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Neuronal modulations in visual cortex are associated with only one of multiple components of attention

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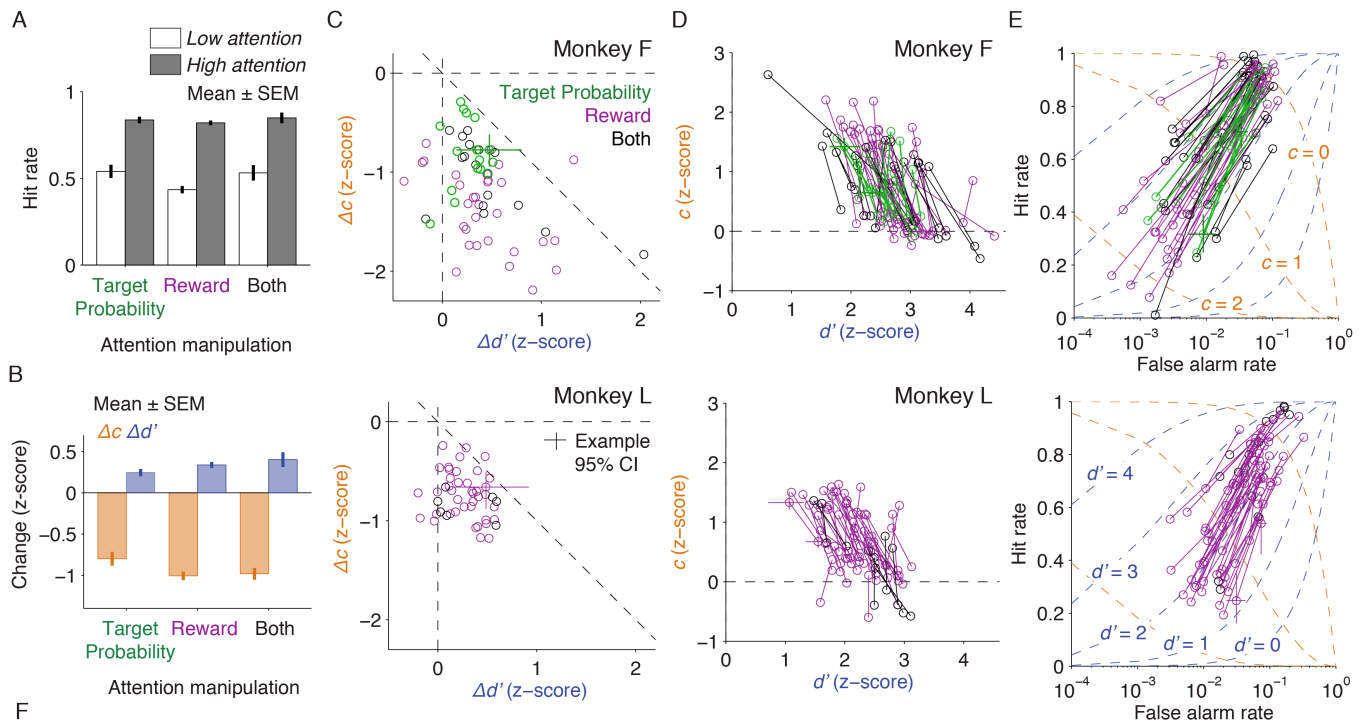
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SUPPLEMENTAL DATA



Median values of behavioral measurements across sessions.

	Monkey F				Monkey L				Both monkeys			
	Target Probability (n = 17)		Reward (n = 32)		Both (n = 16)		Reward (n = 43)		Both (n = 7)		All manipulations (n = 115)	
H	0.86	0.52	0.91	0.41	0.91	0.46	0.77	0.39	0.94	0.74	0.86	0.44
FA	0.05	0.01	0.06	0.004	0.05	0.005	0.07	0.02	0.13	0.03	0.06	0.01
<i>c</i>	0.28	1.10	0.08	1.48	0.13	1.28	0.31	1.25	-0.27	0.58	0.19	1.28
<i>d'</i>	2.68	2.44	2.91	2.46	2.99	2.54	2.26	1.94	2.75	2.48	2.68	2.33
Δc	-0.79		-1.29		-0.89		-0.73		-0.80		-0.90	
$\Delta d'$	0.24		0.41		0.35		0.29		0.21		0.34	

The first column (dark) is the *high attention* condition, and the second column (gray) is the *low attention* condition. Hit rates (H) and false alarm rates (FA) are unit-less. The unit for *c*, *d'*, Δc , and $\Delta d'$ is z-score.

Figure S1 [related to Figure 1]. Different attention manipulations in the standard attention task (preliminary experiment) all changed criterion and sensitivity between attention conditions.

