Long Range Cortical Interactions During Comparison of Sensory and Cognitive Information

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Abstract

Adapting our behavior to our environment depending on contextual demands involves large, distributed networks of cortical and subcortical areas. Prefrontal (PFC) and lateral intraparietal area (LIP) process both sensory and cognitive factors in very similar manner. However, their respective contributions to visual processing and cognitive control remain largely unclear. In this study, macaque monkeys performed a modified delay-match to sample task while we simultaneously recorded neuronal activity from V4, LIP and PFC. We show differential PFC/LIP dynamics: PFC exhibits successive encoding of different cognitive processes, while LIP shows more stable representations that integrate both sensory and cognitive signals.

Keywords: Decision making; cognitive control; working memory; prefrontal cortex; parietal cortex

Introduction

Decision making relies on complex cognitive operations. The prefrontal cortex (PFC) has historically been associated with executive control, working memory (WM) and attention (Buschman & Miller, 2007; Curtis & D'esposito, 2004; Miller & Cohen, 2001). Similarly, areas from the posterior parietal cortex such as the lateral intraparietal area (LIP) exhibit similar activations patterns during WM, decision making, and spatial attention (Freedman & Ibos, 2018). While such cognitive mechanisms might emerge, at least partially, from long range cortical interactions between PFC and LIP (and possibly other areas), their respective influence on one another remains unclear (Sapountzis et al., 2018). Here, we study neural activity recorded in LIP, PFC and cortical area V4 during a complex decision making task, with the goal of disentangling their contributions to visual processing and cognitive control.

Results

Experimental approach

We recorded the activity of ~2000 V4, ~2000 PFC and ~500 LIP neurons from one macaque monkey performing a modified delayed match to sample (DMTS) task (Figure 1.A). Each trial starts when monkey holds a manual lever and gazes at a central fixation point. One sample stimulus composed of one of two colors and one of two orientations is presented either contra- or ipsilateral to the recording site. Following a variable delay, we present successions of 1 to 5 test stimuli (on sample's location) simultaneously with as many distractor stimuli (on the opposite location). Test and distractor stimuli are composed of one of eight colors and one of eight orientations. Monkey is rewarded for releasing a manual lever for test stimuli matching sample stimuli's location, color and orientation. In a subset of trials, neutral sample stimuli cued the monkey to wait passively until trials end. Beside sample identity, neutral and non-neutral trials were visually identical.

Cognitive and sensory subspaces

We used the first two components (explained variance: V4:58%; LIP:68%; PFC:53%) of PCA applied to population responses in order to identify low-dimensional neural subspaces specific to sensory stimulation and involvement of cognitive resources (Figure 1.B). Specifically, stimulus presentation moves V4 population activity along a single sensory axis, showing rotational dynamics whose amplitudes are modulated by cognition, consistent with attention related gain modulations of individual neurons. LIP population responses evolve in a subspace defined by two orthogonal axes specific to sensory stimulation and involvement of cognitive resources. Sample and test stimuli presentation of both neutral and non-neutral trials shifts population responses along sensory axis exclusively. However, engaging cognitive resources and retaining information in WM shift LIP activity along a cognitive axis, orthogonal to sensory axis. This suggests that LIP integrates both types of information independently. PFC dynamics are more complex, with activity evolving within one sensory and two cognitive subspaces, potentially reflecting different cognitive processes such as executive cognitive control or different aspects of WM.

PFC leads cognitive engagement

To determine whether sample's neutral status is sequentially processed within V4, LIP and PFC, we computed the Euclidean distance between neutral and non-neutral neural representations over time in the entire population space. When sample stimuli are located within neurons' receptive fields, population trajectories diverge simultaneously in each region (V4:85ms ($p<0.05$); LIP:85ms ($p<0.05$); PFC:85ms ($p<0.05$)). These similarities could be related to at least two factors: 1. Sensory discrimination of visual features composing neutral and non-neutral sample stimuli; 2. Influence of engaging cognitive resources on neuronal responses. In order to isolate the effect of cognitive factors, we applied similar analyses to conditions in which sample stimuli were presented outside neurons' receptive fields. It revealed a clear hierarchy with PFC leading LIP and V4 (V4:187ms ($p<0.05$); LIP:145ms ($p<0.05$); PFC:107ms ($p<0.05$)).

