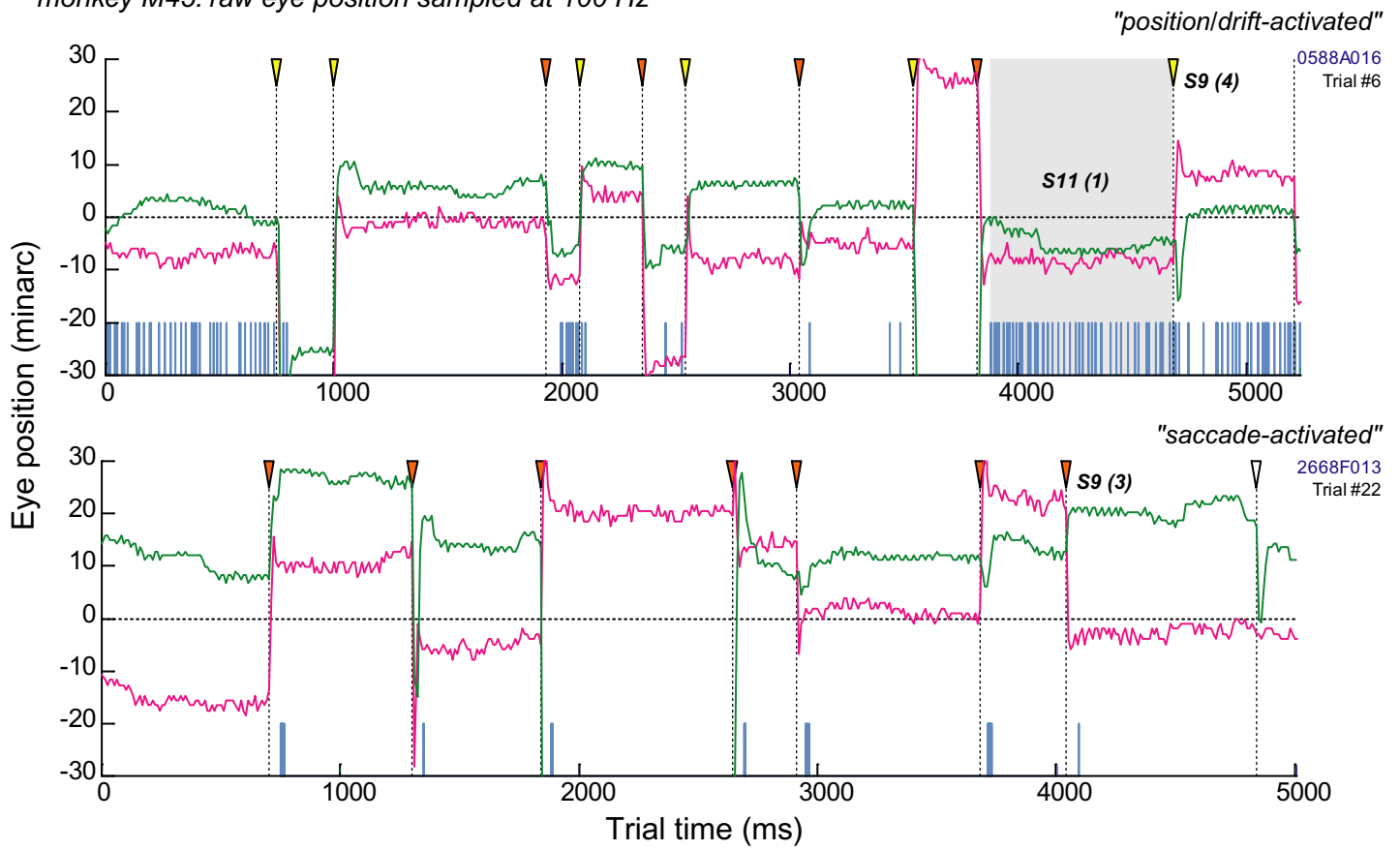monkey M46: eye position sampled at **200 Hz**, 65 neurons - FIXATIONAL SACCADES

