Supplemental Data

Flexibility of Sensory Representations in Prefrontal Cortex Depends on Cell Type

Cory R. Hussar and Tatiana Pasternak

**Supplementary Figure S1**

![Supplementary Figure S1](image)

**Figure S1. Direction selectivity of narrow-spiking and broad-spiking neurons**

We determined whether the previously reported differences between the two classes of neurons in breadth of their tuning for various stimulus dimensions (Diester & Nieder, 2008; Nowak et al, 2008; Rao et al, 1999) also hold for motion direction. The data were collected at the start of recording sessions, during the direction discrimination task used to determine the preferred direction for each cell. During this task the monkeys discriminated 90° direction differences with equally spaced 8 directions of motion. Direction selectivity (DS) was determined by computing
ROC values for the activity recorded during the sample for all stimulus responsive neurons (NS = 26, BS = 91). Firing rates were analyzed for the period of 100-500ms after stimulus onset.

a. Reliability of DS for each cell group. The average DS value for NS neurons (0.72) was somewhat higher than that for BS neurons (0.68), but that difference did not reach significance (p = 0.15; Mann-Whitney U test). b. The significance of DS for each neuron was evaluated by the bootstrap analysis (see Methods). The incidence for NS (81%) and BS cells (74%) was similar (p=0.84, chi-squared test), suggesting that both classes of neurons were equally likely to carry reliable direction selective signals.

c. Tuning for direction of NS and BS neurons. The activity of all cells in response to the preferred direction was normalized to the 0° direction. For this analysis, the available data for all non-suppressive NS (N=15) and BS (N=35) neurons was averaged for each of the 8 directions used during the task. The mean responses were fitted with a Gaussian function with four free parameters: minimal rate, maximum height, preferred direction, and width. The fits were then normalized by subtracting the minimal rate and dividing by the maximal rate. The width at half-heights (0.5) of the normalized response was then taken as the tuning width of each cell type. This analysis revealed the tuning width of 128° for NS cells and 79° for BS cells. Significance of this difference in tuning was tested by a bootstrap test as follows. For each of the 2000 repetitions, the data for individual neurons of both types were chosen at random with replacement from the entire sample of neurons. Average activity of all cells was then taken and the difference between these two shuffled samples was recorded. The resulting distribution of shuffled tuning width differences was compiled. The actual difference in tuning width was deemed significant if it fell in the top or bottom 2.5% of the distribution (p<0.05, 2-tailed t-test). Despite the relatively large difference in the mean tuning width between the two cell groups (49°), this difference failed to reach statistical significance (p = 0.08). The most likely
explanation for this failure is that the data contributing to each direction were based on only 5 trials, the number adequate for estimating the preferred direction of a neuron but not ideal for estimating its tuning width.
Figure S2. Comparison of DS of individual neurons across tasks

**a, b.** DS of individual neurons during the speed and the direction tasks. DS was computed for activity recorded during the period of 200-400ms after stimulus onset, by determining the area under the ROC curve (AROC). The value of 0.5 indicate non-DS activity, the value of 1 indicates that activity dominated by the preferred direction while values between 0.5 and 0 indicated that the anti-preferred activity dominated the response. The data for the narrow-spiking (NS) and broad-spiking (BS) neurons are shown by red and blue symbols, respectively. The data for the sample (a) show an overall significant decrease in DS for the NS and BS neurons (p=0.002 and p=0.007 respectively; Wilcoxon sign-rank test). The magnitude of this loss of direction selectivity was significantly greater in NS neurons (p =0.04, Mann-Whitney U). During the test (b) the decrease in DS was highly significant for both cell types.

**c.** Average DS during the sample and the test based on the data shown in a,b. Note, that both classes of neurons show decreased DS during the speed task, with the exception of BS neurons during the sample. This data confirm the data in Figs 4a-d and 5a-d showing the time-course of DS during the sample and the test.
**d, e.** DS of individual neurons recorded during the passive fixation and during the direction task. The details of the analysis are the same as in a-c. During the sample and the test there was an overall decrease in DS for both classes of neurons. **f.** Average DS during the sample and the test based on the data shown in d,e. The plot illustrates the dramatic decrease of DS during passive fixation.
Figure S3. Direct comparison of task effects for neurons tested in all three tasks.