Data are from the same sessions shown in Figure 1B, E and Figure S2. (A) In some sessions, attention was controlled by setting the target probability to be 2 to 4 times higher at the attended location ($n = 17$). In different sessions, the reward size was 2 to 4 times larger at the attended location ($n = 75$). In the remaining sessions, we changed both target probability and reward size ($n = 23$). All three manipulations increased the subject's hit rate between attention conditions. (B) Both criterion (*c*) and sensitivity (*d'*) changed between task conditions for all three manipulations. (C-E) Top: monkey F; bottom: monkey L. The bootstrapped 95% confidence interval is shown for a representative session for each monkey. (C) Changes in criterion (Δc) and sensitivity ($\Delta d'$) between attention conditions in each session. (D) Criterion (*c*) and sensitivity (*d'*) for attention condition of each session. Each circle represents the behavior in one attention condition of each session, and each line connects the two attention conditions of each session. (E) Plots of the hit rate and false alarm rate of each attention condition of

each session. Each circle represents the behavior in one attention condition of each session. Each solid line connects the two attention conditions of each session. Dashed lines indicate isosensitivity and isocriterion lines. Because the overall false alarm rates were low (~10% or less), the x-axis is plotted in logarithmic scale.

(F) Median values of behavioral measurements across sessions.

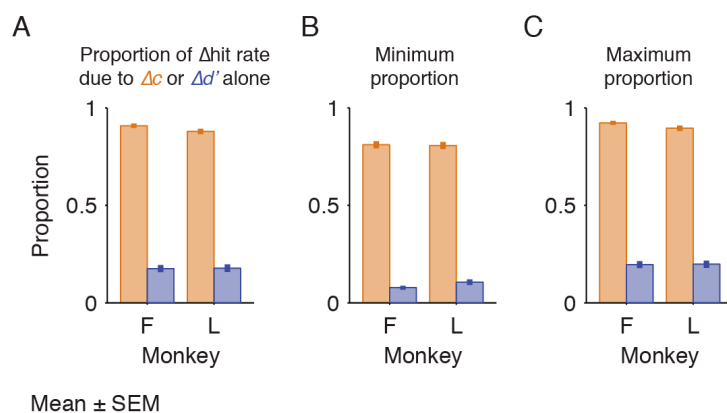
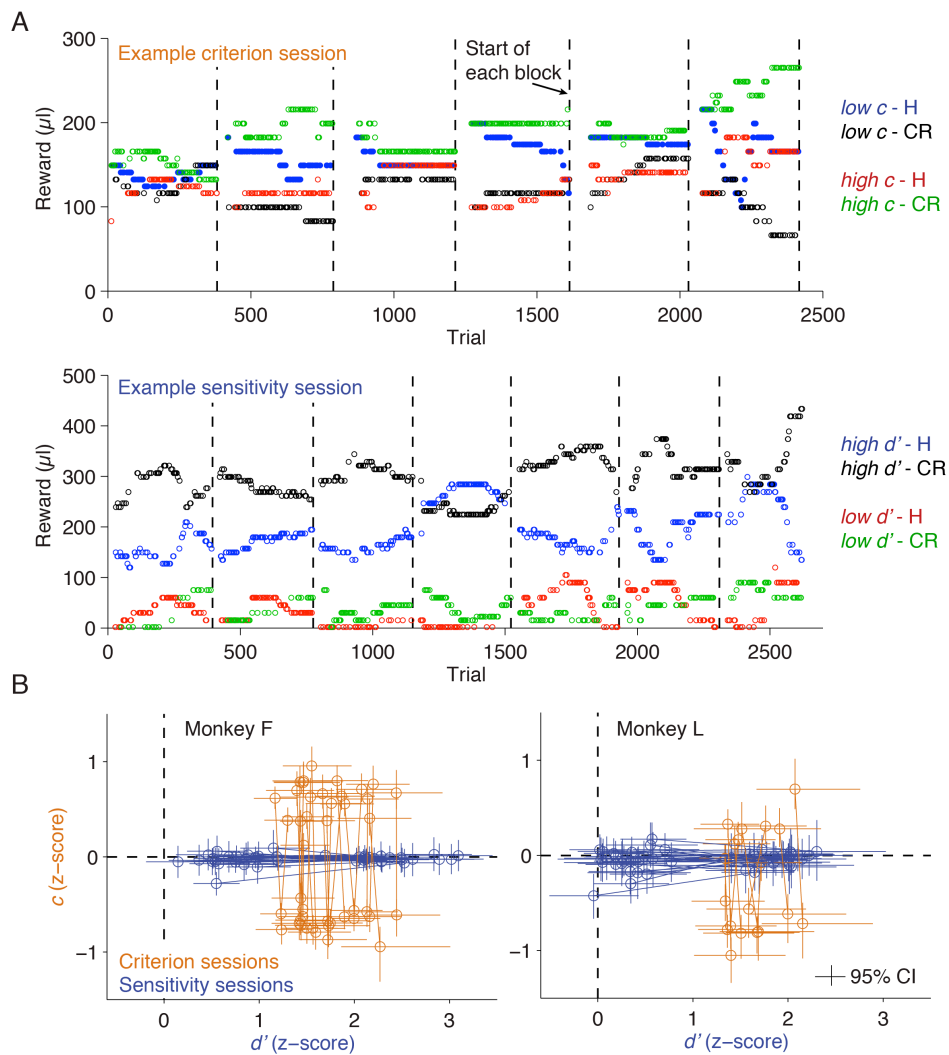