Supplementary Figure S7
Kagan, Gur and Snodderly

Eye movements and neuronal firing in macaque V1

A

$\Delta = (maxA-A)/maxA*100$

"step-like" saccade: Δ = 0%

"intermediate" saccade: Δ = 50%

"spike-like" saccade: Δ = 100%

eye position

A   maxA

A   maxA

A   maxA

B

monkey M45: eye position sampled at 100 Hz

monkey M46: eye position sampled at 200 Hz

% saccades

median 0%
mean 12%

median 0%
mean 6%

"step-like"   "intermediate"   "spike-like"

"step-like"   "intermediate"   "spike-like"

Δ - difference between end-point amplitude and maximal amplitude
as % of maximal amplitude

Supplementary Figure S8
Kagan, Gur and Snodderly

Eye movements and neuronal firing in macaque V1

monkey M45: raw eye position sampled at 100 Hz - FIXATIONAL SACCADES

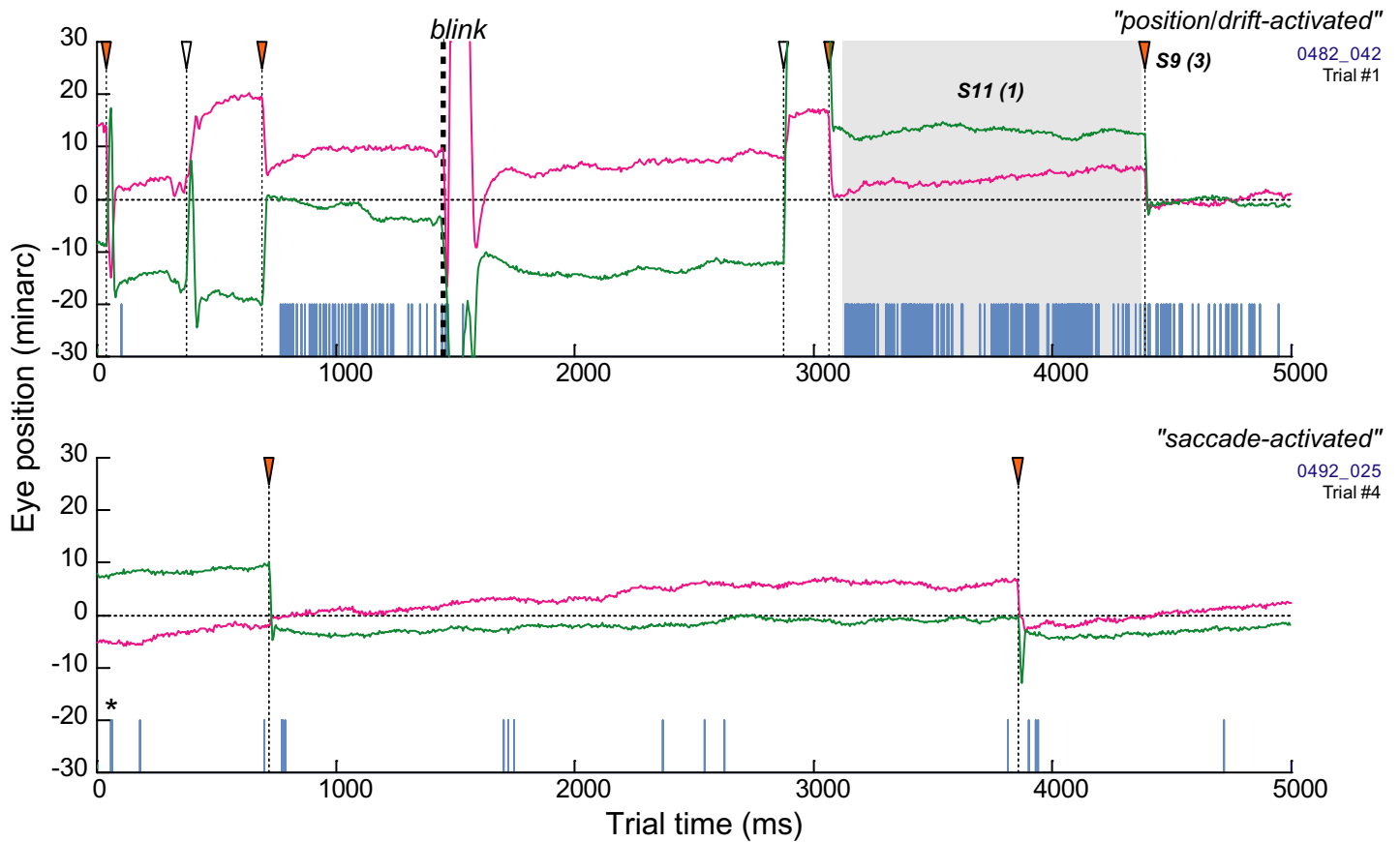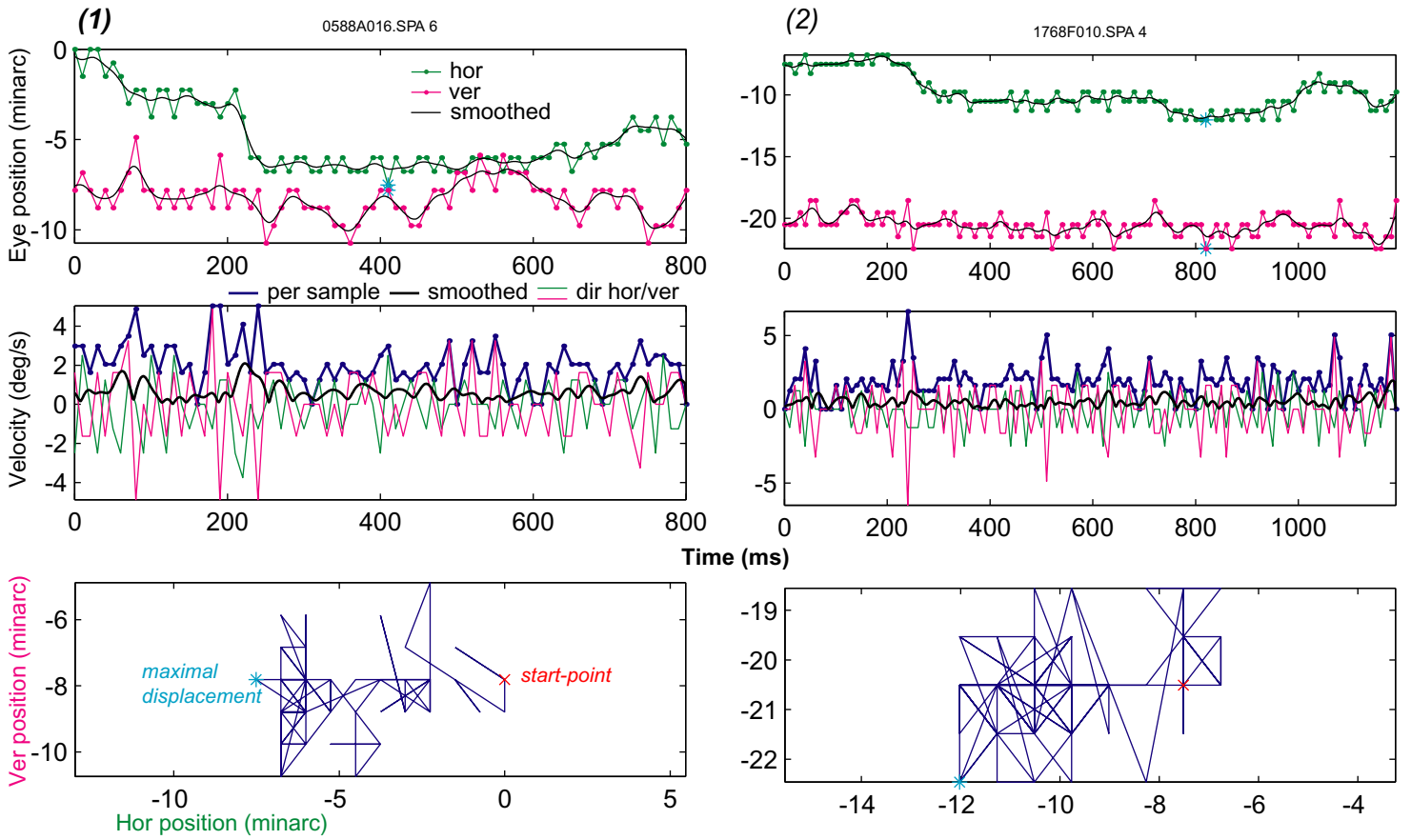*monkey M46: raw eye position sampled at 200 Hz - FIXATIONAL SACCADES*