While every attempt was made to record the activity of each neuron during all three tasks, we were able to obtain such data from 30 neurons (9 NS, 21 BS). This provided the opportunity for the direct comparison of DS during the two tasks that did not involve direction discrimination. In general, the pattern of results for these neurons was nearly identical to that found for the entire
sample of neurons presented in Figs 4 and 5. **a.** Direction selectivity of neurons tested during all three conditions. NS neurons showed large loss in selectivity during the speed and the passive fixation tasks. On the other hand, BS neurons showed only a modest change during the speed task, but a large loss during passive fixation. **b.** Comparison of task effects during the speed task and the passive fixation tasks. Scatter plots compare task effects for individual neurons (difference between DS during the speed (or passive fixation task) and DS during the direction task). **c.** Average task effects for the subset of neurons with sufficient data in all three conditions. Comparisons of the mean task effect for NS neurons (red) and BS neurons (blue) are shown for sample and test responses during the speed task (dark) and passive fixation (light). The difference between the strength of task effect between speed and passive fixation was not found to be significant for NS neurons (sample = 0.84, test = 0.17; Wilcoxon sign-rank test). However, BS neurons showed a significantly stronger loss in direction selectivity during passive fixation compared with the loss in the speed task (sample = 0.01, test = 0.03; Wilcoxon sign-rank test).
Supplementary Figure S4

**Figure S4. Task-driven changes in preferred and anti-preferred responses of individual neurons.**

The data in figures 6 and 7 show the average change in preferred and anti-preferred responses that underlie the observed task effects on DS. We were interested whether the changes in individual neurons in both cell groups in preferred and anti-preferred responses were correlated. For example, a drop in the response of a given neuron to both directions could be indicative of gain changes. However, uncorrelated changes in the response to the two directions would be indicative of a more active process.
The data plotted in this figure illustrate how individual neurons showing DS during the direction task changed their responses to each of the two directions during the two tasks not involving direction discrimination, the speed discriminations task (a) and passive fixation task (b). The change in activity during the direction task (abscissa) is compared to the change during the speed or passive fixation task (ordinate). This change, was computed for each neuron as

\[
\frac{\text{response}_{\text{speed(passive)}} - \text{response}_{\text{direction}}}{\text{response}_{\text{speed(passive)}} + \text{response}_{\text{direction}}} \]

Each data point represents a period of 300ms at the time of each neurons strongest change in DS and to remove any contributions of a baseline shift the mean activity in the 200ms preceding each response was subtracted.

The inserts in the top left quadrant in a provide a key to changes in responses in each quadrant; black arrows pointing up or down indicate an increase or decrease in activity, respectively. Positive values on both axes indicate an increase in response while negative values indicate a decrease. The positive and negative diagonals represent an equivalent increase or decrease in preferred and anti-preferred activity. The data points along the positive diagonal represent cells with little or no change in DS across tasks. The data points to the left of the positive diagonal (shaded area) represent an unequal change in preferred and anti-preferred responses and a decrease in DS. Conversely, the data points to the right of that diagonal represent an unequal change in rates indicative of an increase in DS. The graphs below each plot provide a close-up of the data on a finer scale.

To examine whether changes in preferred and anti-preferred responses were correlated we fitted the data with regression lines (NS cells, solid red line; BS cells, solid blue line) and computed the Pearsons correlation coefficients (Table in c). During the speed discrimination task (a), BS neurons showed a significant positive correlation between the changes in the preferred and anti-preferred direction of motion only during the test (r=0.38, p=0.01), while NS
cells showed no significant correlations between the changes in their preferred and anti-preferred responses. During passive fixation (b), positive correlations were present for both classes of neurons. BS neurons exhibited positive correlations during both the sample and test, and NS neurons showed a strong positive correlation during the test \( (r= 0.73, p=0.02) \).

