To understand cognition and its dysfunction, neuroscientists must learn its rhythms

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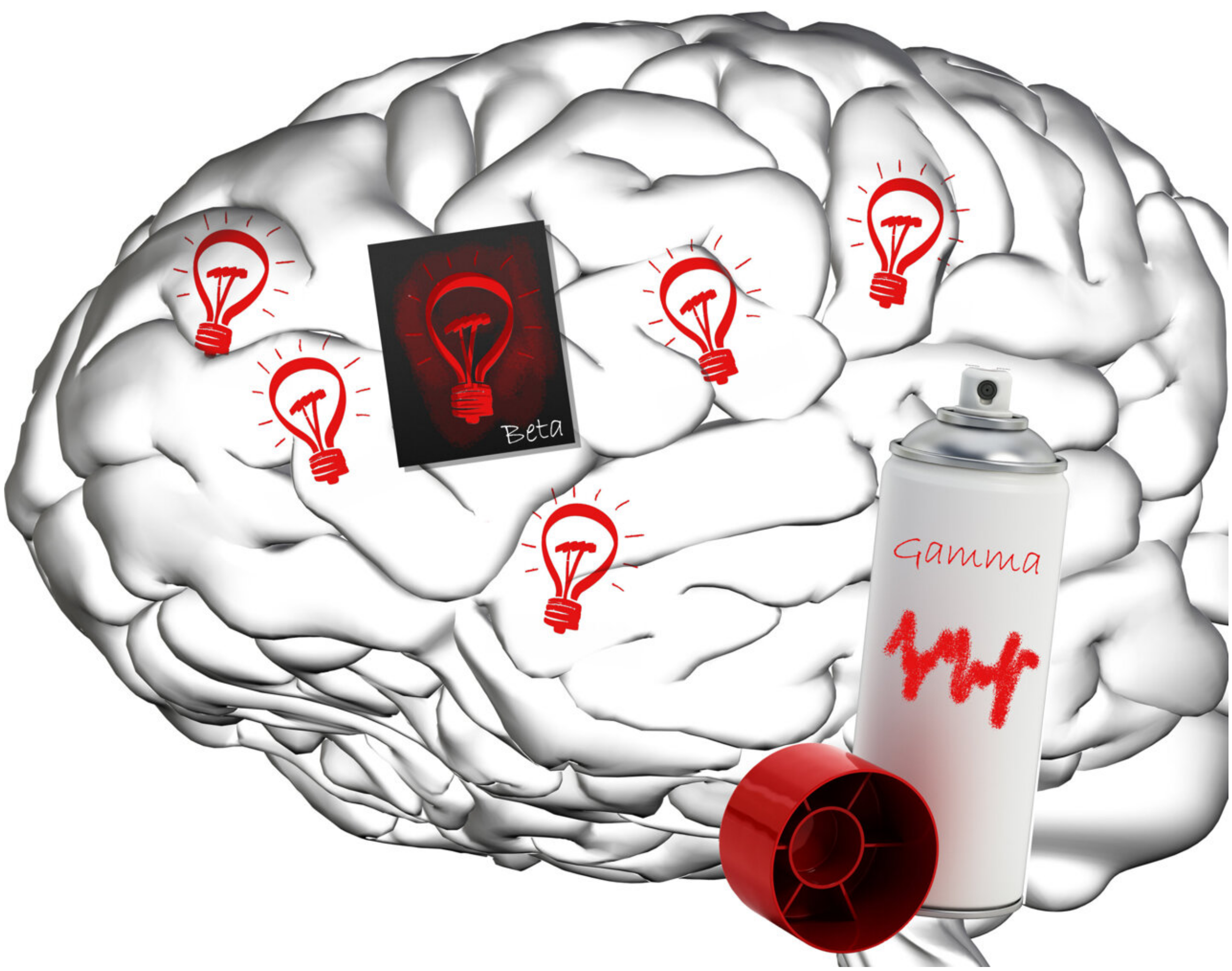

The Spatial Computing theory posits that beta rhythms act like stencils, dictating where gamma rhythms can encode information in the cortex, for instance from the senses. Credit: MIT Picower Institute

It could be very informative to observe the pixels on your phone under a microscope, but not if your goal is to understand what a whole video on the screen shows. Cognition is much the same kind of emergent property in the brain. It can only be understood by observing how millions of cells act in coordination, argues a trio of MIT neuroscientists. In a new article, they lay out a framework for understanding how thought arises from the coordination of neural activity driven by oscillating electric fields—also known as brain "waves" or "rhythms."