Supplementary Figure S9
Kagan, Gur and Snodderly

Eye movements and neuronal firing in macaque V1

monkey M45: raw eye position sampled at 100 Hz

"position/drift-activated"
0588A016
Trial #6
S9 (4)
S11 (1)

"saccade-activated"
2668F013
Trial #22
S9 (3)

monkey M46: raw eye position sampled at 200 Hz

"position/drift-activated"
0482_042
Trial #1
blink
S11 (1)
S9 (3)

"saccade-activated"
0492_025
Trial #4

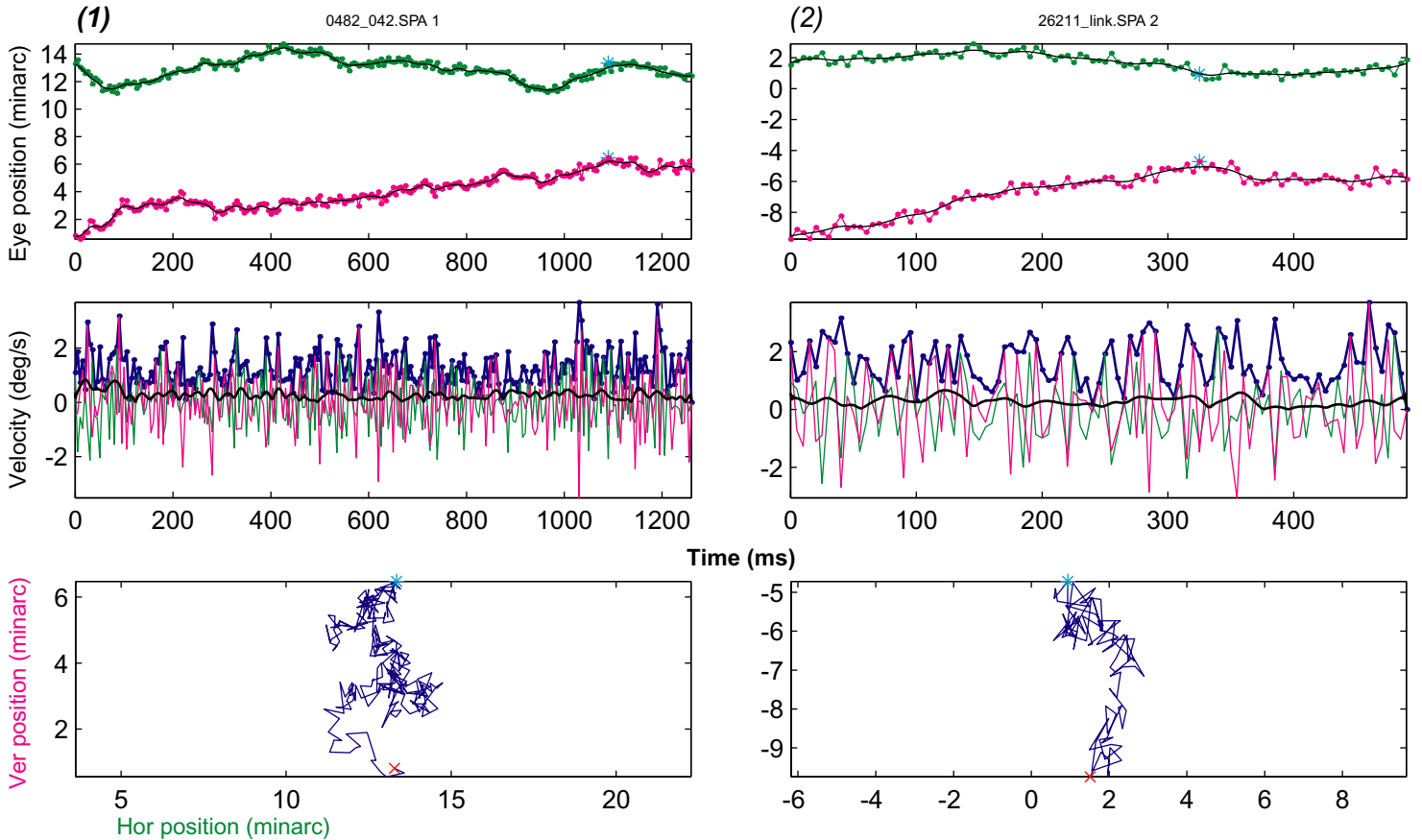**Supplementary Figure S10**
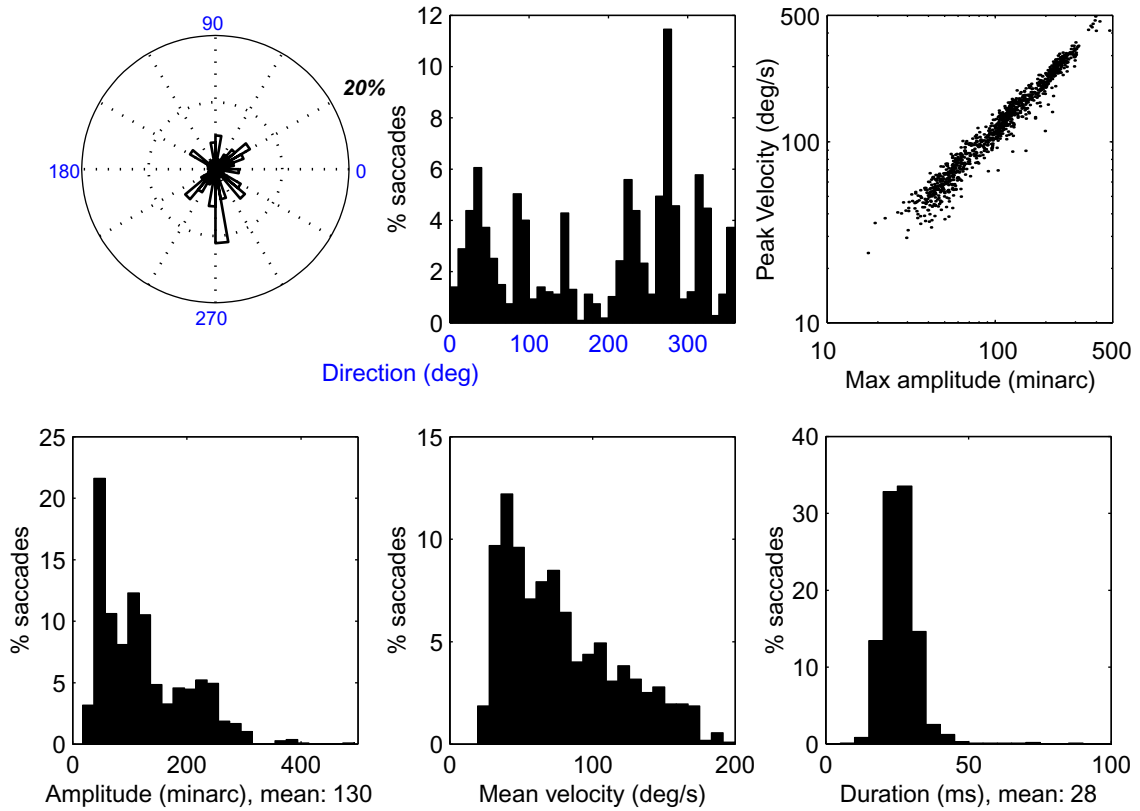*Kagan, Gur and Snodderly*   Eye movements and neuronal firing in macaque V1

