Journal Club

Editor's Note: These short, critical reviews of recent papers in the *Journal*, written exclusively by graduate students or postdoctoral fellows, are intended to summarize the important findings of the paper and provide additional insight and commentary. For more information on the format and purpose of the Journal Club, please see http://www.jneurosci.org/misc/ifa_features.shtml.

Feature-Specific Clusters of Neurons and Decision-Related Neuronal Activity

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Review of Nienborg and Cumming

Seminal work in the 1990s by Britten and colleagues provided empirical and computational support for the idea that the activity of single neurons could be used to predict an animal's perceptual decision (Britten et al., 1996). The measure of decision-related activity they introduced, called "choice probability" (CP), is based on signal detection theory and quantifies the discriminability of the distributions of a neuron's firing rates as a function of behavioral choice (e.g., left vs right). CP provides a relatively straightforward way of relating a neuron's firing rate to an animal's decision.

A recent study by Nienborg and Cumming (2014) addresses the question of why some neurons within a brain region exhibit decision-related activity and others do not. Specifically, the authors make the important insight that CPs are more likely to be found when the brain region examined has an anatomical map for the feature tested in the task. These "feature maps" may be cortical columns or clusters of neurons with similar response properties.

Nienborg and Cumming (2006) previously found significant CPs in visual area V2

in monkeys, but not in primary visual cortex (V1), during a depth-discrimination task involving binocular disparity, the property underlying stereopsis. These findings are consistent with the feature-map hypothesis because V2 has a robust map of disparity, while disparity-sensitive neurons have no strong spatial organization in V1. To test their hypothesis further, Nienborg and Cumming (2014) recorded again in V1 but now used an orientation discrimination task. If feature maps play a critical role in decision-related activity, one would expect that the columnar organization of orientation-selectivity in V1 yields significant CPs.

Two monkeys were trained to discriminate the orientation of a stimulus by making an eye movement to one of two choice targets, corresponding to preferred and null orientations of the recorded neuron. Rapid sequences of noisy gratings were presented and the authors titrated the amount of noise on each trial to regulate task difficulty. Critically, the orientation signal could be removed completely (random noise only) so that the stimulus was perceptually ambiguous (Nienborg and Cumming, 2014, their Fig. 1). These trials were randomly rewarded, and the monkeys' decisions were presumably driven by small fluctuations in neuronal activity that "pushed" a decision in favor of one orientation over the other.

The main results of Nienborg and Cumming (2014) are consistent with previous investigations of CP (Britten et al., 1996) but, for the first time to our knowledge, demon-

strated significant CPs in V1. Overall, when a given neuron fired more during the 0% signal trials, the monkeys were more likely to choose the preferred orientation target, leading to an average population CP significantly greater than chance (Nienborg and Cumming, 2014, their Fig. 4, left). Alongside their previous disparity study (Nienborg and Cumming, 2006), these results suggest that V1 activity can be used to predict behavior if the neurons are spatially organized for the feature being tested.

Nienborg and Cumming (2014) then performed several analyses to demonstrate that CPs were not trivially related to differences in eye movements, variability in the stimulus sequences, or, to a limited extent, experimental subjects. One concern was that random, small fluctuations in the amount of orientation signal during the nominally 0% signal trials could yield small differences in CP. Such stimulus-driven effects would undercut the interpretation of CP as purely decision-based changes in neuronal activity. To address this concern, on a subset of recording sessions ($n = 21$), the authors used identical stimulus sequences twice. They found that CPs calculated using the subset of trial pairs for which monkeys responded differently on each presentation were still significantly greater than chance (Nienborg and Cumming, 2014, their Fig. 4, right). Thus, CPs were not trivially explained by stimulus changes.

A final result by Nienborg and Cumming (2014) further strengthens their hypothesis. One of the two monkeys in this

study of orientation had previously been examined in their work on disparity discrimination (Nienborg and Cumming, 2006) (it is unclear which monkey is in both studies and whether single-electrodes or linear-electrode arrays were used across studies). A direct comparison of V1 activity in the same monkey but different tasks revealed that CPs in V1 were significantly greater in the orientation task, arguing against the possibility that CP differences reflect differences in subjects across tasks.