Figure S2 [related to Results]. Criterion changes accounted for most of the improvement in hit rate in the standard attention task (preliminary experiment). Same sessions as in Figure 1B, E and Figure S1. Monkey F, $n = 65$; monkey L, $n = 50$. (A) Because changes in both criterion and sensitivity contribute to the changes in hit rate, for each session we computed the proportion of the change in hit rate (ΔH) separately due to the change in criterion (Δc) or the change in sensitivity ($\Delta d'$). (B) Because Δc and $\Delta d'$ interact nonlinearly to produce the change in hit rate, we also computed the theoretically minimum proportions of the observed change in hit rate separately due to the observed Δc and $\Delta d'$. (C) The theoretically maximum proportions. All measures indicate that criterion changes accounted for most of the changes in hit rate in the standard attention task.



C

Median values of behavioral measurements across sessions.

	Monkey F				Monkey L			
	Criterion sessions (n = 22)		Sensitivity sessions (n = 22)		Criterion sessions (n = 10)		Sensitivity sessions (n = 25)	
	Low c	High c	High d'	Low d'	Low c	High c	High d'	Low d'
H	0.94	0.62	0.88	0.67	0.94	0.72	0.84	0.58
FA	0.44	0.07	0.14	0.37	0.49	0.17	0.18	0.47
c	-0.67	0.63	-0.02	-0.03	-0.76	0.22	-0.03	-0.04
d'	1.66	1.61	2.28	0.76	1.55	1.49	1.87	0.34
Δc	-1.34		0.02		-0.90		0.02	
$\Delta d'$	-0.001		1.72		0.03		1.60	

Hit rates (H) and false alarm rates (FA) are unit-less. The unit for c , d' , Δc , and $\Delta d'$ is z-score.

Figure S3 [related to Figure 2]. Control of sensitivity and criterion in the dissociation task. (A) Reward time course for an example criterion session and example sensitivity session. (B) Criterion (c) and sensitivity (d') of all sessions. Each circle plots the behavior of each task condition, and each line connects the two task conditions of each session. Error bars indicate 95% bootstrapped confidence intervals. (C) Median values of behavioral measurements across sessions. (B-C) Data are from the same sessions shown in Figure 2, Figure 3, Figure S4C, and Table 1.

