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'Spatial Computing' enables flexible working memory

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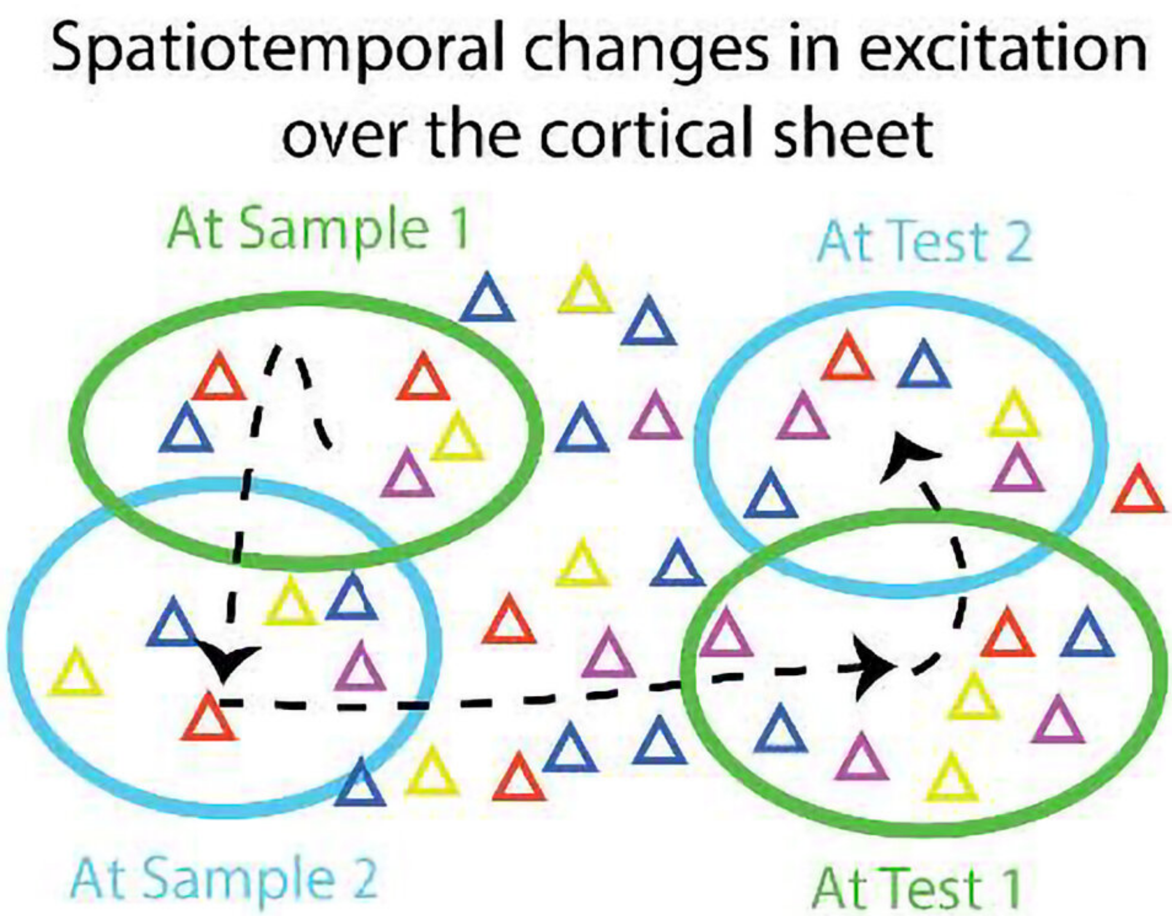

Triangles represent neurons. Colors represent specific information they encode. The ovals represent patches in which brain waves represent task rules. For instance, Sample 1 could be the first instruction to remember.In a specific instance of a task, the neurons representing content presented at sample 1 (say, the yellow triangle) would spike the most in the Sample 1 patch. Credit: Miller Lab/MIT Picower Institute

Routine tasks that require working memory, like baking, involve remembering both some general rules (e.g. read the oven temperature and time from the recipe and then set them on the oven) and some specific content for each instance (e.g. 350 degrees for 45 minutes for a loaf of rye, but 325 degrees for 8 minutes for cookies). A new study provides a novel explanation for how the brain distinctly manages the general and specific components of such cognitive demands.

The research led by scientists at MIT's Picower Institute for Learning and Memory and the Karolinksa Institute and KTH Royal Institute of Technology in Stockholm Sweden, shows that the brain creates distinct spaces in the cortex for each general rule and controls those patches with brain rhythms, a concept the authors call "Spatial Computing."

This system, evident in the study's experiments in animals, explains how the brain can easily sustain a consistent understanding of a process even when the specific contents keep changing (like the time and temperature for bread vs. cookies). It also answers a few questions neuroscientists have wrestled with about the physiological operations that underlie working memory.

