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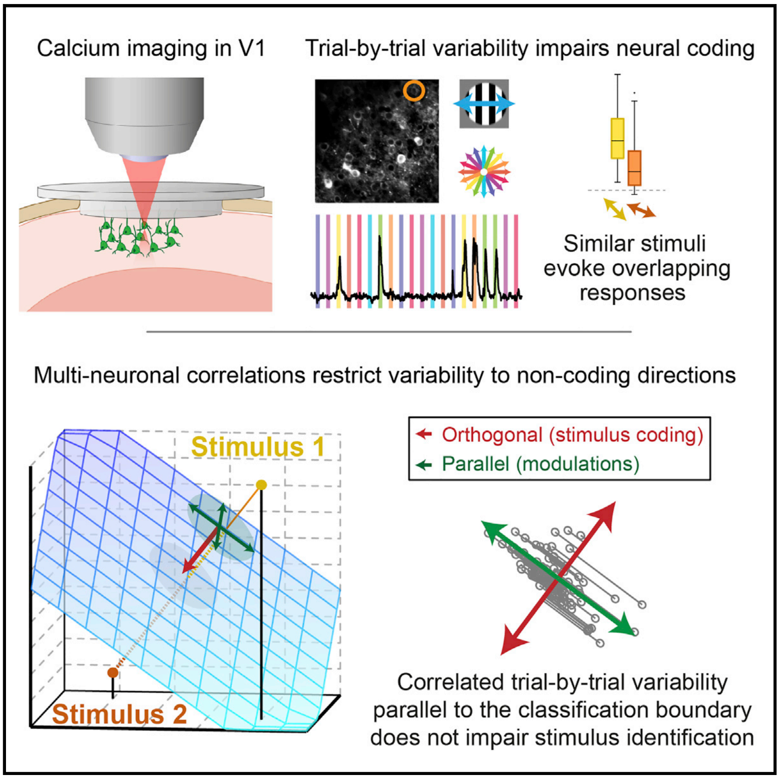
Population-Level Neural Codes Are Robust to Single-Neuron Variability from a Multidimensional Coding Perspective

Graphical Abstract



Highlights

- Correlated trial-by-trial variability can impair the reliability of neural codes
- Multidimensional codes of stimulus orientation are highly stable over weeks
- Multidimensional correlations restrict variability to non-coding directions
- Up to 50% of single-trial, single-neuron “noise” is predictable with correlations

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In Brief

Montijn et al. show that compared to independent codes, the accuracy of V1 population codes improves when using pairwise correlations but improves further when using multidimensional correlations. This may be achieved because high-dimensional correlations restrict trial-by-trial variability to directions that are perpendicular to the trajectories that encode stimulus features.

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Population-Level Neural Codes Are Robust to Single-Neuron Variability from a Multidimensional Coding Perspective

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SUMMARY

Sensory neurons are often tuned to particular stimulus features, but their responses to repeated presentation of the same stimulus can vary over subsequent trials. This presents a problem for understanding the functioning of the brain, because downstream neuronal populations ought to construct accurate stimulus representations, even upon singular exposure. To study how trial-by-trial fluctuations (i.e., noise) in activity influence cortical representations of sensory input, we performed chronic calcium imaging of GCaMP6-expressing populations in mouse V1. We observed that high-dimensional response correlations, i.e., dependencies in activation strength among multiple neurons, can be used to predict single-trial, single-neuron noise. These multidimensional correlations are structured such that variability in the response of single neurons is relatively harmless to population representations of visual stimuli. We propose that multidimensional coding may represent a canonical principle of cortical circuits, explaining why the apparent noisiness of neuronal responses is compatible with accurate neural representations of stimulus features.

INTRODUCTION

The presentation of stimulus features modulates the responses of single neurons in sensory cortex such that the outside world is represented in the activation pattern of neuronal populations. However, the activity of single neurons shows substantial variability in spike rate and timing across repeated presentations of the same stimulus (Faisal et al., 2008). This variability is often called neural noise and poses a problem: how can animals react quickly and reliably to sensory input when the stimulus representation would already be noisy at the first stage of cortical processing? It has been proposed that neural circuits solve this problem by combining information from multiple neurons into a population code. If the variability of neuronal responses were independent, higher precision of stimulus representation would be achieved by combining the responses of more neurons (Beck et al., 2008; Knill and Pouget, 2004; Ma et al., 2006). However, neurons are often correlated in the variability of their response to the same stimulus, which means that simple averaging is insufficient to achieve maximal precision (Averbeck and Lee, 2006; Hansen et al., 2012; Lee et al., 1998; Vinje and Gallant, 2000).

The interdependency between responses of pairs of neurons (i.e., noise correlations [NCs]) has been proposed to influence the amount of information that can be extracted from population codes in different ways, ranging from being beneficial to being mostly irrelevant or harmful (Averbeck et al., 2006; Cafaro and Rieke, 2010; Cohen and Kohn, 2011; Cohen and Maunsell, 2009; Ecker et al., 2011; Fiscella et al., 2015; Herrero et al., 2013; Montijn et al., 2014; Seriès et al., 2004). Another aspect that complicates the study of NCs is that these correlations can be heterogeneous in their size and effects on population codes, depending on factors such as the nature of the presented stimulus features, correlations between neurons other than the pair being studied, and differences in general arousal state (Chelaru and Dragoi, 2016; Ince et al., 2013; Jazayeri and Movshon, 2006; Miller et al., 2014; Moreno-Bote et al., 2014; Pitkow et al., 2015; Schölvinck et al., 2015). Therefore, one of the most relevant challenges in neurophysiology is explaining how accurate sensory representations can be generated by neuronal populations in the face of instantaneous single-neuron response fluctuations.

Pairwise dependencies might be important for neuronal populations that represent sensory information, but it has been hypothesized that the underlying structure of neural responses may be multidimensional—i.e., dependent on interactions among more than two neurons (Franke et al., 2016; Kanitscheider et al., 2015; Latham et al., 2003; Pasupathy and Connor, 2002; Pillow et al., 2008; Schneidman et al., 2006). A related computational problem in natural vision holds that many features are present simultaneously, and these features are thought to be represented with high fidelity by ensembles of neurons in early sensory areas (Baddeley et al., 1997; Eichhorn