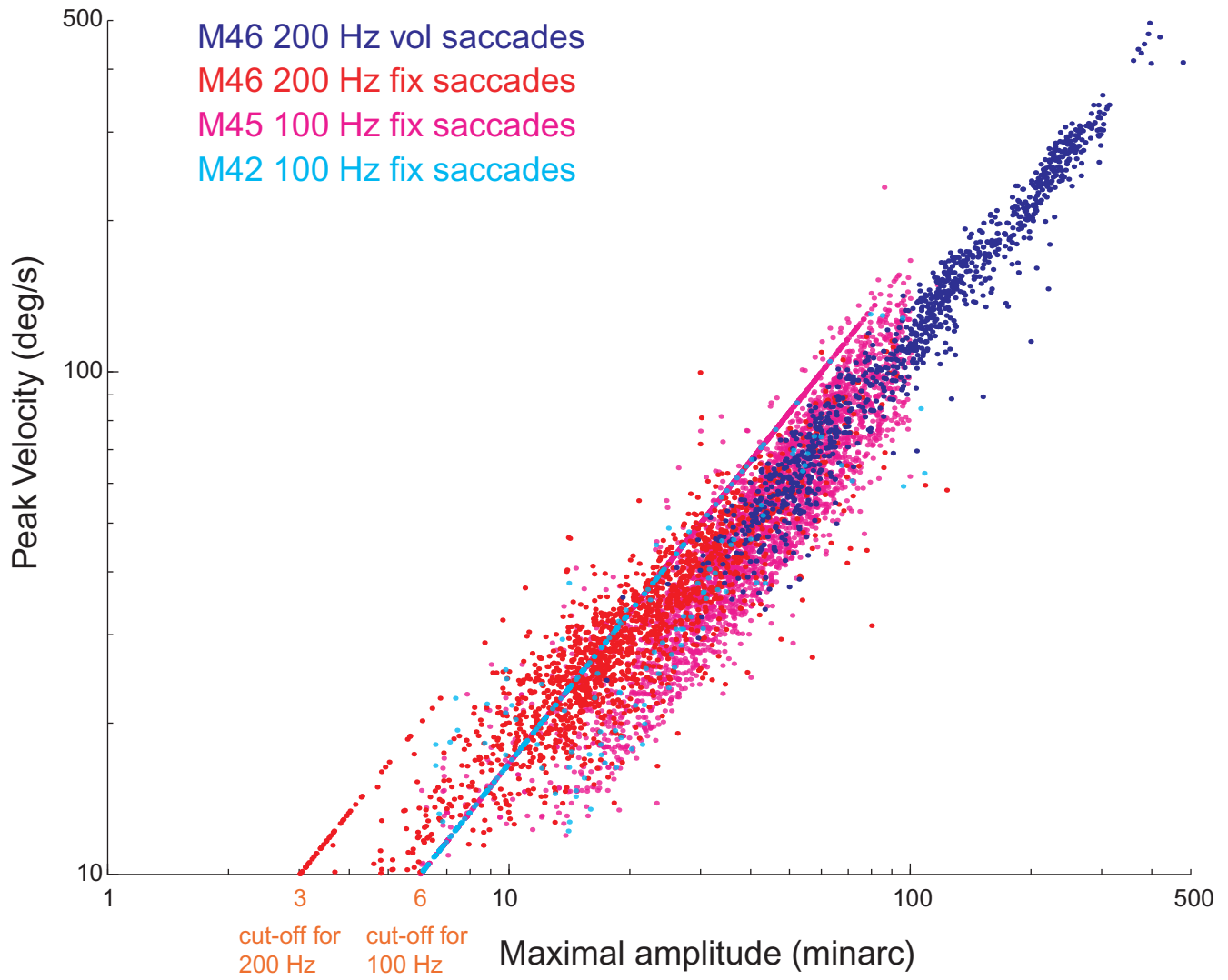*monkey M45: raw eye position sampled at 100 Hz - FIXATIONAL DRIFTS*