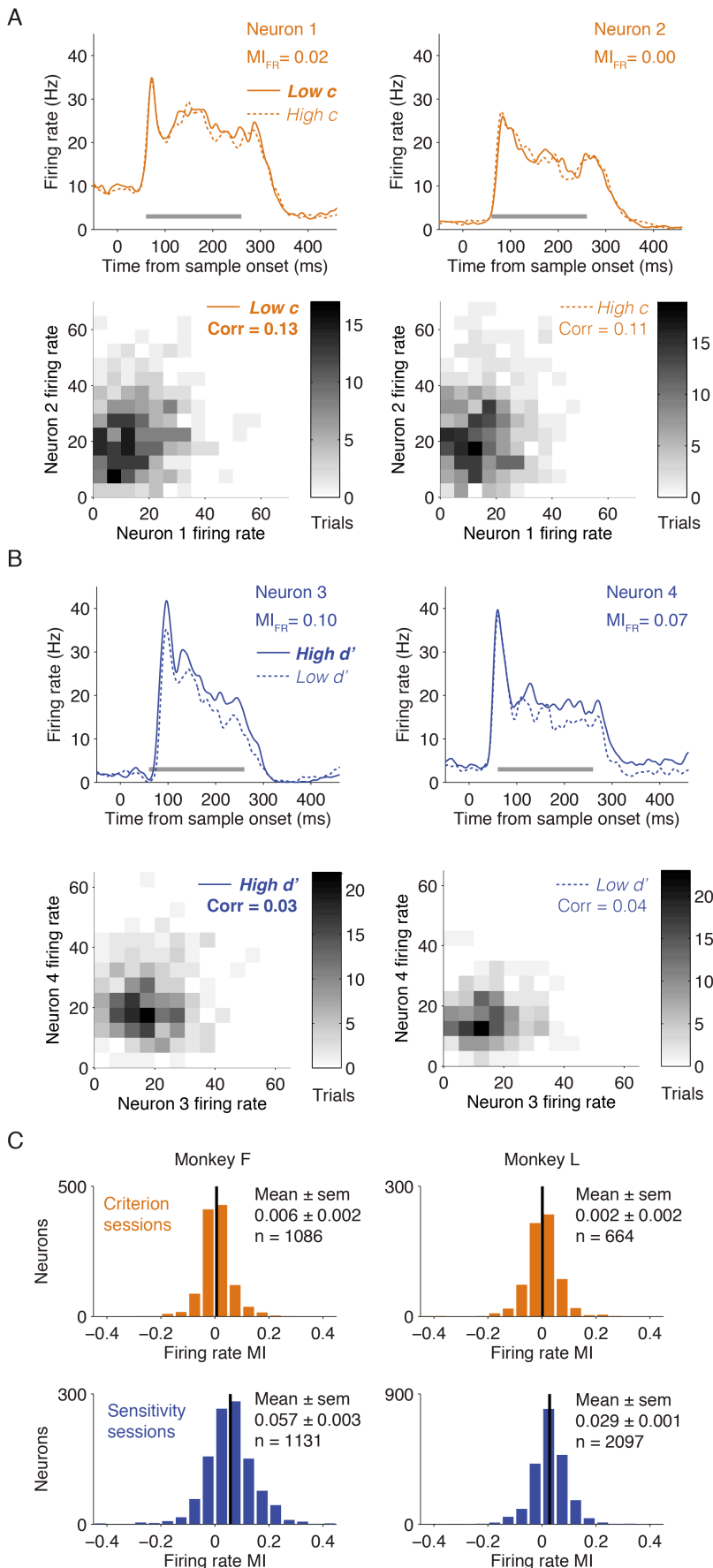


Figure S4 [related to Figure 3]. Changes in neuronal firing rate and pairwise correlations. (A) Two example neurons from a criterion session. Each of the top panels shows the trial-averaged PSTH of one neuron in the *low c* and *high c* task conditions. Gray bar indicates the trial epoch used to compute noise correlation (sample period; 60 ms to 260 ms after sample onset). Each of the bottom panels shows the noise correlation between the two neurons in either the *low c* or *high c* task condition. The color map for the correlations plots the numbers of trials for a given spike count pairing. (B) Two example neurons from a sensitivity session and their noise correlation in the *high d'* and *low d'* task conditions. Although large changes in pairwise correlations were evident for the population of neurons (Figure 3B), the data from individual neurons were noisy.

(C) The distribution of modulation indices of firing rate during the sample period (60 ms to 260 ms after sample onset) for all responsive neurons in criterion sessions and in sensitivity sessions.

SUPPLEMENTAL EXPERIMENTAL PROCEDURES

Neurophysiological Recording

Neuronal activity was recorded while the animal performed the dissociation task as part of the main experiment. Only behavior was recorded for the standard attention task as part of the preliminary experiment.

At the beginning of each recording session, we presented a variety of Gabor stimuli to characterize the receptive fields of the neurons, and then we optimized stimulus parameters in the dissociation task to drive as many neurons as possible. The stimulus inside the receptive fields of the recorded neurons was set to an orientation 90° from the orientation of stimulus in the opposite hemifield to minimize effects of feature attention. The receptive fields were in the lower hemifield and had eccentricities $2-4^\circ$ for monkey F and $5-7^\circ$ for monkey L.

Action potential waveforms were sorted offline using spike-sorting software (Plexon) that computes principal component analysis scores for each spike. Waveforms were classified as a single unit if the waveforms formed a cluster that was separate from other waveforms.

Neuronal Analyses

Neuronal Analyses – Inclusion of Neurons and Trials

A neuronal unit was classified as visually responsive if its firing rate in the sample period (60 ms to 260 ms after the onset of the sample stimulus) was on average greater than its firing rate during the fixation period (200 ms to 0 ms before sample onset), and if its responses in the two periods were significantly different ($p < 0.01$, t -test). The median number of responsive units per session and their percentage among all recorded units were 50 units and 88% for monkey F and 80 units and 93% for monkey L. Only responsive neurons were included in the PSTH in Figure 3A and in analyses of firing rate and Fano factor. All neurons regardless of responsiveness were considered for computing pairwise noise correlation (the results were almost identical if only responsive neurons were used).

Single units and multiunits were combined for analyses. Separate analyses for the two populations showed highly similar results, corresponding to previous findings (Cohen and Maunsell, 2009).

Both correct (H and CR) and incorrect (M and FA) trials were used for neuronal analyses, but we excluded trials with premature fixation breaks and priming trials. The results were highly similar if only correct trials were used instead of both correct and incorrect trials. We included both correct and

incorrect trials in the analyses because that would allow us to use the same set of trials to calculate behavioral and neuronal changes.

Neuronal Analyses – Noise Correlation and Fano factor

Noise correlation between each pair of simultaneously recorded neurons was computed as the Pearson's correlation coefficient of their firing rates across all trials.

$$\rho (FR_i, FR_j) = \frac{Cov (FR_i, FR_j)}{\sigma_i \sigma_j}$$

The noise correlation of the i^{th} neuron and j^{th} neuron, denoted $\rho (FR_i, FR_j)$, is the covariance of the firing rates of the two neurons across trials divided by the product of the standard deviations of each neuron's firing rates.

