Title:

Navigation: How Spatial Cognition is Transformed into Action

Authors:

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Text:

In brief:

Navigation relies on the brain´s ability to build a cognitive map of the environment, and to use such map to guide the animal´s movements to goals. A new study proposes that the secondary motor cortex might convert the map into action.

Main text:

Puzzled by the observation that rats could find shortcuts when navigating a maze, Edward Tolman proposed that the mammalian brain had the ability to represent spatial relationships among the elements of the environment. He called this representation a “cognitive map”, and speculated that maps could support higher psychological functions like navigation, decision making, and imagination [1]. In the decades following Tolman´s proposal, the neural correlates of the cognitive map were identified in the hippocampal formation of the mammalian brain, and it was shown that such a cognitive construct endows animals with the ability to use previous experience to select their future behavior [2, 3]. A new study reported in this issue of *Current Biology* by Olson *et al.* [4] proposes that the secondary motor cortex might use the cognitive map to select and perform planned actions.

In a cognitive map, salient elements of the environment like objects, landmarks, or borders are mapped within multiple reference frames in relation to the animal’s body (“egocentric coding”) or the outside world (“allocentric coding”) [5]. In order for such a map to be exploited for goal-directed navigation, information must be translated between ego- and allocentric reference frames, and must be accessible to the motor-control network (Fig 1). In fact, egocentric information provided by the primary sensory areas is converted into allocentric representations in the hippocampal formation, where the activity of individual neurons is modulated by specific spatial variables that are mapped in a world-centered reference frame [3]. Here, we find neurons whose firing is modulated by location (place and grid cells), the proximity to borders (border cells), direction (head-direction cells), or distance and direction to landmarks (object-vector cells), independently from the orientation of the animal’s body [2]. At the same time, allocentric information should be converted back into an egocentric reference frame centered on the animal's motor output, so that appropriate motor sequences can be released at specific locations of the environment. A rich repertoire of egocentric spatial representations has recently been identified within the parietal and retrosplenial cortices, making these two areas the ideal candidates for self-centered orientation within a map (Fig 1) [5]. In fact, in the parietal cortex we find neurons that encode bearings to external cues and represent the position of an animal in a route-space, independently of the animal's location [6, 7]; in the retrosplenial cortex, we find neurons that encode bearings to boundaries and could be used to coordinate between reference frames [8, 9].

How can the cognitive map inform the motor system about which actions to make? Hypothetically, an area involved in the transformation of spatial cognition into motor actions should be able to receive information from the cognitive map, and use this information to direct the motor system in selecting appropriate movements at specific locations. The secondary motor cortex (M2) could fulfil such a role: it receives extensive connections from the parietal and retrosplenial cortices, and projects to areas involved in motor control including the primary motor cortex, the brainstem, the striatum, and spinal regions [10-12]. In the past, M2 has been considered as a part of the motor network and studied for its role in associating sensory stimuli to actions [10, 12]. Additionally, because of its connections to other prefrontal areas (such as the orbitofrontal cortex), M2 has been studied, mostly in head-fixed rodents, within the framework of decision making and the selection of goal-directed behaviors [10, 13, 14]. Interestingly, an external observer can predict upcoming navigational choices from the activity of M2 neurons, and choice-related activity appears in M2 earlier than any other prefrontal area [13].

In this issue of Current Biology, a new study by Olson *et al* proposes that M2 is part of the network that transforms spatial and directional signals from the navigation system into context-independent signals for movement [4]. To test this hypothesis, the authors recorded the activity of individual M2 neurons while rats traversed specific routes to goals in a Triple-T maze. In this task, rats started their journey into the maze from a single location, and were soon faced with three sequential choice-points that branched into eight exclusive paths leading to eight distinct reward locations. After reward consumption, rats could walk through a series of forced turns along the perimeter of the maze to head back to the start location, in order to begin another outbound journey. Such a clever behavioral design allowed the authors to discriminate the influence of multiple variables associated to spatial context (being at the 1st, 2nd, or 3rd turn along a route), decision making (chosen vs. forced turns), action planning (i.e., the portion of the trajectory approaching a turn), and action execution (i.e., the apex of the turn), on M2 single units firing.

Action was the variable that could be most robustly decoded from the activity of individual neurons in M2. In fact, the majority of neurons could discriminate turn direction (left vs. right) with high reliability at every location of the maze, and did so consistently both during action planning and execution. However, even if the magnitude of their impact was significantly less pronounced than action, spatial variables such as location, progression within a route, orientation, and route being traversed had a significant impact on single neuron's activity. In fact, individual neurons in M2 often exhibited complex firing patterns that were able to encode multiple variables related to both action and context simultaneously and to varying degrees.

