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Dissecting Modulatory Effects of Visual Attention in Primate Lateral Prefrontal Cortex Using Signal Detection Theory

Julio Martinez-Trujillo[1,2,3,4,*] and Roberto Adamo Gulli[1,2,4,5]
[1]Department of Physiology and Pharmacology, University of Western Ontario, London, ON N6A 5C1, Canada
[2]Robarts Research Institute, University of Western Ontario, London, ON N6A 5B7, Canada
[3]Department of Psychiatry, University of Western Ontario, London, ON N6C 0A7, Canada
[4]Brain and Mind Institute, University of Western Ontario, London, ON N6A 5B7, Canada
[5]Integrated Program in Neuroscience, McGill University, Montreal, QC H3A 2B4, Canada
*Correspondence: julio.martinez@robarts.ca
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In this issue of *Neuron*, Luo and Maunsell (2018) use signal detection theory to demonstrate that the modulatory effects of attention on neuronal responses in the lateral prefrontal cortex during change detection can be due to changes in an observer's sensitivity or shifts in their response criterion.

There are costs and benefits to any decision: issuing a response when one isn't warranted creates a false alarm; no response when there should be one is a miss. In the 1950s, engineers formalized signal detection theory (Marcum, 1952), which provides a quantitative framework for factors that affect hit rates and false alarm rates. In signal detection theory, the separation between the distribution of noisy signal measurements with no stimulus present versus the distribution of signal measurements when a stimulus is present (Figure 1A) is termed "sensitivity" or "discriminability" (*d'*). The threshold signal measurement at which one chooses to report the presence of a stimulus is termed "bias" or "decision criterion" (*c*).

A decision-maker may manipulate *d'* and *c* to alter the proportion of hits, misses, false alarms, and correct rejections (Figures 1B–1D). A decision-maker may improve *d'* by reducing the overlap between signal and noise distributions (Figures 1B and 1D). Alternatively, the decision-maker may value hits and false alarms differently, and alter *c* accordingly (Figures 1C and 1D). Churchill once claimed, "I never worry about action, only inaction." As an executive decision-maker, he'd exhibit a liberal criterion, favoring false alarms to missed responses. A conservative decision-maker would rather withhold a response in uncertain circumstances.

Psychophysicists have widely applied signal detection to isolate changes in *d'* and *c*. However, electrophysiological studies of attention in macaque monkeys have not done so systematically. Decades of study in macaques have shown that attention modulates firing rates of individual neurons throughout the brain, increasing the gain of tuning curves (Treue and Martínez Trujillo, 1999), changing noise correlations (Cohen and Maunsell, 2009), or changing response variability (McAdams and Maunsell, 1999). However, most studies have quantified the performance of the animals as the proportion of correct responses (hits) relative to chance as a proxy for demonstrating attentional modulation. Since most studies do not manipulate correct rejections rates, it is not clear whether changes in *d'* or *c* are linked to the behavioral or neurophysiological response modulation.

To address this, Luo and Maunsell conducted a clever series of studies using an attention paradigm to incentivize monkeys to independently modulate *d'* or *c* during a detection task (Luo and Maunsell, 2015, 2018). Briefly, a trial started with a Gabor patch appearing on each side of a central fixation point (Figure 1E, Sample). After a short disappearance, a patch re-appeared on one side, with the same or a different orientation (Cue). If the orientation changed, monkeys responded with a saccade (Test). Thus, there were four possible trial outcomes: orientation change with a response (hit) or no response (miss), or no orientation change with a response (false alarm) or no response (correct rejection).

In half of all sessions, changes in *c* were achieved by increasing the relative reward for correct rejections versus hits in one hemifield or the other (the average reward across hemifields was unchanged; Figure 2C of Luo and Maunsell, 2018). This incentivized monkeys to withhold responses (conservative, high *c* condition) in ambiguous trials within one hemifield. The reward contingencies per hemifield would later switch, such that only changes in *c* within each hemifield, rather than global effects of arousal, could account for changes in neural activity. In the remaining half of sessions, isolated changes in *d'* were achieved by simultaneously increasing the reward for both hits and correct rejections in one hemisphere at a time (relative reward value for hits and correct rejections was unchanged; Figure 2D of original manuscript). This incentivized monkeys to improve performance in the high-reward hemifield without a bias toward hits or correct rejections. Again, alternating blocks of high-reward trials between each hemifield negated global effects.

Luo and Maunsell recorded from neurons in the right lateral prefrontal cortex (LPFC) (areas 8A and 45/46) of two animals and found that the neurons' responses were modulated by both changes in *d'* and changes in *c*. Both modulations were qualitatively similar and correlated on a cell-by-cell basis (Figure 1F), suggesting that the same population of neurons is modulated in

