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A fundamental goal of systems neuroscience is to determine the neural mechanisms that govern perception. These mechanisms can be broadly divided into two classes: changes in the strength of individual synaptic connections and circuit-wide changes in the pattern of neuronal population activity. Given the large difference in scale between synaptic plasticity and network dynamics, it may be surprising that one mechanism could be mistaken for the other. Yet recent work by Quiroga and colleagues [1] suggests that neuronal adaptation, often thought to be a form of sensory response modulation dependent on synaptic plasticity [2,3], can be carried out via recurrent neuronal connections with constant synaptic weights (Figure 1). This result provides insight into one of the most ubiquitous mechanisms of sensory encoding and highlights a promising, reliable avenue of investigation for researchers interested in relating brain function to local circuitry.

Neuronal adaptation is a general term that encompasses a variety of response profiles that depend on recent stimulus

history. Quiroga *et al.* [1] focused on one of the best-described forms of adaptation, orientation adaptation in primary visual cortex (V1) [4]. Using an established model of thalamocortical processing in the mammalian visual system, the researchers first built a recurrent network that incorporated orientation-specific thalamic inputs to cortical neurons. The network's parameters were fit to ensure that basic response properties such as the response latency and orientation selectivity of individual neurons, as well as the breadth of excitatory and inhibitory connections between neurons, approximated previously reported experimental values. Importantly, the two species-specific models (cat and monkey) were constrained to fit the relevant experimental data before they were tested for adaptation.

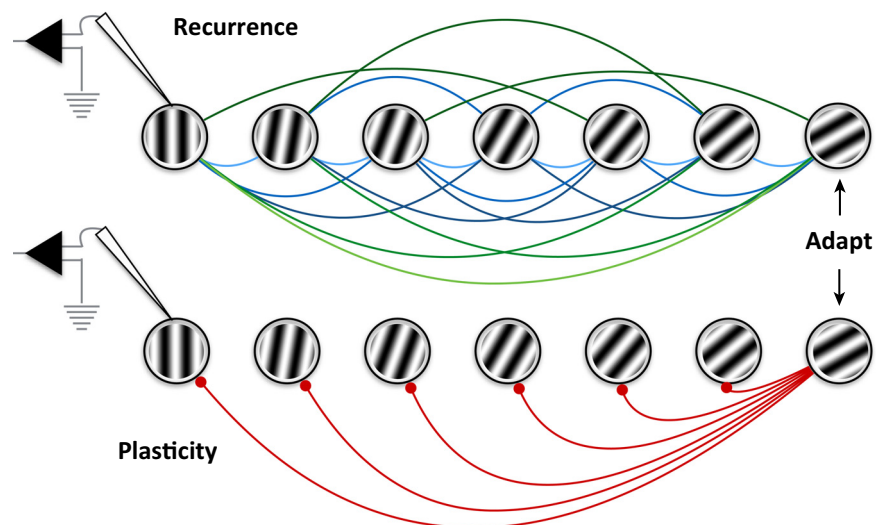
Without changing the synaptic weights between neurons and relying solely on the recurrent connectivity between cortical neurons, Quiroga *et al.*'s models exhibited a remarkable number of response properties associated with

Spotlight

Neuronal Adaptation: Tired Neurons or Wired Networks?

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Neuronal adaptation – time-dependent modulation of sensory responses following sequential stimuli – is thought to be a consequence of synaptic plasticity. But recent, empirically-grounded, modeling by Quiroga and colleagues demonstrates that the adaptation of visual cortical responses can be described by recurrent network connections with fixed synaptic weights.



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Figure 1. Illustration of Candidate Adaptation Mechanisms. Adaptation has often been proposed to occur through synaptic plasticity (bottom); a recorded neuron (leftmost circle) with a preference for vertical orientation could undergo a tuning curve shift away from the adapted orientation due to a loss of excitatory input. Quiroga *et al.*'s results demonstrate that the same tuning curve shift can occur through the temporal dynamics of recurrent network connections (top, nearby connections in blue and distant connections in green). Each circle represents a population of similarly tuned V1 neurons.

orientation adaptation. Adaptation led to repulsive shifts in preferred orientation; that is, the preferred orientations of simulated neurons shifted away from their pre-adapted preferred orientation in the adapted state, as seen experimentally [4]. The presence and direction of adaptation-related changes in visual responses also changed over time, similar to the time course observed experimentally. While the recurrent network architecture appeared to be the key factor underlying adaptation without synaptic plasticity, the authors went on to test this idea directly. Broadening the distribution of connections between neurons increased the magnitude and duration of adaptation, and increasing the amount of inhibitory connections, relative to excitatory ones, decreased the size of the repulsive shifts. Thus, the model parameters that regulated the sign and strength of recurrent connections changed the dynamics of adaptation.

Quiroga *et al.* modeled the basic structure and functional connectivity of thalamic inputs and horizontal connections in primary visual cortex. But adaptation is seen in many sensory modalities and at most stages of sensory processing [3,4]. Thus, it remains unclear how recurrent connections could support adaptation in less retinotopically organized brain regions, if at all. The degree to which recurrent network-based adaptation depends on stereotyped cellular organization or clusters of feature-selective neurons [5] is also critical when considering alternative animal models of vision (e.g., mouse) that lack columnar organization in V1. One intriguing possibility is that synaptic plasticity and recurrent network properties both contribute to adaptation, but synaptic changes

are supplanted by recurrent connections as brain regions and their neuronal response properties become more uniform and specialized. If true, this scenario raises the possibility that gross anatomical differences across species would severely limit the generalizability of adaptation results in the mouse to primate vision. Detailed species-specific models, such as those of Quiroga *et al.*, could help resolve this issue.

The adaptation model of Quiroga *et al.* [1] is exciting because it readily lends itself to data-driven expansions. Specifically, first, while the authors modeled both excitatory and inhibitory interactions (as well as distinct excitatory and inhibitory populations, their Fig. S3), the richness of inhibitory circuitry and the differing spatial and temporal characteristics of inhibition and excitation [6] also play important roles in recurrent network dynamics, and likely in adaptation. Second, their model connected neurons based solely on their preferred orientation tuning, ignoring the physical distance between neurons and their retinotopic or physical positions. The spatial extent of recurrence can provide insight into population-level neuronal interactions [7] and may help the model account for additional characteristic features of adaptation [4]. Third, variability in individual neurons [8] and populations [9] can be shaped by stimulus history and may be involved in adaptation to a degree not well-described in Quiroga *et al.*'s model of the average neuronal response. The incorporation of noise into their model, both independent as well as shared among neurons, could be important to extend its inferential power. Finally, a long-standing question is whether adaptation generalizes from fixation to natural vision, when eye movements

frequently and dramatically disrupt the image that impinges on the receptive fields of visual neurons [10]. While these additional considerations may guide future model development, Quiroga *et al.*'s [1] current results highlight the longstanding, proven interaction between systematic measurements of sensory activity and computational modeling of empirical results. These tools remain fundamental for disentangling and understanding the functional circuitry that supports active vision, both in the study of adaptation and likely in myriad other phenomena, including short-term memory, object recognition, and motor planning.

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