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# Everything, everywhere, all at once: Functional specialization and distributed coding in the cerebral cortex

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In this issue of *Neuron*, Tseng and colleagues reveal functional gradients in the mouse posterior cortex that reconcile specialized and distributed processing during flexible, goal-directed navigation.

Supported by histological, stimulation, and lesion studies since the 19th century and electrophysiological studies from the 20th century, a prevailing hypothesis on the functional organization of the cerebral cortex has been one of modularity. In this view, anatomically distinct areas of the cortex specialize in processing specific types of information (Casanova and Casanova, 2019). For example, neurons in primary sensory and motor areas are thought to process sensory and motor information, while neurons in association areas are thought to mix signals from multiple modalities, forming conjunctive representations. However, more recent discoveries have challenged this long-established hypothesis (Wallace et al., 2004). For instance, the primary visual cortex (V1), once thought to be a specialized module for vision, has been shown to also carry information about movement (Steinmetz et al., 2019) and spatial position (Saleem et al., 2018). In addition, information related to decision making, such as accumulated evidence and reward expectation, is encoded by the ac-

tivity of neurons across several regions of the rodent cortex (Hattori et al., 2019; Koay et al., 2022; Steinmetz et al., 2019). Together, these observations support an alternative model of functional organization in the cortex in which information processing is highly distributed.

How can we reconcile these two models of functional organization in the cortex? In this issue of *Neuron*, Tseng and colleagues address this question through large-scale, high-resolution imaging of neural calcium dynamics in awake-behaving mice (Tseng et al., 2022). The authors survey tens of thousands of neurons across several adjacent areas of the posterior cortex as mice navigate a maze in virtual reality and make decisions about which path to take. This approach allows for a systematic analysis of how neural representations of behavior, internal state, and environmental stimuli vary across the cortical sheet.

How are visual stimuli, movement, spatial position, and choice represented in the posterior cortex during goal-directed navigation? Tseng et al. (2022)

reveal that the neuronal encoding of each information modality forms a functional gradient across the surface of the posterior cortex. This creates multiple overlapping functional maps with regions of strong encoding, or “peaks,” in different locations. For example, the gradient for visual information runs anterior to posterior with a peak in V1. The gradient encoding movement unfolds along the same axis, but it peaks in parietal area A (a region between visual and somatosensory cortices) and flattens across more posterior areas. A third gradient, reflecting spatial and choice encoding, unfurls laterally from the medial parts of the posterior cortex and peaks in the retrosplenial cortex (RSC). Functional gradients in neural representation, such as topographic maps in sensory areas (Kaas, 1997), have been well documented. However, the gradients described here, related to both sensory processing and behavior, extend across multiple regions.

The peaks of these functional gradients are consistent with previous findings that supported the hypothesized roles of V1,



A, and RSC as specialized cortical modules for vision, movement, and navigation and decision making, respectively. However, the distributed tails of these gradients span the entire posterior cortex, consistent with a distributed model of cortical functions. In this way, the functional specialization of cortical areas exists amidst redundant and distributed encoding of information.

Interestingly, Tseng et al. (2022) also show that each of these functional gradients varies in how steep or shallow they are over the cortical surface. Gradients associated with cognitive functions, like choice and strategy, are shallower than those associated with sensory or motor information. This structure may support broad, flexible recruitment of cortical areas in response to an increase in cognitive demands. It should be noted that the widespread distribution choice and strategy encoding may also reflect ambiguity in estimates of the animal's decision process. Unlike sensory and motor variables, which can be measured directly, cognitive variables are estimated using statistical inference. Therefore, future studies may be useful to determine whether the distribution of encoding for choice and strategy reflects a widespread involvement of cortical areas in navigation-based decision making.

In addition to characterizing these functional gradients and mapping their peaks, the authors report many individual neurons exhibit mixed representations, allowing cells to participate in multiple gradients. Interestingly, the degree to which individual neurons mixed information was similar across the various regions of the parietal cortex. Neurons that encode multiple modes of information are typically cited as a hallmark of higher cognitive function (Rigotti et al., 2013). Therefore, the fact that cells with mixed encoding are so broadly distributed could indicate that multiple cortical areas have the capacity to drive complex learned behaviors, an idea considered over a century ago (Lashley, 1920).

Tseng et al. (2022) unravel several key features of the functional organization in the mouse posterior cortex during goal-directed navigation. They show that the distributed encoding of information forms overlapping gradients over the surface of the posterior cortex, with prominent peaks in V1, A, and RSC for visual, movement, and spatial and choice encoding, respectively. These functional gradients provide a new model for understanding the organizational principles of cortical functions that reconcile functional specialization with distributed representations. The authors additionally unveiled a shared conjunctive code across different areas of the posterior cortex, which may indicate parallel structures for robust and flexible information integration. However, several important questions arise: (1) what are the neural circuit mechanisms that generate these functional gradients? Some plausible candidates are local connectivity patterns, feedback signals from downstream areas, or input patterns from upstream projections. (2) To what degree are these multi-area functional gradients found in other parts of the rodent brain and in other species? The cellular and laminar architecture of the neocortex varies greatly across the cortical sheet and the mammalian lineage, so the properties of these functional gradients may also change. Therefore, similar mapping studies in other species would be of value.

In addition to providing a framework that can reconcile modular and distributed models of cortical information processing, Tseng and colleagues raise intriguing questions about cortex, its anatomy and computational propensity, and how it endows animals with flexible cognition.

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#### DECLARATION OF INTERESTS

The authors declare no competing interests.

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