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News & views

Neurobiology

Mental replays enable flexible navigation

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While rats pause to eat or rest during navigation tasks, neuronal sequences in the brain are replaying routes around moving obstacles, allowing the animals to reach their goals even in changing environments.

The ability to navigate is essential to daily life, whether someone is driving to work or walking to the coffee machine. To negotiate complex environments, one can follow instructions: 'turn right at the bakery', for example. This strategy is simple and requires little effort, but is inflexible — if the bakery is no longer there, one is lost. One could use a map instead: with external cues, one can locate oneself on the map and plot the shortest path to one's destination. This requires more effort but has the advantage that all routes (even unfamiliar ones) can be seen at a glance, allowing flexibility if, say, a street is blocked by traffic. Yet humans (and other animals) can also flexibly navigate complex and changing environments without instructions, and were able to do so well before the advent of maps (let alone GPS technology). How? Writing in *Neuron*, Widloski and Foster[1] report a role for replays of neuronal activity that represent spatial trajectories.

The hippocampus is a brain structure that is essential for flexible navigation in humans and many other animals, such as non-human primates, rodents and bats. Together with other structures in the temporal lobe, the hippocampus participates in the formation of a cognitive map — an internal representation of the external environment[2]. At the cellular level, the hippocampus is made up of neurons called place cells, the activity of which is modulated by someone's position in the environment. When the individual moves around, place cells are sequentially activated and indicate in real time the first piece of information needed for navigation: the current location[3].

This information is not, however, sufficient for navigation towards goals. The individual must also be able to locate those goals and evaluate the routes for getting there[4]. Is it possible for them to achieve this by mentally exploring their cognitive maps?

Research over the past 15 years has shown that sequences of place-cell activation that correspond to routes recently explored by an animal can be replayed about 20 times faster when animals are immobile (resting or eating, for example)[5] or asleep[6] than when they are moving. This replay occurs during short bouts of fast oscillating brain activity called ripples, and could represent high-speed mental travel through the cognitive map. Interestingly, these sequences feature trajectories in the forward order, but also backwards (akin to rewinding a tape). So it has been unclear whether they represent the simulation of a path to a future goal, for planning purposes, or the recall of a previously explored path to a past goal, for memory formation[7]. Answering this question was difficult because, in these experiments, animals ran back and forth in linear corridors for rewards at both ends: there were only two trajectories to be replayed, with both moving simultaneously away from one goal and towards the next.

To investigate, Widloski and Foster devised a more difficult navigation task in a more complex setting. In their experiment, rats had to navigate between two wells in a square environment to obtain a reward. One well ('home') was fixed for the duration of a recording session, whereas the other varied from trial to trial (Fig. 1). The animals' movements were also constrained by a series of transparent, odour-permeable barriers. The fact that the