The paper is published in the journal *Current Opinion in Behavioral Sciences*.

Historically dismissed solely as byproducts of neural activity, brain rhythms are actually critical for organizing it, write Picower Professor Earl Miller and research scientists Scott Brincat and Jefferson Roy. And while neuroscientists have gained tremendous knowledge from studying how individual brain cells connect and how and when they emit "spikes" to send impulses through specific circuits, there is also a need to appreciate and apply new concepts at the brain rhythm scale, which can span individual—or even multiple—brain regions.

"Spiking and anatomy are important but there is more going on in the brain above and beyond that," said senior author Miller, a faculty member in The Picower Institute for Learning and Memory and the Department of Brain and Cognitive Sciences at MIT. "There's a whole lot of functionality taking place at a higher level, especially cognition."

The stakes of studying the brain at that scale, the authors write, might not only include understanding healthy higher-level function but also how those functions become disrupted in disease.

"Many neurological and psychiatric disorders, such as schizophrenia, epilepsy and Parkinson's involve disruption of emergent properties like neural synchrony," they write. "We anticipate that understanding how to interpret and interface with these emergent properties will be critical for developing effective treatments as well as understanding cognition."

The emergence of thoughts

The bridge between the scale of individual neurons and the broader-scale coordination of many cells is founded on electric fields, the researchers write. Via a phenomenon called "ephaptic coupling," the electrical field generated by the activity of a neuron can influence the voltage of neighboring neurons, creating an alignment among them. In this way, electric fields both reflect neural activity but also influence it.

In a paper in 2022, Miller and colleagues showed via experiments and computational modeling that the information encoded in the electric fields generated by ensembles of neurons can be read out more reliably than the information encoded by the spikes of individual cells. In 2023, Miller's lab provided evidence that rhythmic electrical fields may coordinate memories between regions.

At this larger scale, in which rhythmic electric fields carry information between brain regions, Miller's lab has published numerous studies showing that lower-frequency rhythms in the so-called "beta" band originate in deeper layers of the brain's cortex and appear to regulate the power of faster-frequency "gamma" rhythms in more superficial layers. By recording neural activity in the brains of animals engaged in working memory games the lab has shown that beta rhythms carry "top down" signals to control when and where gamma rhythms can encode sensory information, such as the images that the animals need to remember in the game.

Some of the lab's latest evidence suggests that beta rhythms apply this control of cognitive processes to physical patches of the cortex, essentially acting like stencils that pattern where and when gamma can encode sensory information into memory, or retrieve it. According to this theory, which Miller calls "Spatial Computing," beta can thereby establish the general rules of a task (for instance, the back and forth turns required to open a combination lock), even as the specific information content may change (for instance, new numbers when the combination changes).

More generally, this structure also enables neurons to flexibly encode more than one kind of information at a time, the authors write, a widely observed neural property called "mixed selectivity." For instance, a neuron encoding a number of the lock combination can also be assigned, based on which beta-stenciled patch it is in, the particular step of the unlocking process that the number matters for.

In the new study, Miller, Brincat and Roy suggest another advantage consistent with cognitive control being based on an interplay of large-scale coordinated rhythmic activity: "Subspace coding." This idea postulates that brain rhythms organize the otherwise massive number of possible outcomes that could result from, say, 1,000 neurons engaging in independent spiking activity. Instead of all the many combinatorial possibilities, many fewer "subspaces" of activity actually arise, because neurons are coordinated, rather than independent.

It is as if the spiking of neurons is like a flock of birds coordinating their movements. Different phases and frequencies of brain rhythms provide this coordination, aligned to amplify each other, or offset to prevent interference. For instance, if a piece of sensory information must be remembered, neural activity representing it can be protected from interference when new sensory information is perceived.

"Thus the organization of neural responses into subspaces can both segregate and integrate information," the authors write.

The power of brain rhythms to coordinate and organize information processing in the brain is what enables functional cognition to emerge at that scale, the authors write. Understanding cognition in the brain, therefore, requires studying rhythms.

"Studying individual neural components in isolation—individual neurons and synapses—has made enormous contributions to our understanding of the brain and remains important," the authors conclude. "However, it's becoming increasingly clear that to fully capture the brain's complexity, those components must be analyzed in concert to identify, study, and relate their emergent properties."

More information: Earl K Miller et al, Cognition is an emergent property, *Current Opinion in Behavioral Sciences* (2024). DOI: 10.1016/j.cobeha.2024.101388

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