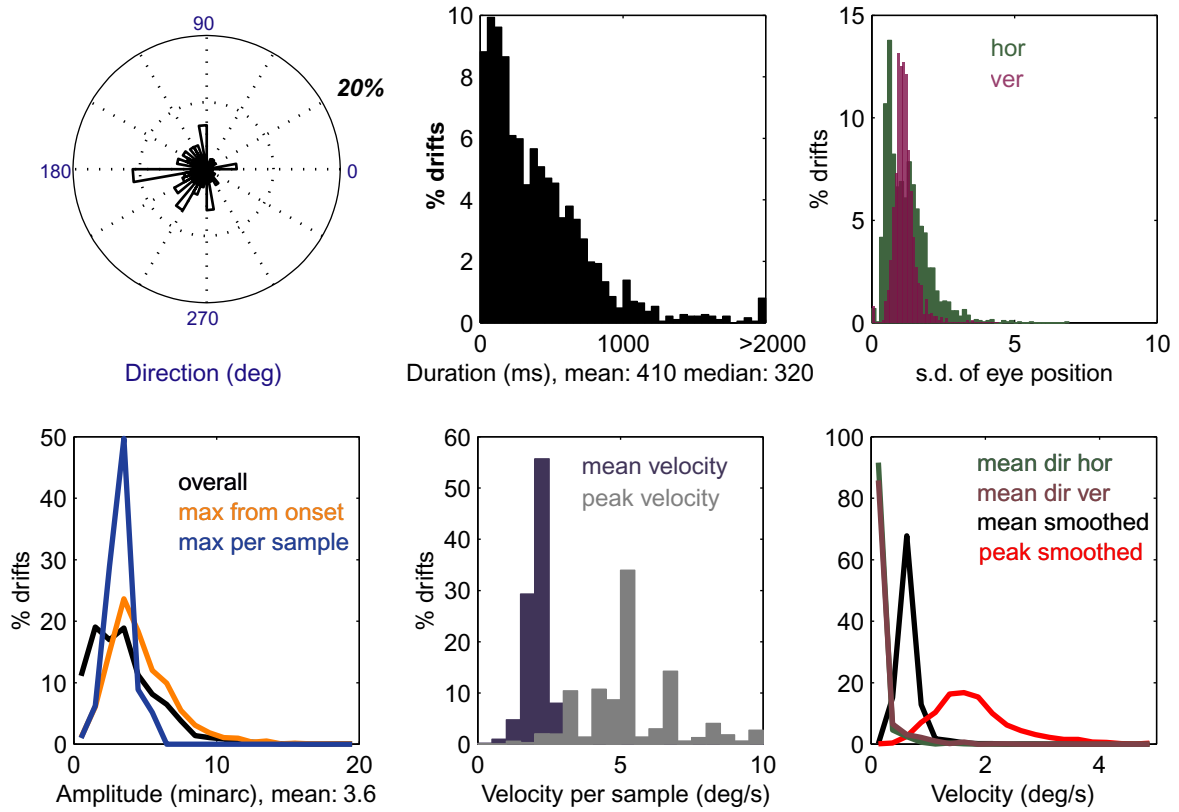*monkey M46: raw eye position sampled at 200 Hz - FIXATIONAL DRIFTS*

Supplementary Figure S11
Kagan, Gur and Snodderly   Eye movements and neuronal firing in macaque V1

monkey M46: eye position sampled at 200 Hz, 44 neurons - VOLUNTARY SACCADES

Peak Velocity (deg/s)

