

in 2020, there is no need to clear forest for beef production in these scenarios, and some of the land that was once used for pasture can be converted to cropland. Moreover, in all of the substitution scenarios, the annual deforestation rates decline during the first 15–20 years and increase afterwards. This can be explained by structural changes in agriculture that occur over time, such as changes in agricultural yields and in the level of land degradation. Compared with the baseline scenario, all substitution levels resulted in large reductions in greenhouse-gas emissions from livestock production and land-use changes, but only minor changes in agricultural water use and nitrogen fixation.

Studies known as product-level assessments have previously estimated the environmental impacts of cell-cultured foods, per unit produced. Humpenöder and colleagues' study is a first step towards assessing how production affects specific types of land use and associated greenhouse-gas emissions over time. However, the study does not provide a complete picture of the environmental consequences of the transition from beef to cell-cultured foods. That's because its scope is limited to impacts associated with land use, and it does not consider all the ingredients and other resources needed for mycoprotein production.

Future research should expand the scope of the current study by considering the environmental impacts of other factors involved in food production. For example, product-level assessments have shown that producing cell-cultured food can require more electricity than does raising livestock¹. The environmental impacts of energy generation therefore need to be considered, taking into account future capacity to expand sustainable electricity supplies. Glucose sources other than sugar cane should also be assessed; these could include crops such as sugar beet or grains that can be cultivated in boreal regions, as well as by-products from the production of other types of food or animal feed⁶.

It should be noted that Humpenöder and colleagues' modelling is likely to overestimate the impacts of beef production and underestimate those of culturing mycoproteins. Beef production provides many by-products, such as milk, hides for leather production and fat for the chemical industry. If beef production were reduced, the by-products would need to be made in alternative ways, which would increase environmental impacts. Furthermore, large reductions in beef consumption would require a parallel reduction in the consumption of dairy products, at least in regions where most beef originates from dairy systems⁷.

Further research into the environmental consequences of producing cell-cultured foods should include a wider range of

products. These could include proteins produced by microorganisms that use CO₂ or methane as a carbon source⁴; milk and egg proteins produced by microbial cells⁸; and cultured meat made of animal cells¹. The estimates of the environmental impacts would be improved by using scenarios that consider the availability and realistic adoption rates of cell-cultured foods in different socio-economic contexts. Global assessments will also be needed to find ways of making food systems more sustainable through innovative technologies combined with dietary changes, sustainable agricultural practices and reduced food waste.

Neurobiology

Mental replays enable flexible navigation

Jérôme Epsztejn

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 Foster¹ 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 environment². 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.

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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 location³.

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 there⁴. 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

“These discoveries bring researchers one step closer to understanding the properties of our cognitive map.”

faster when animals are immobile (resting or eating, for example)⁵ or asleep⁶ 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

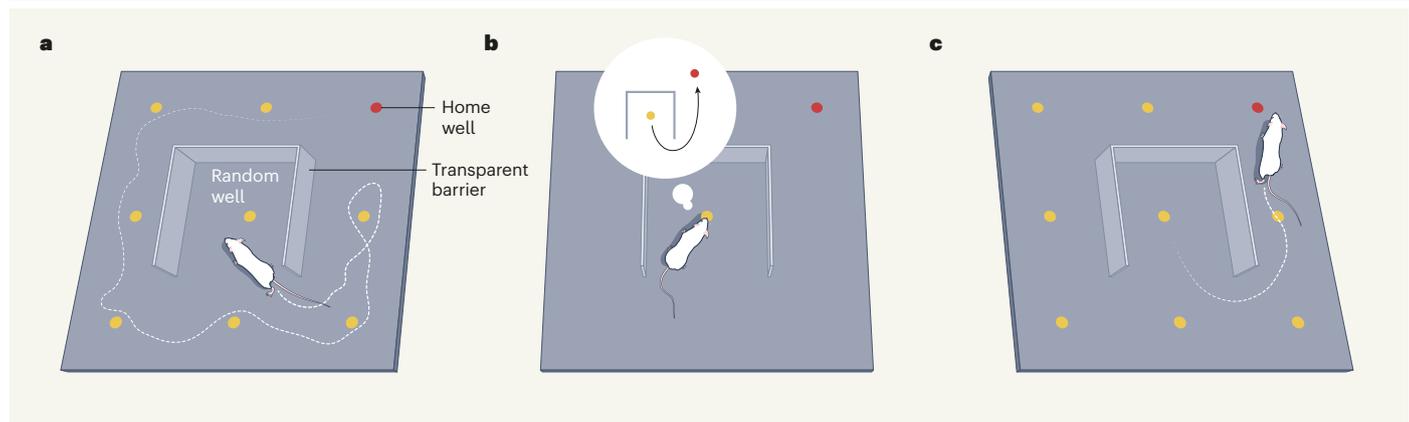


Figure 1 | Flexible navigation. Widloski and Foster¹ investigated the neuronal mechanisms underlying rats' ability to navigate in complex (and changing) environments. **a**, In a complex maze with transparent barriers, a rat learnt to navigate from a fixed location (home well) to a random well to find 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).

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 formation⁷. 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 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 work⁸ 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 observations⁹. 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 avoid¹⁰?

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 goal¹¹, 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 optogenetics¹².

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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