

Overlooked cells might explain the human brain's huge storage capacity

MIT researchers developed a new model of memory that includes critical contributions from astrocytes, a class of brain cells.

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MIT researchers have a new hypothesis for how brain cells called astrocytes might contribute to memory storage in the brain. Their model, based on dense associative memory networks, would help explain the brain's massive storage capacity.

Image: MIT News

The human brain contains about 86 billion neurons. These cells fire electrical signals that help the brain store memories and send information and commands throughout the brain and the nervous system.

The brain also contains billions of astrocytes — star-shaped cells with many long extensions that allow them to interact with millions of neurons. Although they have long been thought to be mainly supportive cells, recent studies have suggested that astrocytes may play a role in memory storage and other cognitive functions.

MIT researchers have now put forth a new hypothesis for how astrocytes might contribute to memory storage. The architecture suggested by their model would help to explain the brain's massive storage capacity, which is much greater than would be expected using neurons alone.

“Originally, astrocytes were believed to just clean up around neurons, but there’s no particular reason that evolution did not realize that, because each astrocyte can contact hundreds of thousands of synapses, they could also be used for computation,” says Jean-Jacques Slotine, an MIT professor of mechanical engineering and of brain and cognitive sciences, and an author of the new study.

Dmitry Krotov, a research staff member at the MIT-IBM Watson AI Lab and IBM Research, is the senior author of the open-access [paper](#), which appeared May 23 in the *Proceedings of the National Academy of Sciences*. Leo Kozachkov PhD '22 is the paper's lead author.

Memory capacity

Astrocytes have a variety of support functions in the brain: They clean up debris, provide nutrients to neurons, and help to ensure an adequate blood supply.

Astrocytes also send out many thin tentacles, known as processes, which can each wrap around a single synapse — the junctions where two neurons interact with each other — to create a tripartite (three-part) synapse.

Within the past couple of years, neuroscientists have shown that if the connections between astrocytes and neurons in the hippocampus are disrupted, memory storage and retrieval are impaired.

Unlike neurons, astrocytes can't fire action potentials, the electrical impulses that carry information throughout the brain. However, they can use calcium signaling to communicate with other astrocytes. Over the past few decades, as the resolution of calcium imaging has improved, researchers have found that calcium signaling also allows astrocytes to coordinate their activity with neurons in the synapses that they associate with.

These studies suggest that astrocytes can detect neural activity, which leads them to alter their own calcium levels. Those changes may trigger astrocytes to release gliotransmitters — signaling molecules similar to neurotransmitters — into the synapse.

“There's a closed circle between neuron signaling and astrocyte-to-neuron signaling,” Kozachkov says. “The thing that is unknown is precisely what kind of computations the astrocytes can do with the information that they're sensing from neurons.”

The MIT team set out to model what those connections might be doing and

how they might contribute to memory storage. Their model is based on Hopfield networks — a type of neural network that can store and recall patterns.

Hopfield networks, originally developed by John Hopfield and Shun-Ichi Amari in the 1970s and 1980s, are often used to model the brain, but it has been shown that these networks can't store enough information to account for the vast memory capacity of the human brain. A newer, modified version of a Hopfield network, known as dense associative memory, can store much more information through a higher order of couplings between more than two neurons.

However, it is unclear how the brain could implement these many-neuron couplings at a hypothetical synapse, since conventional synapses only connect two neurons: a presynaptic cell and a postsynaptic cell. This is where astrocytes come into play.

“If you have a network of neurons, which couple in pairs, there's only a very small amount of information that you can encode in those networks,” Krotov says. “In order to build dense associative memories, you need to couple more than two neurons. Because a single astrocyte can connect to many neurons, and many synapses, it is tempting to hypothesize that there might exist an information transfer between synapses mediated by this biological cell. That was the biggest inspiration for us to look into astrocytes and led us to start thinking about how to build dense associative memories in biology.”

The neuron-astrocyte associative memory model that the researchers developed in their new paper can store significantly more information than a traditional Hopfield network — more than enough to account for the brain's memory capacity.

Intricate connections

The extensive biological connections between neurons and astrocytes offer support for the idea that this type of model might explain how the brain's memory storage systems work, the researchers say. They hypothesize that within astrocytes, memories are encoded by gradual changes in the patterns of calcium flow. This information is conveyed to neurons by gliotransmitters released at synapses that astrocyte processes connect to.

“By careful coordination of these two things — the spatial temporal pattern of calcium in the cell and then the signaling back to the neurons — you can get exactly the dynamics you need for this massively increased memory capacity,” Kozachkov says.

One of the key features of the new model is that it treats astrocytes as collections of processes, rather than a single entity. Each of those processes can be considered one computational unit. Because of the high information storage capabilities of dense associative memories, the ratio of the amount of information stored to the number of computational units is very high and grows with the size of the network. This makes the system not only high capacity, but also energy efficient.

“By conceptualizing tripartite synaptic domains — where astrocytes interact dynamically with pre- and postsynaptic neurons — as the brain's fundamental computational units, the authors argue that each unit can store as many memory patterns as there are neurons in the network. This leads to the striking implication that, in principle, a neuron-astrocyte network could store an arbitrarily large number of patterns, limited only by its size,” says Maurizio De Pitta, an assistant professor of physiology at the Krembil Research Institute at the University of Toronto, who was not involved in the

study.

To test whether this model might accurately represent how the brain stores memory, researchers could try to develop ways to precisely manipulate the connections between astrocytes' processes, then observe how those manipulations affect memory function.

"We hope that one of the consequences of this work could be that experimentalists would consider this idea seriously and perform some experiments testing this hypothesis," Krotov says.

In addition to offering insight into how the brain may store memory, this model could also provide guidance for researchers working on artificial intelligence. By varying the connectivity of the process-to-process network, researchers could generate a huge range of models that could be explored for different purposes, for instance, creating a continuum between dense associative memories and attention mechanisms in large language models.

"While neuroscience initially inspired key ideas in AI, the last 50 years of neuroscience research have had little influence on the field, and many modern AI algorithms have drifted away from neural analogies," Slotine says. "In this sense, this work may be one of the first contributions to AI informed by recent neuroscience research."

 [Paper: "Neuron-astrocyte associative memory"](#)

