Neuroscientists suggest a model for how we gain volitional control of what we hold in our minds

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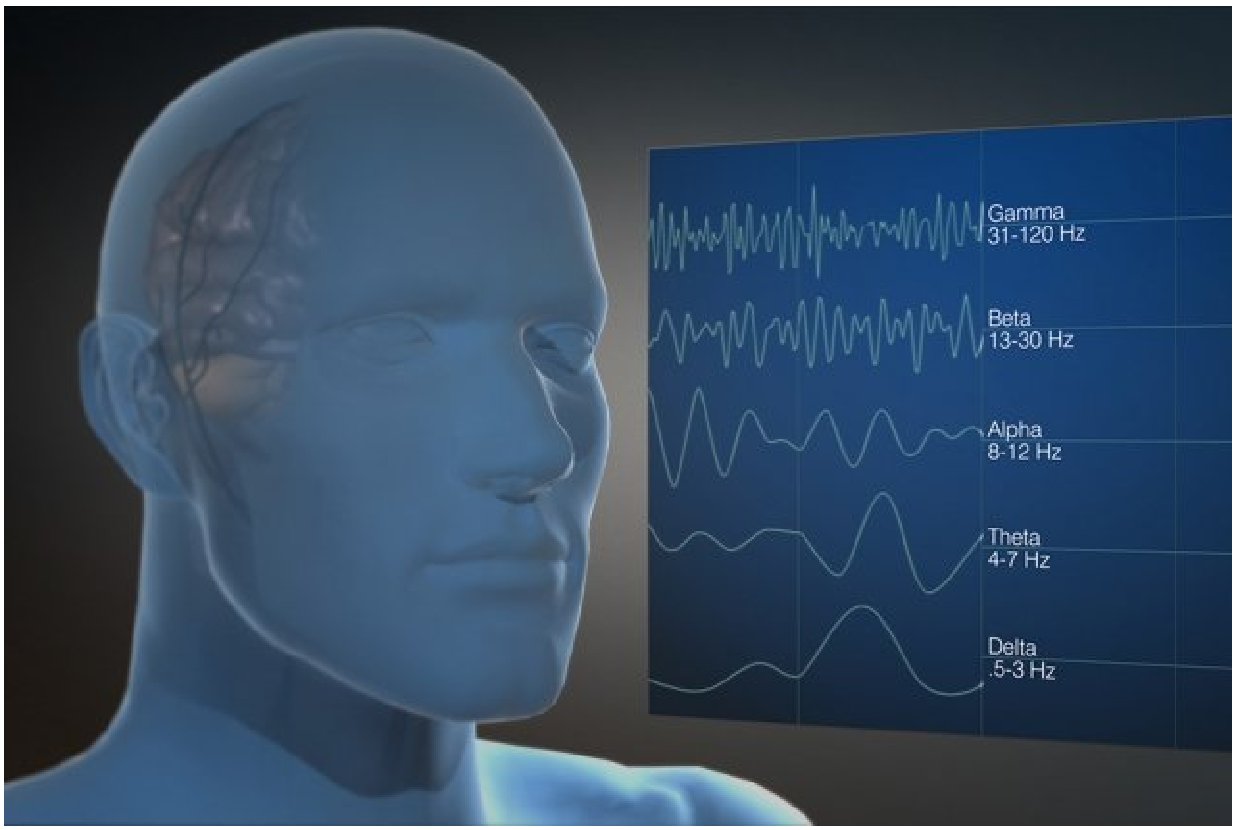

Credit: Massachusetts Institute of Technology

Working memory is a sort of "mental sketchpad" that allows you to accomplish everyday tasks such as calling in your hungry family's takeout order and finding the bathroom you were just told "will be the third door on the right after you walk straight down that hallway and make your first left." It also allows your mind to go from merely responding to your environment to consciously asserting your agenda.

"Working memory allows you to choose what to pay attention to, choose what you hold in mind, and choose when to make decisions and take action," says Earl K. Miller, the Picower Professor in MIT's Picower Institute for Learning and Memory and the Department of Brain and Cognitive Sciences. "It's all about wresting control from the environment to your own self. Once you have something like working memory, you go from being a simple creature that's buffeted by the environment to a creature that can control the environment."