In their Discussion, Nienborg and Cumming (2014) suggest that certain properties associated with neuronal clusters provide the foundation for the previously proposed relationship between decision-related activity and correlated trial-by-trial fluctuations in the neuronal responses. These "noise correlations" may contribute to decision-related activity because correlated noise does not average out and therefore can drive decisions based on a weighted sum of activity within a population. Yet significant noise correlations are not sufficient to explain decision-related activity. For example, when the correlated activity within a population of neurons with similar stimulus preferences is also shared with a population of neurons with opposite preferences, a decision based on the difference in average activity between the populations would eliminate the correlated activity through subtraction, thereby preventing it from influencing the decision. Hence, to explain decision-related activity, some activity should be shared within a population but not across populations (Shadlen et al., 1996).

However, this conclusion leaves many unresolved experimental questions. Specifically, it is unclear why neuronal clusters should share more activity within than between them. One possibility is that different clusters have different shared inputs, as suggested by the stronger noise correlations between nearby neurons and neurons with similar feature preferences (Lee et al., 1998). Alternatively, theoretical work has shown that clustered connections in recurrent neuronal networks can induce state transitions in activity that are correlated within but anticorrelated between clusters (Litwin-Kumar and Doiron, 2012). Furthermore, feedback signals such as those related to feature attention have often been suggested as a source of differential noise correlations and CP (Nienborg and Cumming, 2009). However, one study (Cohen and Maunsell, 2011) empirically measured the impact of feature attention on noise correlations and found that feature attention actually decreases noise correlations, mainly between neurons with similar tuning properties (i.e., putative

clusters), thereby changing the noise-correlation structure in a way that seems to oppose instead of facilitate CP. Thus, what properties of neuronal clusters underlie the noise correlation pattern and CP is an important question for future research.

Nevertheless, the findings of Nienborg and Cumming (2006, 2014) are consistent with a relation between decision-related activity and cortical clustering. A remaining question is whether neurons in parts of the cortex with heterogeneous feature preferences have lower CPs, as the authors' hypothesis suggests. To answer this question, both CPs and feature maps need to be measured. A more stringent test would entail measuring decision-related activity within the same cortical area for neurons in populations with either homogeneous or heterogeneous feature preferences. Such experiments seem feasible in parts of extrastriate cortex where clustered neurons for, say, faces or shapes are often flanked by neurons with similar feature selectivities but mixed preferences.

Interestingly, studies using electrical microstimulation to determine the influence of neuronal activity on perception often stimulate neurons in the same clusters as those in which significant CPs have been observed (Salzman et al., 1990; DeAngelis et al., 1998). Microstimulation in feature-specific clusters influences the monkeys' perceptual choices and appears to increase the perceptual evidence in favor of the preferred stimulus of the stimulated neurons. These findings suggest that neurons with decision-related activity contribute to rather than merely correlate with task performance.

Although Nienborg and Cumming (2014) did not illustrate changes in CP over time, significant decision-related activity often arises soon after stimulus onset when neurons become selective for the task's stimulus feature (Nienborg and Cumming, 2006). After its peak, the CP often stays relatively high. Notably, studies using reaction-time tasks or psychophysical-reverse-correlation analyses (Nienborg and Cumming, 2009) have shown that monkeys mostly rely on the perceptual evidence presented at the start of the trial, a point in time where significant CPs are already present. The early component of the decision-related activity may therefore primarily reflect a feedforward influence on task performance (or, perhaps, a pre-established behavioral bias), consistent with the microstimulation results discussed above. The later, sustained part of the CP likely happens when the monkey has already made its decision so it may

encompass working-memory and feedback activity. Consequently, the "feedforward versus feedback" debate in the CP literature might not have a straightforward solution. Instead, these observations suggest that the source of decision-related activity could lie in both feedforward and feedback activity, where the weight of each component varies as a function of poststimulus time.

The hypothesized relationship between decision-related activity and cortical clustering links several research topics in system neuroscience, including decision making, noise correlations, microstimulation, and cortical architecture. The authors' hypothesis therefore provides a fertile ground for further research. The merits of forthcoming research could be high, as they may provide us with insights into the origin of decision-related activity and, more broadly, into the functional interplay between feedforward and feedback neuronal circuitry.

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