In Figure 3B, the noise correlation of each pair of neurons is binned according to the geometric mean of the evoked response of the two neurons. The evoked response of each neuron was calculated as the firing rate during the sample period (60 ms to 260 ms after sample stimulus onset), averaged across trials, minus the firing rate in the fixation period (200 ms to 0 ms before sample onset), also averaged across trials. The bin less than 0 spikes/s includes all pairs of neurons whose geometric mean evoked response is less than 0 spikes/s, and the bin greater than 30 spikes/s includes all pairs of neurons whose mean evoked response is greater than 30 spikes/s.

A single value of Fano factor was computed for each task condition of each session. For each task condition, the spike count variance of each responsive unit was plotted against its spike count mean, and we then fitted a line that was constrained to pass through zero. The slope of the regression line was then taken as the Fano factor. Similar results were found if we instead computed a single Fano factor for each responsive neuron in each task condition and then average across neurons to compute the Fano factor for that task condition.

Neuronal Analyses – Modulation Index

Modulation indices of firing rate were defined as the difference in mean firing rate between the two task conditions divided by the sum. In sensitivity sessions, the modulation index was defined such that a positive index indicates higher firing rates in the *high d'* condition.

$$MI_{FR}^{\Delta d'} = \frac{(FR_{high d'} - FR_{low d'})}{(FR_{high d'} + FR_{low d'})}$$

In criterion sessions, a positive index indicates higher firing rates in the *low c* condition (the task condition with the higher hit rate).

$$MI_{FR}^{\Delta c} = \frac{(FR_{low c} - FR_{high c})}{(FR_{low c} + FR_{high c})}$$

Modulation indices for noise correlation and Fano factor were similarly defined: a positive index indicates a higher value in the *high d'* condition in sensitivity sessions and a higher value in the *low c* condition in criterion sessions.

For firing rates, a modulation index was computed for each neuron and then averaged across the visually responsive neurons recorded in each session to provide a single modulation index for that session. Highly similar results were found if we pool spikes across visually responsive neurons to compute a population firing rate and calculate a modulation index of the population firing rate.

Noise correlation was first averaged across all pairs of simultaneously recorded neurons for each task condition. The noise correlation of the two task conditions of a daily session was then used to compute the modulation index for that session.

Fano factor was computed for each task condition as a single value (as described above), and the modulation index was calculated using the Fano factor of each condition.

In each session, the sample stimuli had one of two different orientations: the base or the base plus change (e.g. 40° and 60° in a session in which the orientation change was 20°). Modulation indices were computed separately for each orientation and then averaged between the two orientations to provide a single index for each session.

Standard Attention Task

The standard attention task was part of the preliminary experiment. Video display and visual stimuli were the same as those in the dissociation task of the main experiment. The standard attention task was a variant of the Posner attention paradigm frequently used in single-neuron studies of attention. In each trial, monkeys fixated within a 1.5° window in the center of a video display. Two Gabor stimuli flashed on for 200 ms and off for 200-400 ms, one in each visual hemifield. At an unexpected time, a target stimulus appeared in one of the two locations. The monkey had to look at the

target to receive a juice reward. The target was a change in the stimulus: an orientation change for monkey L and a small white spot in the center of the Gabor for monkey F. When the target appeared, the monkey had to saccade to it within 100-500 ms to receive a juice reward. The target could appear on the third through seventh stimulus presentation (selected from a uniform distribution to discourage guessing at the beginning of trials). No target appeared in 5% of the trials, and the monkey received a reward if it maintained fixation past the seventh stimulus appearance.

Monkeys alternated between blocks of 100-200 trials in which attention was directed to one of two locations. Attention was controlled by setting the target probability to be 2 to 4 times higher at the attended location, or in different sessions, the reward size to be 2 to 4 times larger at the attended location. In the remaining sessions, we changed both target probability and reward size.

To compute c and d' , each stimulus presentation in which a target could occur (third to seventh) was categorized as a hit (H), miss (M), false alarm (FA), or correct rejection (CR). Stimulus presentations with no target were classified as either correct rejections or false alarms, and presentations with a target were categorized as hits or misses. Each presentation that was categorized as a correct rejection was scored for both stimulus locations, and each presentation that was classified as a hit, false alarm, or miss was scored only for the stimulus location where the target occurred or the saccade was directed. For presentations that were hits, false alarms, or misses, it was equally valid to score a correct rejection for other stimulus location or not to do so. We tried both methods of scoring, and the results were highly similar because of the large number of correct rejections. We chose not to score a correct rejection for the other stimulus location for presentations that were hits, misses, or false alarms.

Dissociation Task

Dissociation Task – Reward Titration

At the beginning of each session, reward parameters were set to values that were expected to approximately isolate the behavioral difference appropriate for that session. As described in the Experimental Procedures, a difference between the H:CR reward ratio at each stimulus location results in a criterion difference between locations, and a difference between the overall reward size of the two locations results in a sensitivity difference between locations. However, the animal's criterion and sensitivity at each stimulus location fluctuates over the course of a session. If reward contingencies were kept constant throughout the session, we would not achieve reliable behavioral isolation throughout each session. To achieve reliable isolation within each session, we adjusted the reward

sizes by a small amount (typically 10%) to control for the animal's fluctuating criterion and sensitivity (reward time courses of two example sessions are shown in Figure S3A).

