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How Can Single Sensory Neurons Predict Behavior?

Highlights

- Responses of single neurons correlate with heading percepts
- This can be explained by optimally decoding populations with limited information …
- … Or by suboptimally decoding populations with extensive information
- Electrophysiological data support the model with limited information

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In Brief

The activity of just one sensory neuron in the brain often accurately predicts what an animal will perceive in simple tests. Pitkow et al. provide a new theory of why this happens, and offer experimental data that support their theory.

Pitkow et al., 2015, Neuron *87*, 411–423
July 15, 2015 ©2015 Elsevier Inc.
http://dx.doi.org/10.1016/j.neuron.2015.06.033

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How Can Single Sensory Neurons Predict Behavior?

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http://dx.doi.org/10.1016/j.neuron.2015.06.033

SUMMARY

Single sensory neurons can be surprisingly predictive of behavior in discrimination tasks. We propose this is possible because sensory information extracted from neural populations is severely restricted, either by near-optimal decoding of a population with information-limiting correlations or by suboptimal decoding that is blind to correlations. These have different consequences for choice correlations, the correlations between neural responses and behavioral choices. In the vestibular and cerebellar nuclei and the dorsal medial superior temporal area, we found that choice correlations during heading discrimination are consistent with near-optimal decoding of neuronal responses corrupted by information-limiting correlations. In the ventral intraparietal area, the choice correlations are also consistent with the presence of information-limiting correlations, but this area does not appear to influence behavior, although the choice correlations are particularly large. These findings demonstrate how choice correlations can be used to assess the efficiency of the downstream readout and detect the presence of information-limiting correlations.

INTRODUCTION

Individual sensory neurons in the brain are often predictive of animals' choices in simple perceptual decision-making tasks. It is said that these neurons have a significant choice probability. This remarkable fact has been demonstrated in numerous tasks and brain areas, including those dedicated to sensing visual motion (Britten et al., 1996), depth (Uka and DeAngelis, 2004; Nienborg and Cumming, 2007), and self-motion (Gu et al., 2008; Fetsch et al., 2012; Chen et al., 2013; Liu et al., 2013). Many of these cells have neural thresholds, which quantify sensitivity to stimulus variations, that are not much greater than psychophysical thresholds (Cohen and Newsome, 2009). It is therefore puzzling why pooling these signals does not predict sensitivity much greater than that exhibited by behavior. Perhaps the brain merely selects a small subset of neurons to inform its decisions (Tolhurst et al., 1983; Ghose and Harrison, 2009)—but then how could experiments so frequently encounter these extremely rare neurons that influence behavior? A proposed explanation for these puzzling observations was that response variability is correlated across neurons (Zohary et al., 1994): even with very weak correlated noise between pairs of neurons, the total information content of a neural population may saturate to a finite value as the number of neurons increases, such that optimally pooling more responses cannot improve behavioral sensitivity. Additionally, neurons are correlated not only with each other but also with the pooled signal that presumably drives the perceptual decision, which would generate high choice probabilities.

This solution (Zohary et al., 1994) was established for a very simplified model of neural responses, correlations, and decoding. Subsequent studies relaxed some of these simplifications and found consistent results for broad correlations in neural populations tuned to a one-dimensional stimulus (Sompolinsky et al., 2001). However, it was suggested that diversity in the amplitude and width of neural tuning curves would change the picture (Abbott and Dayan, 1999), and later calculations demonstrated that weak noise correlations do *not* limit information in heterogeneous neural populations: information continues to increase linearly with the number of neurons (Shamir and Sompolinsky, 2006; Ecker et al., 2011). We say that such a population has "extensive information." If correct, this would imply that correlated noise cannot explain the frequent occurrence of significant choice probabilities, for the following reason: in optimally decoded populations with extensive information, each neuron provides a tiny contribution, inversely proportional to the size of the neural pool, toward the perceptual decision. This prediction is at odds with observed choice probabilities and ratios of neural to psychophysical thresholds.

Perhaps the neural population contains vast amounts of information, but it is not all used in perception. There are many forms of such suboptimal decoding that misuse neural signals. We will show that suboptimal decoding could indeed explain both why behavioral thresholds are barely better than single neuron thresholds and why choice probabilities are so large and common.

A second explanation of these phenomena does not rely on suboptimal decoding but instead blames a subtle form of neural noise correlations (Moreno-Bote et al., 2014) that limit the information contained in a population code. These information-limiting noise correlations cause massive redundancy between neurons, which restricts behavioral thresholds to be not much