For years Miller has been curious about how working memory—particularly the volitional control of it—actually works. In a new study in the *Proceedings of the National Academy of Sciences* led by Picower Institute postdoc Andre Bastos, Miller's lab shows that the underlying mechanism depends on different frequencies of brain rhythms synchronizing neurons in distinct layers of the prefrontal cortex (PFC), the area of the brain associated with higher cognitive function. As animals performed a variety of working memory tasks, higher-frequency gamma rhythms in superficial layers of the PFC were regulated by lower-frequency alpha/beta frequency rhythms in deeper cortical layers.

The findings suggest not only a general model of working memory, and the volition that makes it special, but also new ways that clinicians might investigate conditions such as schizophrenia where working memory function appears compromised.

Layers of waves

To conduct the study, Bastos worked from several lines of evidence and with some relatively new technology. Last year, for example, co-author and Picower Institute postdoc Mikael Lundqvist led a study showing that gamma waves perked up in power when sensory (neuroscientists call it "bottom-up") information was loaded into and read out from working memory. In previous work, Miller, Bastos, and their colleagues had found that alpha/beta rhythms appeared to carry "top-down" information about goals and plans within the cortex. Top-down information is what we use to make volitional decisions about what to think about or how to act, Miller says.

The current study benefitted from newly improved multilayer electrode brain sensors that few groups have applied in cognitive, rather than sensory, areas of the cortex. Bastos realized that if he made those measurements, he and Miller could determine whether deep alpha/beta and superficial gamma might interact for volitional control of working memory.

In the lab Bastos and his co-authors, including graduate students Roman Loonis and Simon Kornblith, made multilayer measurements in six areas of the PFC as animals performed three different working memory tasks.

In different tasks, animals had to hold a picture in working memory to subsequently choose a picture that matched it. In another type of task, the animals had to remember the screen location of a briefly flashed dot. Overall, the tasks asked the subjects to store, process, and then discard from working memory the appearance or the position of visual stimuli.

"Combining data across the tasks and the areas does lead to additional weight for the evidence," Bastos says.

A mechanism for working memory

Across all the PFC areas and all tasks, the data showed the same thing: When sensory information was loaded into working memory, the gamma rhythms in superficial layers increased and the alpha/beta rhythms in deep layers that carried the top-down information decreased. Conversely, when deep-layer alpha/beta rhythms increased, superficial layer gamma waned. Subsequent statistical analysis suggested that gamma was being controlled by alpha and beta rhythms, rather than the other way around.

"This suggests mechanisms by which the top-down information needed for volitional control, carried by alpha/beta rhythms, can turn on and off the faucet of bottom-up sensory information, carried by gamma, that reaches working memory and is held in mind," Miller says.

With these insights, the team has since worked to directly test this multilayer, multifrequency model of working memory dynamics more explicitly, with results in press but not yet published.

Charles Schroeder, research scientist and section head in the Center for Biomedical Imaging and Neuromodulation at the Nathan S. Kline Institute for Psychiatric Research, describes two contributions of the study as empirically important.

"First, the paper clearly shows that critical cognitive operations (in this case working memory) are underlain by periodic (oscillatory) network activity patterns in the brain, and that these must be addressed by single trial analysis," Schroeder says. "This provides an important conceptual alternative to the idea that working memory must involve continuous neural activation. Secondly, the findings strongly reinforce the notion that dynamic coupling across high- and low-frequency ranges performs a clear mechanistic function: Lower frequency activity dominant in the lower layers of the prefrontal area network controls the temporal patterning of higher frequency information representation in the superficial layers of the same network of areas. The important conceptual innovation in this case lies in allowing lower frequency control operations to act directly on higher frequency information representation within each cortical area."

Bastos says the model could be useful for generating hypotheses about clinical working memory deficits. Aberrations of deep-layer beta rhythms, for example, could lead to a lessened ability to control working memory for goal-directed action. "In a schizophrenia model or schizophrenia patients, is the interplay between beta and gamma lost?" he asks.

More information: André M. Bastos el al., "Laminar recordings in frontal cortex suggest distinct layers for maintenance and control of working memory," *PNAS* (2018). www.pnas.org/cgi/doi/10.1073/pnas.1710323115

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