In criterion sessions, reward was titrated after every 10-20 trials. If the animal's d' fluctuates to be higher at one location than the other, the overall reward size for the location with higher d' would be decreased by a small amount, and reward at the location with lower d' would be increased by the same amount. The overall reward at the *low c* location averaged 90% of the reward at the *high c* location. The H:CR ratios were adjusted to keep the criterion at the *low c location* near $c = -1$ and at the *high c* location near $c = 1$. We found these values to produce the largest criterion difference while providing statistically reliable measures of c and d' given the number of trials an animal typically worked in a day.

In sensitivity sessions, after each miss trial at either location, the hit reward at that location would be increased by a small amount (typically 10%) and the CR reward at that location would be decreased by the same amount. After each FA trial, the CR reward would be increased by a small amount and the hit reward would be decreased by the same amount at the location of the error. The ratio in overall reward size between the *high d'* and *low d'* locations averaged 5:1, and this ratio was adjusted after every 10-20 trials. This difference in reward size between locations was adjusted to maximize d' difference while at the same time keeping the animal motivated to respond to the *low d'* location so that we could obtain accurate behavioral measures at that location.

Dissociation Task – Priming Trials

At the beginning of each task condition (one block of 240-360 trials), 10-80 priming trials were presented to habituate the monkey to the reward contingencies of that task condition. In priming trials, the test stimulus occurred at only one stimulus location, rather than appearing at a random one of the two locations. Priming trials were presented as a continuous sequence and never interleaved with non-priming trials and not used in behavioral or neuronal analyses.

Priming trials were important for producing large, isolated differences in criterion or sensitivity. Repeatedly testing the same location helped the animal to recognize the reward contingencies at that location and stabilized its behavior. Typically, priming trials were presented to test a single location until the monkey's behavior stabilized for that location, and then priming trials were presented to test the other location until behavior stabilizes there. Occasionally, a continuous sequence of 5-20 priming trials was presented in the middle of a block to stabilize the animal's behavior. On average, priming trials made up 8% of all trials in a session for monkey F and 10% of all trials for monkey L.

Dissociation task – Choice of Reward Parameters

We chose to manipulate reward size and not target probability (probability of an orientation change) because the animals adjusted their behavior more quickly to changes in reward size than to changes in target probability. This was expected, as changes in reward size are apparent within a single trial, whereas changes in target probability can only be assessed over many trials. We could achieve much finer control over the animal's behavior using reward size. Additionally, for a given number of trials, more reliable statistics of behavioral performance are obtained when target probability is 0.5.

Either reward size or target probability would likely elicit the same neuronal signal, because neuronal modulations associated with larger reward size and with higher target probability have similar magnitude and timing, and these two types of neuronal modulations are also strongly correlated among neurons in visual cortex (Stanisor et al., 2013).

One potential concern is that because the behavioral changes in d' are induced by differences in relative reward, it is plausible that corresponding neuronal changes are more closely associated with spatial differences in relative reward than with d' changes. But there is good reason to believe that the V4 neuronal changes are more closely associated with behavioral d' than with relative reward. Task difficulty modulates V4 responses in much the same ways as does attention (Spitzer et al. 1988; Boudreau et al., 2006; Ruff and Cohen, 2014), even though changes in task difficulty do not involve any change in relative reward. But, like higher relative reward, higher task difficulty increases behavioral d' . Because higher relative reward and higher task difficulty are two separate experimental manipulations that increase both the subject's d' and neuronal responses, we view the V4 modulations that we observed in this study to be more closely related to changes in d' than to changes in relative reward.

Dissociation Task – Sessions

On each day, the monkey performed only a criterion session or only a sensitivity session. We focused on isolating a single behavioral change each day to maximize the number of trials, which maximized the statistical reliability of the behavioral measurements of criterion and sensitivity.

Only two orientations were used for the sample and test stimuli at each location in each session. On each trial, either orientation was equally likely to be selected to be the sample, and the orientation was independently selected at each location. The difference between the two orientations specified the task difficulty for that session, and it was selected to keep the animal challenged.

Task difficulty was similar between criterion and sensitivity sessions for each monkey. For monkey F, the orientation change averaged 20° (16° to 23°) in criterion sessions and 18° (14° to 25°) in sensitivity sessions. For monkey L, the change was 90° for both criterion and sensitivity sessions.

The session type was alternated every six to eight days for monkey F. For monkey L, we alternated after 31 days, but neuronal signals from the array degraded after 41 days of recording. For each monkey and each session type, the results from the first half of the sessions were highly similar to the results to the second half.

