Trends in Neurosciences

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Spotlight

Shifting ensembles in visual cortex: context-dependent encoding of learned cues

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In a recent study in mice, Faulkner and colleagues revealed that visual cortex representations of learned cues rapidly shifted with a change in the external context. This work highlights the flexible recruitment of distinct neuronal ensembles to maintain behavioral relevance, providing new insights into how the brain balances stability and adaptability in sensory coding.

A core challenge for sensory systems is to preserve stable representations of stimuli that carry behavioral significance, yet remain flexible enough to adjust these representations when the outcome they predict changes. In other words, the brain must preserve what it has learned about the environment while remaining ready to adapt when circumstances change. How this balance is achieved within sensory cortical circuits remains not well understood.

In a recent publication, Faulkner *et al*. [1] showed that the visual cortex preserved this balance by recruiting distinct neuronal populations as context changes. Using longitudinal two-photon calcium imaging in awake mice, the authors tracked neurons in layer 2/3 as the animals learned to associate an oriented grating with a reward. Consistent with earlier studies showing that learning biases sensory cortical representations toward behaviorally relevant stimuli [2], Faulkner *et al*. found that training produced a robust population bias: the rewarded cue elicited stronger responses than a neutral stimulus. This bias did not result from uniform amplification alone but involved two complementary processes: the recruitment of previously unresponsive neurons and stronger responses in neurons already active. These changes grew more pronounced with continued training, reinforcing the view that cortical representations are refined by experience to highlight information relevant for behavior.

The authors then asked whether these learned representations remained stable when the context shifts, even if the sensory cues themselves do not. To test this, they introduced a threat cue that predicted an unavoidable tail shock, while leaving the original reward association unchanged. Despite consistent task performance, the neuronal population encoding the cues reorganized: many neurons active under normal conditions fell silent in the threat context, while a largely distinct set became engaged. When the threat was removed, the representation shifted back to more closely match its original form, underscoring the capacity of the cortex for flexible, context-dependent reorganization.

This flexibility echoes changes seen with shifts in internal state, such as hunger or locomotion, which can modulate gain and alter the composition of responsive ensembles in the visual cortex [3,4]. It also aligns with recent work showing that cortical ensembles can be recruited selectively for specific contexts, such as novelty or deviance detection [5]. One of the elements that distinguish Faulkner *et al*.'s study is the demonstration that external factors, in this case the presence of threat, can determine which neurons participate in encoding a visual cue.

To explore changes at the neural population level, the authors used dimensionality reduction to compare activity subspaces across contexts. Principal component analyses showed that the subspace for the threat condition was partly orthogonal to that of the original learned state, while the post-threat subspace realigned more closely with the initial representation. This suggests that visual cortex can shift between distinct population codes depending on context. By tracking individual neurons, Faulkner *et al*. showed that context reconfigured population codes in a manner reminiscent of learning [6]. Notably, these shifts remained reversible when the original context returned, highlighting a balance between stability and flexibility.

How this reconfiguration is orchestrated remains an open question. One possibility is that long-range projections from regions such as orbitofrontal or retrosplenial cortex provide top-down signals that determine which neurons are recruited, consistent with other studies of sensory-guided learning and top-down modulation [7,8]. While structures such as the amygdala could convey threat-related information to visual cortex, neuromodulatory systems, including cholinergic and noradrenergic pathways, may add another layer of context sensitivity [9,10]. However, it remains unclear which pathways and signals actually initiate these shifts and how local circuit interactions interact with broader top-down and neuromodulatory influences. Clarifying this balance will be crucial for pinpointing where context exerts its strongest effects on ensemble recruitment.

Another open question is whether the increased responses seen for the rewarded cue reflect shifts in basic sensory tuning, such as orientation preference, or whether they mainly represent changes in the strength and recruitment of ensembles. Detailed mapping of tuning properties will be needed to resolve this. It also remains to be seen whether this form of context-dependent reorganization is a general feature across sensory cortices, or whether it reflects a specialization of visual cortical areas engaged by associative tasks. Finally, although overall task performance remained stable in this paradigm, it is not yet clear whether such flexible representations directly support an animal's capacity to adapt when familiar cues change meaning or become unreliable. Subtle factors such as freezing behavior or shifts in arousal and anticipation could also contribute to this population-level flexibility. Clarifying how these internal states interact with ensemble recruitment will help link population dynamics more directly to adaptive behavior.

In summary, Faulkner *et al.'s* study demonstrated how chronic imaging in behaving animals can reveal the interplay between stability and plasticity in cortical circuits, showing that contextual modulation, particularly in the presence of an aversive cue, can dynamically reshape visual representations in the cortex without any change to the sensory input itself. By showing that learned representations in visual cortex can remain robust yet flexible when context demands it, their work offers new insight into how sensory systems stay anchored in past experience while remaining poised to adapt. Resolving the circuits and cell types that govern these shifts will deepen our understanding of how context sculpts perception, balancing stability with the flexibility needed for adaptive behavior.

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Declaration of interests

The author declares no competing interests related to this work.

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