M46 200 Hz vol saccades
M46 200 Hz fix saccades
M45 100 Hz fix saccades
M42 100 Hz fix saccades

cut-off for
200 Hz

cut-off for
100 Hz

Maximal amplitude (minarc)

Supplementary Figure S13
Kagan, Gur and Snodderly

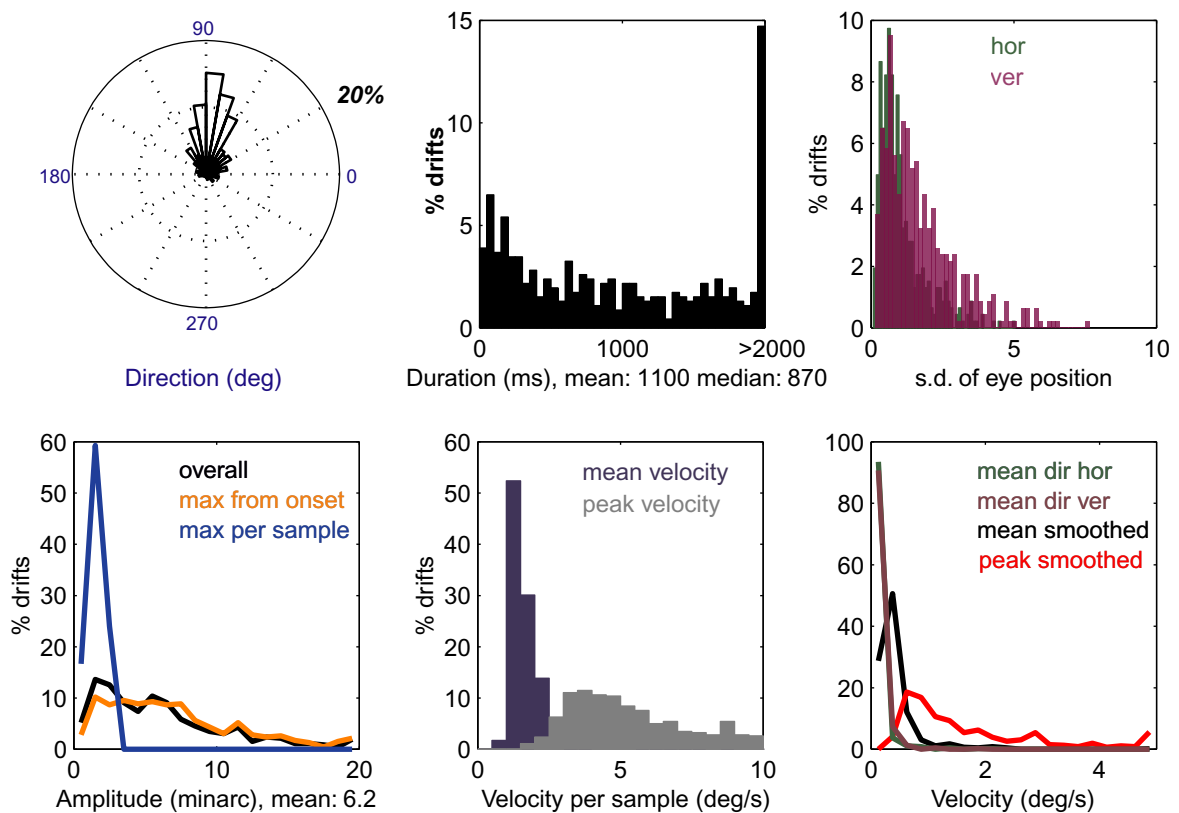Eye movements and neuronal firing in macaque V1

monkey M45: eye position sampled at 100 Hz, 53 neurons - DRIFTS

monkey M46: eye position sampled at 200 Hz, 65 neurons - DRIFTS

Supplementary Figure S14
Kagan, Gur and Snodderly

Eye movements and neuronal firing in macaque V1