Overlapping networks in LIP

We next explored the dynamics of the neural code across time. We trained classifiers to decode sample stimuli's neutral status from each population activity (Figure 1.C). In V4, decoding performances show dynamic encoding during sample and delay, and stability during test epoch. In PFC, performances are initially stable during sample presentation but fail to generalize during delay and test epochs. However, PFC switches to stable encoding during delay and test epochs. This biphasic representation might reflect the initiation of cognitive control followed by different aspects of WM processing. Decoding performances in LIP are less dependent on task epoch and show higher stability across times. We interpret this stability as reflecting cognitive-dependent gating of bottom-up flow of sensory information integrated by LIP.

Summary

In this preliminary work we find that sensory processing predominantly involves V4 and LIP while cognitive information processing is prominent in a parieto-frontal network, with PFC being more dynamic and dimensional. These results reflect differential contributions to engagement of cognitive resources such as working memory. Future work and analyses will focus on further characterizing the different roles and computational mechanisms within this network.

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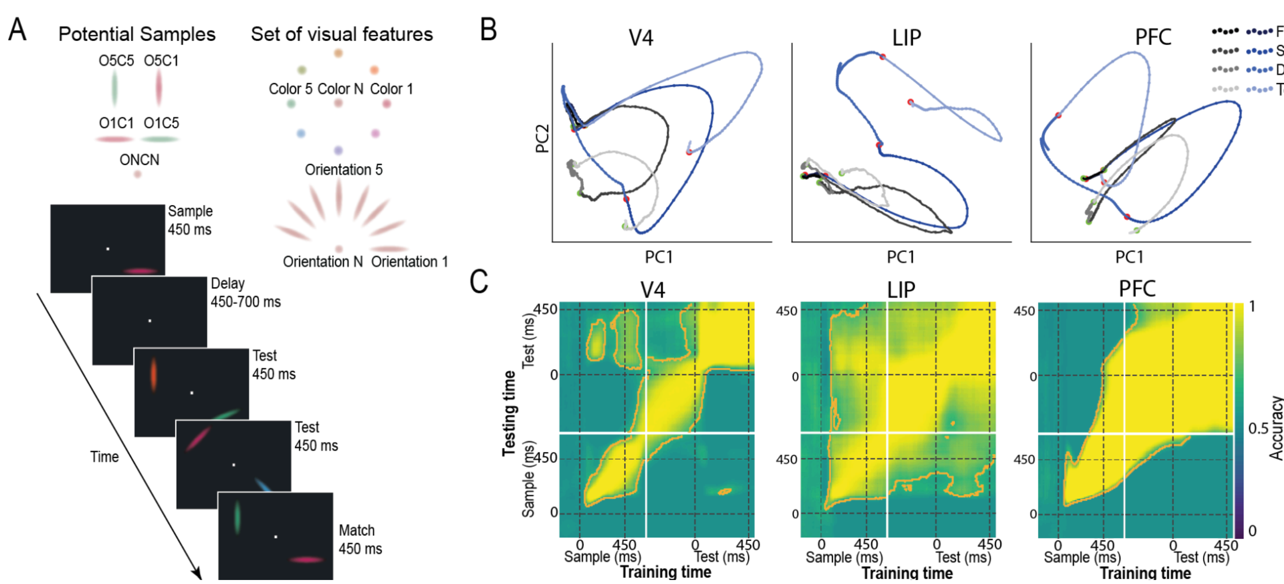

Figure 1: A) DMTS task. Top left: the five possible sample stimuli; top right: the set of possible visual features. Bottom: an example of a non-neutral trial. B) Neural trajectories in V4, LIP, and PFC along the first two principal components. Neutral trajectories are shown in grayscale, from black (fixation) to light gray (test epoch). Non-neutral trajectories are shown in bluescale, from dark blue (fixation) to light blue (test epoch). C) Temporal decoding accuracies in V4, LIP, and PFC. Orange lines indicate time periods with significant accuracy ($p < 0.05$).

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