Dissociation Task – Inclusion of Sessions

A session was excluded from analysis if the magnitude of the behavioral measure we sought to keep constant (c or d') had a z-score greater than 0.3 (resulting median 0.04) or if that measure was greater than 1/3 of the behavioral measure we sought to vary (resulting median ratio 1/34). We excluded 1 of 45 sessions for monkey F and 6 of 41 sessions for monkey L. Including these sessions in the analyses did not affect the conclusions.

Dissociation task – Confidence intervals

We calculated binomial confidence intervals for the hit rate and false alarm rate in each task condition (Figure 3C-D, Figure S1E). Confidence intervals for c and d' in each task condition (Figure S3B) were computed through a bootstrapping method assuming binomial error around the observed hit rate and false alarm rate. Confidence intervals were similarly calculated for the difference in c and d' between the two task conditions of each session (Figure 3E).

Methods for Figure S2

Figure S2A: Proportion of the change in hit rate (ΔH) separately due to criterion change (Δc) alone or due to sensitivity change ($\Delta d'$) alone

In most sessions, changes in both criterion and sensitivity contributed to the changes in hit rate between attention conditions in the standard attention task. Figure S2 shows analyses that isolate the proportion of the change in hit rate (ΔH) separately due to the change in criterion (Δc) or the change in sensitivity ($\Delta d'$). The intuition behind these analyses is to recalculate ΔH while keeping either c or d' to be the same in the *high attention* condition as in the *low attention* condition. The recomputed ΔH is then divided by the observed ΔH to obtain a proportion of the observed ΔH that is due to Δc alone or due to $\Delta d'$ alone.

We first denote the hit rate (H) as a function of c or d' :

$$H = \Phi\left(\frac{d'}{2} - c\right)$$

In this equation, Φ is the normal cumulative distribution function. The hit rate for each attention condition (*high attention* or *low attention*) can be denoted as a function of the c and d' measured in that condition.

$$H_{high\ attention} = \Phi \left(\frac{d'_{high\ attention}}{2} - c_{high\ attention} \right)$$

$$H_{low\ attention} = \Phi \left(\frac{d'_{low\ attention}}{2} - c_{low\ attention} \right)$$

For each session, the observed change in hit rate (ΔH) between the two attention conditions is the difference in hit rate between the *high attention* condition and the hit rate in the *low attention* condition.

$$\Delta H = H_{high\ attention} - H_{low\ attention}$$

$$\Delta H = \Phi \left(\frac{d'_{high\ attention}}{2} - c_{high\ attention} \right) - H_{low\ attention}$$

We first show the calculations for the proportion of ΔH due to Δc alone. To obtain this proportion, we recalculate ΔH as $\Delta H^{\Delta c}$, the change in hit rate solely due to the change in criterion. To compute $\Delta H^{\Delta c}$, we recalculated the hit rate for the *high attention* condition by fixing the d' to be the same as the d' in the *low attention* condition:

$$\Delta H^{\Delta c} = H_{high\ attention}^{d'\ equalized} - H_{low\ attention}$$

$$\Delta H^{\Delta c} = \Phi \left(\frac{d'_{low\ attention}}{2} - c_{high\ attention} \right) - H_{low\ attention}$$

The expression for $H_{high\ attention}^{d'\ equalized}$ is the expression for $H_{high\ attention}$ except that $d'_{high\ attention}$ is changed to $d'_{low\ attention}$. Finally, to obtain the proportion of ΔH solely due to the Δc , we divided $\Delta H^{\Delta c}$ by observed ΔH .

$$\text{Proportion of } \Delta H \text{ due to } \Delta c \text{ alone} = \frac{\Delta H^{\Delta c}}{\Delta H}$$

We then similarly calculate the proportion of ΔH due to $\Delta d'$ alone. To obtain this proportion, we need to calculate $\Delta H^{\Delta d'}$, the change in hit rate solely due to the change in sensitivity.

$$\Delta H^{\Delta d'} = H_{high\ attention}^{c\ equalized} - H_{low\ attention}$$

$$\Delta H^{\Delta d'} = \Phi \left(\frac{d'_{high\ attention}}{2} - c_{low\ attention} \right) - H_{low\ attention}$$

In the second equation, the first term is the expression for $H_{high\ attention}$ except with $c_{high\ attention}$ changed to $c_{low\ attention}$. Finally, to obtain the proportion of ΔH solely due to the change in d' , we divided $\Delta H^{\Delta d'}$ by the observed ΔH .

$$\text{Proportion of } \Delta H \text{ due to } \Delta d' \text{ alone} = \frac{\Delta H^{\Delta d'}}{\Delta H}$$

These proportions are computed for each session and averaged across sessions to provide the plot in Figure S2A.

Figure S2B-C: Minimum and maximum proportions of the change in hit rate (ΔH) separately due to criterion change (Δc) alone or due to sensitivity change ($\Delta d'$) alone

The analyses shown in Figure S2B and S2C were performed because Δc and $\Delta d'$ interact nonlinearly to determine ΔH . For each session we computed the theoretically minimum and maximum proportions of the observed ΔH separately due to the observed Δc and $\Delta d'$.