Is the modulation of M2 activity by context given by the involvement of this area in the decision-making process? To answer this question, the authors analyzed the spatial and temporal profile of M2 discriminatory activity (quantified as the probability that an external observer could successfully predict the outcome of an action from the firing of individual neurons, i.e. the "choice probability"). On a population level, choice probability was distributed across the whole trajectory leading to a turn and exhibited a ramping profile peaking at the choice point, as it would be expected in a decision-making task. However, the choice probability of individual neurons peaked within a limited portion of the trajectory, with varying distances from the apex of the turn. At the same time, the ability to discriminate between right and left turns was not lost in locations where no choice was to be made (i.e., on the "forced" turns along the perimeter of the maze). This evidence led the authors to question the involvement of M2 in decision-making processes in conditions where animals were able to move freely in complex environments, and to support the hypothesis that the function of M2 lied at the transition from action planning to execution.

What Olson et al present here is a study that makes use of a clever behavioral design and statistical frameworks to quantify the influence of multiple variables on individual neurons' firing, thereby proposing a promising approach to disentangle the neural code in those associative areas whose function cannot be boxed down to one individual cognitive domain. The fact that action-discriminating activity was significantly modulated by multiple spatial and directional variables suggests that M2 takes part in the process that transforms spatial cognition into action, and supports the hypothesis that M2 might be involved in coordinating external stimuli and internal states to drive motion [10, 15]. Notably, it was previously shown that M2 inactivation disrupted the ability to learn and execute internally-guided motor routines but not the ability to orient oneself toward an external sensory stimulus [16], thus strengthening the idea that M2 is involved in the production of internally-guided, but not externally instructed, actions [15]. In the current study, action modulated M2 activity to a larger degree than context did, suggesting that, in a continuum of transformations, M2 is closer to the motor output than to the cognitive map. Future experimental work will however be necessary to confirm this hypothesis.

Surprisingly, the deliberative process of choosing which direction to take seemed to have limited influence on M2. In fact, single neurons' discriminating activity showed discrete and restricted peaks at varying distances from the apex of the turn, where the choice was to be implemented. This profile defined a sequential neural trajectory covering the whole route to the goal, including action planning and execution. Choice-related sequential activity has previously been found in multiple areas of the brain, most importantly in those involved in navigation or motor control such as the hippocampus, the parietal cortex, and the striatum [17-19]. The mechanism by which sequential activity emerges in M2 and other areas during training, and if neural sequences are coordinated across the hippocampal/prefrontal/striatal circuit is however still unknown. Strikingly, M2 has monosynaptic projections to medium spiny neurons of the dorsal striatum, and these cortico-striatal projections are specifically strengthened by learning the serial order of actions [20]. It will be interesting to understand when during learning, and at which level of the cognitive-to-motor transformation, sequential activity first appears, in order to dissect the mechanisms that coordinates the transformation of planned actions into motor routines.

Several decades after Tolman, we are now beginning to appreciate the heterogeneity of the neural correlates of the cognitive map, and to understand the intricate mechanisms that regulate its formation and exploitation. The new study from Olsen *et al* offers new indications about the areas of the brain that could take part in transforming the map into movements, and bring us closer to understanding how we use cognitive representations to plan and execute actions.

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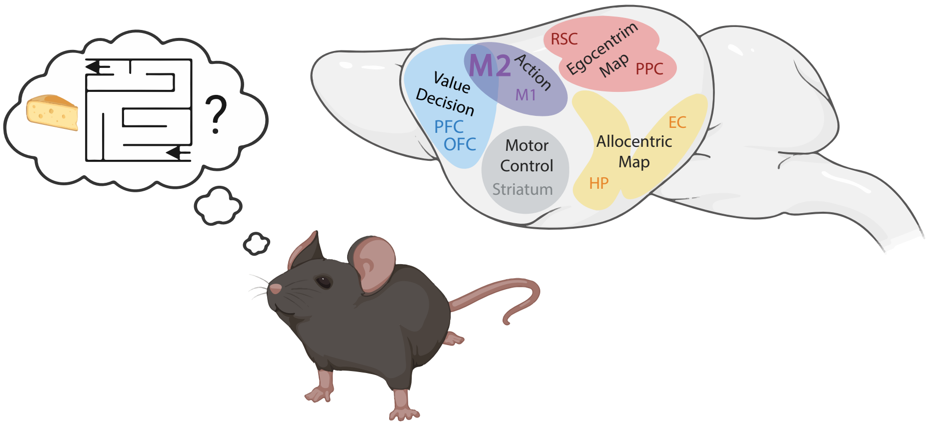
Figure Legend:

Figure 1. Schematic representation of cortical and subcortical networks for navigation and action. Sensory information about the environment supports the emergence of a world-centered (allocentric) cognitive map in the hippocampal formation, which includes the hippocampus (HP) and entorhinal cortices (EC). Spatially-tuned activity patterns are additionally present in two high-order association cortices, retrosplenial (RSC) and posterior parietal cortex (PPC), which perform egocentric-allocentric transformations and are ideally suited for self-centered orientation within cognitive maps. RSC and PPC send strong connections to the secondary motor cortex (M2), which might combine spatial signals with information about rewards and the expected value of choices (relayed by the orbitofrontal cortex (OFC) and other areas of the prefrontal cortex (PFC)), to elicit specific movements to goals via its projections to areas involved in motor control, like the primary motor cortex (M1) and striatum.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