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Upending Decades of Debate, Scientists Discover Most Neurons are Jacks-of-All-Trades

Findings that neurons in mice are mostly generalists, instead of specialized for specific functions, has scientific community abuzz



(Credit: Columbia's Zuckerman Institute)

Date: July 15, 2026

NEW YORK, NY — What scientific findings proved so compelling that more than 11,000 [preliminary](#) copies of them have been downloaded before they finally appeared in today's [Nature](#)?

The new research focuses on a mystery as old as neuroscience. Is each neuron in the brain a specialist devoted to a limited task, like a hammer or a saw, or do they tend to be generalists, jacks-of-all-trades like Swiss Army Knives?

By combing through a trove of recordings from an [international collaboration](#) that analyzed the brains of mice, researchers at Columbia's Zuckerman Institute reveal that specialist neurons certainly do exist, but the majority appear to be generalists.

"We have to move away from this image of the brain as a machine made of gears, with every gear having an exact purpose that we can attach a label to," said [Stefano Fusi](#), PhD, a principal investigator at Columbia's Zuckerman Institute, a member of the Kavli Institute for Brain Science and the paper's co-senior author. "The brain doesn't work like that. Instead, most neurons can display a huge diversity of responses, and this can help the brain solve a huge number of different tasks."

These new findings shed light on how the brain may ultimately prove capable of performing complex tasks. In doing so, they may help reveal what happens when something goes wrong in the brain, and how those processes might be steered to go right again.

Whether neurons are specialists or generalists "is an old, important question, and one which researchers have really strong opinions on," said [Lorenzo Posani](#), PhD, the study's co-lead author and a principal investigator at the [Paris Brain Institute](#) and France's [CNRS](#), who conducted this work while at Columbia's Zuckerman Institute. Previous research found the brain is organized into modules devoted to vision and smell and other processes; so perhaps such specialization might extend all the way down to the level of neurons. On the other hand, the brain is an incredibly powerful general-purpose computer that can respond in an extraordinary number of ways to a huge variety of situations, so maybe its neurons are similarly generalist in nature.

The problem with answering this question was that scientists often each tackled it with different approaches — for instance, they looked at different types of animals or brain regions or had the animals perform different tasks, Dr. Posani said. This often led to conflicting results — in some studies, some neurons were clearly specialized, while others appeared not to be.

To help resolve the debate, in the new study, the researchers developed a strategy where they looked only at mice, across many brain areas at once as the rodents all performed the same type of activity. This involved analyzing datasets much larger than typically studied, recordings of lots of neurons from [the International Brain Laboratory consortium](#) of activity in 43 regions across the mouse cortex on the level of single neurons.

In primary sensory areas, such as the brain region devoted to vision, neurons behaved in specialized ways. However, elsewhere, neurons generated far more diverse

responses. In other words, when it comes to the question of whether neurons are typically specialists or generalists, these new findings suggest the latter holds true.

"We're not saying that there are no specialized neurons," said Dr. Fusi, also a professor of neuroscience at Columbia's Vagelos College of Physicians and Surgeons and a member of Columbia's Center for Theoretical Neuroscience. "We're saying they are the exceptions. They're not the rule."

The scientists did find that based on a neuron's pattern of responses to a given task, they could pinpoint with surprising accuracy which specific module in the brain it belonged to. However, these neurons still generally display generalist behavior.

"For example, compare this to maps of voter opinions," Dr. Posani said. "There are clear clusters where people generally vote the same way. But when you zoom in, you see mixes of opinions."

In addition, not only are most neurons generalists, but they rarely duplicate the behavior of one another. "Each is versatile in its own way," says study co-lead author Shuqi Wang, a doctoral student at École Polytechnique Fédérale de Lausanne in Switzerland. This helps enable the brain's flexibility and computational power, she explained.

All in all, the researchers suggest the multi-purpose nature of most neurons lets each of them encode information about multiple variables, such as whether a shape is red or black, or a circle or square. In turn, neurons collectively encode "high-dimensional" representations, which combine several different variables at the same time, such as, say, a red circle or black square. Such high-dimensional representations let populations of neurons behave flexibly in terms of what input they receive and output they generate. "You can reuse these high-dimensional representations for lots of different tasks," Dr. Fusi said.

A key implication of these findings is that while each neuron generally encodes multiple variables, it is difficult to decode what any of these variables are from an individual neuron. It is only upon examining populations of neurons, like the brain does, that variables can be decoded. This is a major shift in thinking for the neuroscience community, "which for decades focused on one neuron at a time, discarding all neurons whose responses could not be understood," Dr. Fusi said.

The scientists are now working with [Ueli Rutishauser](#)'s group at Caltech to investigate whether similar results are seen in humans, Dr. Fusi said. They also would like to see if neurons behaved more as generalists or specialists depending on what tasks a brain is asked to perform, he added. "There is still a lot to discover," he said.

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The [paper](#), “Rarely categorical and highly separable: how neural representations change along the cortical hierarchy,” was published in *Nature* on July 15, 2026.

The full list of authors includes Lorenzo Posani, Shuqi Wang, Samuel P. Muscinelli, Liam Paninski and Stefano Fusi.

This work was funded by grants from the National Institutes of Health (RF1AG080818, U19NS123716), the Simons Foundation, the Kavli Foundation, the Gatsby Foundation (GAT3708), and the Swartz Foundation. This work is also supported by the funds provided by the National Science Foundation and by the DoD Office of the Under Secretary of Defense (R&E) under Cooperative Agreement PHY-2229929 (the NSF AI Institute for Artificial and Natural Intelligence). Dr. Posani was also supported by the NIH 1K99MH135166-01 grant.

The authors report no conflicts of interest.