We first show computations for the minimum proportion of observed ΔH that could be attributed to the observed Δc . To obtain this proportion, we needed to calculate $\Delta H_{min}^{\Delta c}$, the minimum ΔH that could be attributed to Δc . In calculating $\Delta H_{min}^{\Delta c}$, criterion values for both attention conditions are not changed from the observed values, while d' is a parameter that is varied to minimize the difference in hit rate between attention conditions.

$$\Delta H_{\min}^{\Delta c} = \min_{d'} \left[H_{\text{high attention}}^{\text{varying } d'} - H_{\text{low attention}}^{\text{varying } d'} \right]$$

$$\Delta H_{\min}^{\Delta c} = \min_{d'} \left[\Phi \left(\frac{d'}{2} - c_{\text{high attention}} \right) - \Phi \left(\frac{d'}{2} - c_{\text{low attention}} \right) \right]$$

$$d' \in \left[d'_{\text{low attention}}, d'_{\text{high attention}} \right]$$

A single value of d' is chosen for both attention conditions to minimize $\Delta H_{\min}^{\Delta c}$. This value of d' is selected from the interval delimited by the observed d' values in the *low attention* and *high attention* task conditions ($d'_{\text{low attention}}$ and $d'_{\text{high attention}}$, respectively). The d' that minimizes $\Delta H_{\min}^{\Delta c}$ was obtained using the MATLAB algorithm *fminbnd*. Finally, we obtained the minimum proportion of observed ΔH that could be attributed to the observed Δc :

$$\text{Minimum proportion of } \Delta H \text{ due to } \Delta c = \frac{\Delta H_{\min}^{\Delta c}}{\Delta H}$$

We similarly computed maximum proportion of observed ΔH that could be attributed to the observed Δc :

$$\Delta H_{\max}^{\Delta c} = \max_{d'} \left[H_{\text{high attention}}^{\text{varying } d'} - H_{\text{low attention}}^{\text{varying } d'} \right]$$

$$\Delta H_{\max}^{\Delta c} = \max_{d'} \left[\Phi \left(\frac{d'}{2} - c_{\text{high attention}} \right) - \Phi \left(\frac{d'}{2} - c_{\text{low attention}} \right) \right]$$

$$d' \in \left[d'_{\text{low attention}}, d'_{\text{high attention}} \right]$$

$$\text{Maximum proportion of } \Delta H \text{ due to } \Delta c = \frac{\Delta H_{\max}^{\Delta c}}{\Delta H}$$

The minimum and maximum proportions of observed ΔH that could be attributed to the observed $\Delta d'$ were similarly calculated. We first computed $\Delta H_{\min}^{\Delta d'}$ and $\Delta H_{\max}^{\Delta d'}$, the minimum and maximum ΔH that could be attributed to $\Delta d'$. To obtain $\Delta H_{\min}^{\Delta d'}$ and $\Delta H_{\max}^{\Delta d'}$, sensitivity values for both

attention conditions are not changed from the observed values, while c is a parameter that is varied to minimize or maximize the difference in hit rate between attention conditions.

$$\Delta H_{\min}^{\Delta d'} = \min_c \left[H_{high\ attention}^{varying\ c} - H_{low\ attention}^{varying\ c} \right]$$

$$\Delta H_{\min}^{\Delta d'} = \min_c \left[\Phi \left(\frac{d'_{high\ attention}}{2} - c \right) - \Phi \left(\frac{d'_{low\ attention}}{2} - c \right) \right]$$

$$c \in \left[c_{high\ attention}, c_{low\ attention} \right]$$

$$\Delta H_{\max}^{\Delta d'} = \max_c \left[H_{high\ attention}^{varying\ c} - H_{low\ attention}^{varying\ c} \right]$$

$$\Delta H_{\max}^{\Delta d'} = \max_c \left[\Phi \left(\frac{d'_{high\ attention}}{2} - c \right) - \Phi \left(\frac{d'_{low\ attention}}{2} - c \right) \right]$$

$$c \in \left[c_{high\ attention}, c_{low\ attention} \right]$$

A single value of c is chosen for both attention conditions to minimize $\Delta H_{\min}^{\Delta d'}$ or maximize $\Delta H_{\max}^{\Delta d'}$, and this value comes from the interval determined by observed c values in the *low attention* and *high attention* task conditions ($c_{low\ attention}$ and $c_{high\ attention}$, respectively). Finally, $\Delta H_{\min}^{\Delta d'}$ and $\Delta H_{\max}^{\Delta d'}$ are each divided by ΔH to obtain the proportions:

$$\text{Minimum proportion of } \Delta H \text{ due to } \Delta d' = \frac{\Delta H_{\min}^{\Delta d'}}{\Delta H}$$

$$\text{Maximum proportion of } \Delta H \text{ due to } \Delta d' = \frac{\Delta H_{\max}^{\Delta d'}}{\Delta H}$$

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