This analysis reveals both similarities and differences in the way the two cell classes adjusted their DS. BS neurons showed largely parallel changes in their responses to the two directions with positive correlations under nearly all conditions. This pattern suggests that BS cells modulate their selectivity largely through changes in their response gain, increasing or decreasing their activity together. Conversely, NS cells showed no significant correlations in the way these cells changed their activity in response to the two directions pointing to an alternative, more active mechanism involved in the regulation of DS. The exception was strong positive correlation in NS responses during in the passive fixation task during the test, the stimulus that concludes each trial. These results show that putative inter-neurons have access to alternative mechanisms regulating their response selectivity that become operational dependent on the behavioral significance of a given stimulus.
Supplementary Figure S5

Figure S5. Task effects on baseline activity.

The analysis of baseline activity was based on firing rates recorded during the last 200ms of the fixation period preceding sample onset. a, b. Comparison of baseline activity recorded during the speed task (a) and the passive fixation task (b) compared to that recorded during the direction task. During the speed task, only BS neurons showed a small but significant change (increase) in firing rates (BS cells,
\[ p = 0.02; \text{NS cells, 0.33, Wilcoxon sign-rank test}. \] During passive fixation, neither cell class showed a significant change in average baseline activity (BS, \( p=0.92; \text{NS}=0.07, \text{Wilcoxon signed-rank test} \)), although within each group many individual neurons exhibited significant effects. Specifically, 72\% of NS cells and 50\% of BS cells showed a significant changes in baseline. The majority of NS cells with significant baseline changes showed lower firing rates. BS cells also showed changes in baseline, although their effects were less consistent, with 34\% of these neurons showing significant increase and 38\% showing a decrease. \( c, d \). Task effects for baseline activity, computed as

\[
\frac{(\text{baseline}_{\text{task}} - \text{baseline}_{\text{direction}})}{(\text{baseline}_{\text{task}} + \text{baseline}_{\text{direction}})}.
\]

The histograms illustrate the distribution of task effects on baseline activity among individual neurons. Filled columns indicate cells with significant shifts in baseline activity between tasks (Mann-Whitney U, \( p < 0.05 \)). Note the consistent shift to the right (higher baseline) for BS cells during the speed task and less consistent changes in baseline activity of these cells during the passive fixation task.
Supplementary Figure S6

**Figure S6. Firing rates and direction selectivity measured at the start and the end of direction discrimination sessions**

Since each recording session always began with direction discrimination task it is important to rule out the possibility that reduced DS observed during subsequent tasks was not due to the introduction of these tasks later in the recording session. To check for this possibility we compared firing rates and DS recorded during the first and the last 15 trials of the direction discrimination task. To check for this possibility we compared the preferred and anti-preferred responses of all sample responsive DS cells used in the main analysis (n=75). Each testing session consisted of 200 trials and lasted 45-60 minutes. Thus, the first and the last 15 trials were separated by approximately 50 minutes. Activity was averaged 100-500ms from the onset of the sample stimulus. **a. Normalized responses of individual neurons to preferred and anti-preferred directions of each neuron.** The response of each neuron to each direction was normalized by the average response to the two directions. The data show no significant difference in the average activity measured at the beginning and the end of the direction discrimination session for either cell class (NS: p=0.18; BS: p=0.74, Wilcoxon signed-rank test). **b. DS**
recorded during the first and the last 15 trials of the direction discrimination task. DS Index (DI) was calculated as the difference between the mean activity to the preferred and anti-preferred response divided by their sum. The DI, rather than the AROC, was used to compute direction selectivity because of the small number of trials used for the analysis. Activity was averaged 100-500ms from the onset of the sample stimulus. The data show no significant difference in DI measured at the start and the end of the direction discrimination session (NS: p=0.97; BS=0.72, Wilcoxon signed-rank test), suggesting the decrease in DS measured during the speed discrimination and the passive fixation tasks is unlikely to be due to the elapsed time.