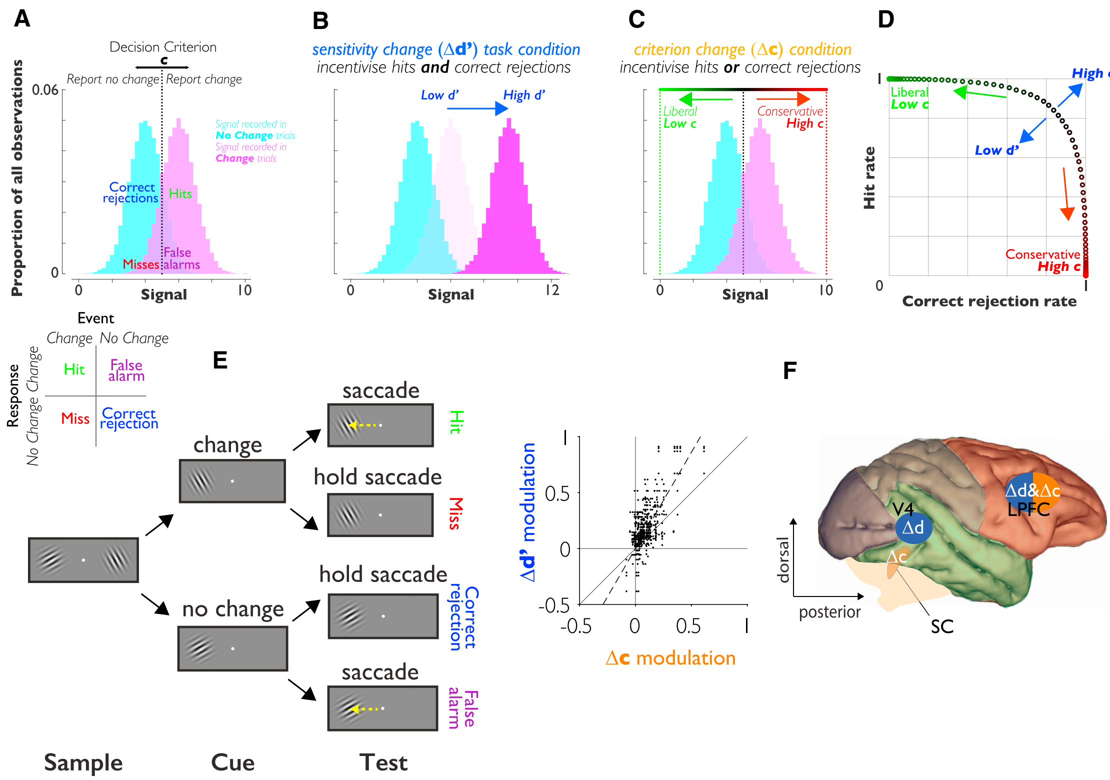

Figure 1. Modulation of PFC Neuronal Activity by Changes in Sensitivity and Bias

(A) Noisy distributions of signal are recorded in trials with a change in the stimulus (purple) or no change in the stimulus (cyan). The observer's sensitivity describes how much of each distribution overlaps. The observer's decision criterion (dotted line) marks the minimum signal measurement at which they report a change. Therefore, each report has one of four possible outcomes: hit, miss, correct rejection, or false alarm.
(B) Changes in sensitivity (*d'*) reduce the overlap between distributions. This changes hit rates and correct rejection rates when the criterion is kept at the isopleth.
(C) Changes in criterion (*c*) affect the observer's report independently without changes in signal distributions.
(D) A schematic of the effect of *d'* or *c* changes on hit rates and correct rejection rates.
(E) Luo and Maunsell (2018) use a change detection paradigm with four possible trial outcomes at the change detection test phase. Incentivizing monkeys to favor hits versus correct rejections in some sessions, and hits and correct rejections in other sessions, allowed the authors to determine the effect of each on neuronal activity in lateral prefrontal cortex (LPFC) (reproduced from Luo and Maunsell, 2018 with permission).
(F) Activity of LFPC neurons was modulated by changes in *d'* and changes in *c* (reproduced from Luo and Maunsell, 2018 with permission). The magnitude of each effect was correlated across individual neurons. In contrast, previous studies showed only *d'* affects neuronal activity in V4, while *c* primarily affects neuronal activity in the superior colliculus.

both scenarios. Interestingly, in a previous study using the same paradigm, the authors showed that neurons' firing rates in visual area V4 are modulated by shifts in *d'*, but not in *c* (Luo and Maunsell, 2015). These results can be considered in conjunction with two recent studies in the superior colliculus (SC) (Lovejoy and Krauzlis, 2017; Sridharan et al., 2017). They found that SC contributes to attention through changes in both *d'* and *c*, with the latter being the dominant contribution. Though these studies did not use the same paradigm as Luo and Maunsell, their conclusions may still be complementary. In area V4, closer to the sensory end of the sensorimotor transformation, attentional modulation is mainly linked to changes in *d'*; in the LPFC, an executive control area, attentional modulation is linked to both changes in *d'* and *c*; finally, in the SC, closer to the motor end of the transformation, attentional modulation is mainly linked to changes in *c* (Figure 1F).

It is tempting to hypothesize that the results of these studies reflect a fundamental principle of how cognitive control systems favor the processing of behaviorally relevant signals along different areas of the sensorimotor transformation. The LPFC, an executive center that encodes priority maps (Tremblay et al., 2015), can send signals to sensory and premotor regions. Signals reaching sensory regions such as V4 can affect separation between signal and noise (*d'*) (Luo and Maunsell, 2015). Signals reaching premotor regions, such as SC, could modify decision criterion (*c*) and thus whether or not to trigger a motor response (Koval et al., 2011). Importantly, with *d'* and *c* as orthogonal decision variables, behavioral flexibility expands.

It would be very informative to determine whether this framework implied by Luo and Maunsell can be generalized to discrimination tasks, or to paradigms where multiple stimuli are located inside the neurons' receptive field (Treue and Martínez Trujillo, 1999) and the attentional modulation is the strongest. Furthermore, whether modulations associated to *d'* and *c* within a region are layer specific remains unclear. Future studies using emerging technologies are well positioned to address these issues.

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