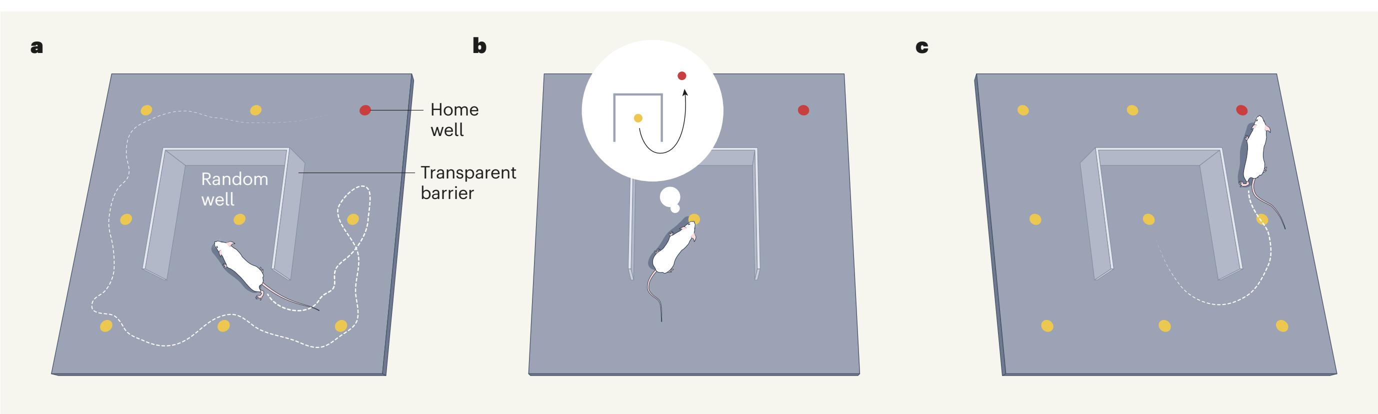

Figure 1 | Flexible navigation. Widloski and Foster[1] investigated the neuronal mechanisms underlying rats' ability to navigate in complex (and changing) environments. **a**, In a complex maze with transparent barriers, a rat learnt to navigate from a fixed location (home well) to a random well to find rewards. The white trace shows the path followed by the rat during a trial. **b**, During pauses to consume a liquid reward, brain activity replayed trajectories leading from the current location back home, where another reward could be found. The simulated mental travel made detours around barriers. **c**, On the next trial, the rat took a path similar to the one simulated, suggesting that such brain activity could be used to plan navigation. Replayed trajectories could also adapt to changes in barrier configurations between recording sessions (not shown).

random well's position varied from trial to trial allowed the evaluation of different behavioural trajectories and for a clear distinction to be drawn between past journeys towards the current goal and future journeys towards subsequent goals.

The authors observed that both types of trajectory could be replayed during immobile periods, but that future trajectories towards the home goal were favoured over past trajectories. Interestingly, the replayed trajectories respected the geometric organization of the barriers, bypassing them if necessary, even though this organization was systematically changed from one recording session to the next, often during the same day. This observation is compatible with the fact that the replayed trajectories mainly corresponded to paths actually taken by the animal during a recording session. So, just as the rats could not cross the barriers when exploring, replayed trajectories also very rarely crossed the barriers, often travelling parallel to them. Altogether, these results convincingly show that replayed mental trajectories respect physical constraints, making detours around them if necessary — just as humans do when a road is blocked.

But what mechanism could explain such flexibility? Because replayed trajectories correspond to the sequential reactivation of place cells that are active during navigation, a simple hypothesis would be that place cells reorganize their spatial specificity to adapt to any new barrier configuration. Indeed, previous work[8] has shown that place cells can modify their spatial activity when changes occur in an environment (in terms of shape, odour and so on). To investigate, Widloski and Foster compared the spatial specificity of place cells between different barrier configurations. They found that most cells remained stable, with only a few — representing positions close to moving barriers — being less stable, in line with previous observations[9]. The authors conclude that this mechanism is unlikely to explain the rapid adaptation of replayed trajectories.

These findings raise many questions. For instance, do replayed trajectories respect only physical barriers, or can they also take account of other obstacles, such as a danger to be avoided? Do they indicate only the next location to which someone wants to go, or also past locations that the individual might wish to avoid[10]?

If these sequences are used to evaluate paths, it would be interesting to determine whether different paths can be replayed and compared, so as to determine which is likely to lead most directly or effortlessly to the goal. It also remains unclear how goal information (such as positive feedback at the goal) is incorporated into these sequences, and what mechanisms determine where each sequence begins and ends. Finally, these observations remain correlative, and an interesting experiment would be to interrupt the sequences before the replay reaches the goal[11], or to reroute them away from the goal, to see whether this could affect subsequent navigation. It should be possible to manipulate the sequences by using techniques for stimulating hippocampal neurons, such as optogenetics[12].

These discoveries bring researchers one step closer to understanding the properties of our cognitive map. The fact that these mental trajectories respect physical barriers that constrain behaviour — as well as the trajectories' flexibility with regard to changes in the spatial organization of obstacles — makes them particularly suitable for flexible navigation. So the next time you are stuck in a traffic jam, forget your favourite navigation software and trust your hippocampus and its internal sequences to find an alternative route.

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