"Your brain can instantly generalize. If I teach you to follow some rules, like remembering C, A, and B and putting them into alphabetical order, and then I switch the contents to F, D and E you wouldn't miss a beat," said Earl K. Miller, Picower Professor in MIT's Picower Institute for Learning and Memory and co-senior author of the study in *Nature Communications*. "Your brain can do this because it represents the rules and the contents at different physical scales. One can just be plugged into the other."

Working memory workings

Years of research by Miller's lab, much of it led by lead author Mikael Lundqvist who is now at Karolinska have shown that working memory tasks are governed by an interplay of brain rhythms at distinct frequencies. Slower beta waves carry information about task rules and selectively yield to faster gamma waves when it's time to execute operations such as storing information from the senses or reading it out when recall is needed.

But these waves operate on networks of millions of neurons, only a smattering of which are actually storing the individual items of information relevant at any particular time. Moreover, neurons that carry information about specific items are found all over the place. Some become electrically excited, or "spike," in response to different task rules than others, and they often tend to spike at least somewhat even when their information isn't relevant.

So how can these rather imprecise rhythms selectively control just the right neurons at the right times to do the right things? Why are neurons whose spiking relates to specific items scattered and redundant? What makes one neuron that's particular to "350 degrees" perk up when that information has to be stored but another neuron with that information perk up when it needs to be recalled?

The researchers realized that all these questions could be resolved by the Spatial Computing theory. Individual neurons representing information items can be scattered widely around the cortex, but the rule that's applied to them is based on the patch of the network they are in. Those patches are determined by the pattern of beta and gamma waves.

"By analyzing a lot of single neurons throughout the years, we had always wondered why so many of them appeared to behave similarly," Lundqvist said.

"Regardless of if they preferred the same external stimulus or not, many neurons shared similar patterns of activity during working memory. And these patterns switched from task to task. It also appeared that neurons that were closer together within prefrontal cortex more often shared the same pattern. It started us thinking that memory representations might actually dynamically flow around in prefrontal cortex to implement task rules."

So say your friend calls you at the gym, asking you to retrieve a watch they accidentally left in their locker. This requires turning the padlock dials to the numbers in the combination (e.g. 24, 17, 32). Spatial Computing says that when you hear the combination your brain creates distinct patches for each step (first, second, third).

Within each patch the neurons representing the combination number of that particular step become especially excited by gamma waves applied at the time the rule is relevant (i.e. 24 in the "first" patch, 17 in the "second" patch and 32 in the "third" patch).

In this way individual neurons encoding specific items of information can be selectively associated with general rules by the brain waves controlling the patches they inhabit. In any given patch, all the neurons may be excited somewhat by the gamma waves, but the ones representing the item that fits the rule will spike the most.

"This way memory representations could be dynamically reshaped to fit current task demands independent of how individual neurons are connected or which stimulus they prefer," said co-senior author Pawel Herman of KTH. "It may explain our impressive generalization capabilities in novel situations."

This is not to say that any patch is forever fixed. The patches can come and go for however long they are needed wherever the brain happens to form them for the task at hand. There is no permanent "remember oven temperature" patch in the brain.

"This gives the brain flexibility," Miller said. "Cognition is all about flexibility."

Experimental evidence

The researchers weren't just theorizing. To test Spatial Computing in real physical brains, they made four experimental predictions about what they should observe as animals played working memory games such as remembering a set of images in an order.

The first prediction was that there should be distinct neural signals about the rules and individual item information. Indeed, the team measured that bursts of waves carried rule information. Individual neural spikes, meanwhile, carried a mix of individual items and task rules, consistent with them representing individual items and having specific rules imposed on them.

The second prediction was that rules information should be spatially organized and the third prediction was that these rule-enforcing spatial patterns should be consistent so long as the game rules remained the same, regardless of whether the individual items changed. Sure enough, the researchers found that there were different locations for gamma bursts for different rules and that these stayed stable even when the individual items varied during each game.

The final prediction was that the activity of the brain waves should cause neural spiking activity to represent the right information at the right times. This was reflected in the experimental observations, as well. The researchers saw different brain wave patterns for when the brain had to store images in memory and when it had to recall the "right" one. Generally, beta waves were more reduced and neurons spiked more and in a wider area during recall than during storage.

The paper doesn't answer every question about working memory. It's not clear yet, how neurons encoding specific information in one patch might be associated with their brethren in another patch or how the brain controls the patches. More research can answer those further questions about the implications of the new theory of Spatial Computing.

More information: Earl K. Miller et al, Working memory control dynamics follow principles of spatial computing, *Nature Communications* (2023). DOI: 10.1038/s41467-023-36555-4

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