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Fronto-parietal Cortical Circuits Encode Accumulated Evidence with a Diversity of Timescales

Highlights

- Voluntary restraint allows two-photon Ca^{2+} imaging during decision-making in rats
- Neurons with diverse dynamics collectively represent accumulated sensory evidence
- Cortical dynamics support the existence of multiple weakly coupled accumulators
- Neurons across fronto-parietal cortex encode the memory of past behavioral choices

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In Brief

Leading models of decision-making postulate that individual fronto-parietal neurons encode accumulated sensory evidence with stable changes in firing rate. Using cellular resolution calcium imaging during a pulse-based accumulation task, Scott et al. reveal that stable representations of accumulated evidence in rat fronto-parietal cortex instead arise from neuronal populations with temporally diverse responses.

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Fronto-parietal Cortical Circuits Encode Accumulated Evidence with a Diversity of Timescales

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SUMMARY

Decision-making in dynamic environments often involves accumulation of evidence, in which new information is used to update beliefs and select future actions. Using in vivo cellular resolution imaging in voluntarily head-restrained rats, we examined the responses of neurons in frontal and parietal cortices during a pulse-based accumulation of evidence task. Neurons exhibited activity that predicted the animal's upcoming choice, previous choice, and graded responses that reflected the strength of the accumulated evidence. The pulsatile nature of the stimuli enabled characterization of the responses of neurons to a single quantum (pulse) of evidence. Across the population, individual neurons displayed extensive heterogeneity in the dynamics of responses to pulses. The diversity of responses was sufficiently rich to form a temporal basis for accumulated evidence estimated from a latent variable model. These results suggest that heterogeneous, often transient sensory responses distributed across the fronto-parietal cortex may support working memory on behavioral timescales.

INTRODUCTION

Perceptual decision-making often requires integration of sensory information over time. Behaviorally, this is frequently modeled as an accumulation process, in which a subject's perceptual judgment is described as a latent variable evolving under the influence of sensory events, comparable to the movement of particles in drift diffusion processes (Forstmann et al., 2016). Over the last several decades, this accumulation process has been investigated using electrophysiological recordings from single neurons in primate and rodent cortex. Continuous presentation of noisy sensory evidence produces ramping activity in neurons in posterior parietal cortex (PPC; Roitman and Shadlen, 2002) and frontal eye field (FEF; Kim and Shadlen, 1999), while brief pulses of sensory evidence produce sustained firing rate increases in PPC (Hanks et al., 2015; Huk and Shadlen, 2005), leading to the hypothesis that the brain represents the accumulated sensory evidence in forebrain neuronal activity.

Recently, the frontal orienting field (FOF) and PPC have been implicated in accumulation of evidence and memory-guided decision-making in rats. FOF and rat PPC share similar thalamocortical and corticothalamic projections with primate FEF and PPC, respectively (Erlich et al., 2011; Whitlock et al., 2012), and inactivation of FOF causes disruptions in accumulation of evidence and memory-guided orienting tasks, but not in cued sensory-motor responses (Erlich et al., 2011, 2015; Hanks et al., 2015; Kopec et al., 2015). Tetrode recordings in these regions revealed neurons tuned to the strength of evidence in a pulse-based auditory accumulation task (Hanks et al., 2015).

Most previous electrophysiological studies of fronto-parietal cortex during accumulation of evidence have focused on how firing rates of individual neurons correlate with the magnitude of sensory evidence in favor of a particular choice as predicted by an accumulator model. Typically, the responses of different neurons are analyzed as amplitude-scaled versions of a prototype temporal waveform representing the latent variable of the accumulator, implying relatively homogeneous dynamics across the neural population (Figures 1A and 1B). However, theoretical work has suggested that neural networks could also encode the memory of sensory events using a population code with heterogeneous dynamics (Figure 1B). Whether these responses could also underlie an accumulation process has not been explored. For example, Goldman (2009) demonstrated that networks of simulated neurons with complex, temporally heterogeneous responses of increasing response width can encode memories