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# Attention, Please: Earl Miller Wants to Make Us All Smarter

MIT neuroscientist Earl Miller has changed the way we think about working memory — the brain's scratchpad.

By Adam Piore | Thursday, September 01, 2016

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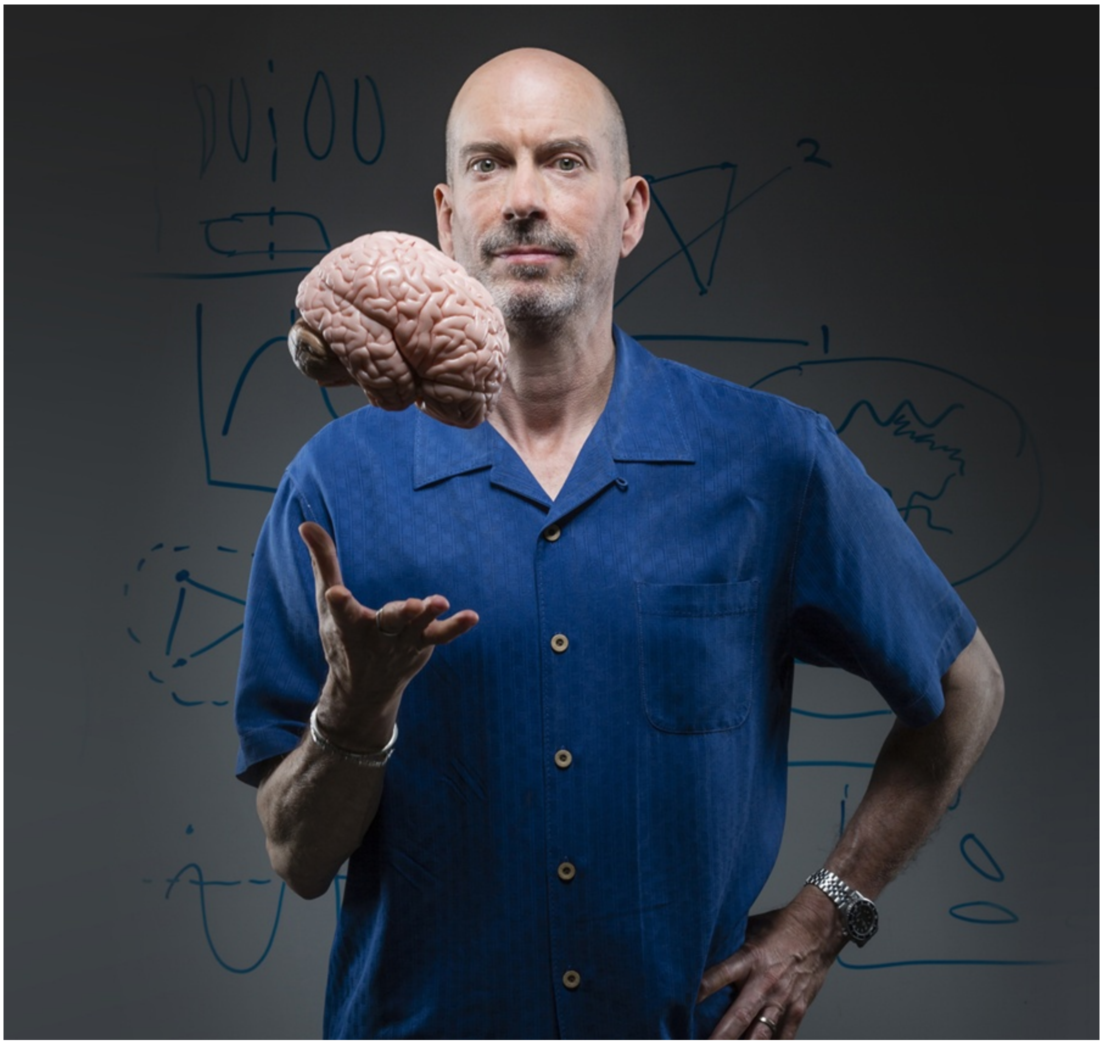


EARL MILLER sees the prefrontal cortex — home to working memory — as a switch operator working the brain's railroad tracks.

Jason Grow

In the rehearsal space of the Boston band What She Said, Earl Miller lays into his bass guitar, plucking out a funky groove. He sticks out his tongue Mick Jagger style, as the band's drummer hammers away behind him, clowning it up for photos splashed onto social media. In a black band tee, faded cargo pants and signature newsboy cap, Miller looks like a seasoned musician you'd see in any corner dive bar.

But at his nearby office at MIT, Miller is nothing if not professorial. How could that rocker in the cap be the same bookish academic now gazing solemnly at me across his paper-strewn desk at the Picower Institute for Learning and Memory?

The jarring contrast between the two Earl Millers is a fitting way to begin a discussion of the pioneering neuroscientist's work.

After all, some of Miller's biggest contributions to the field over the past 20 years have explored exactly how contrasts like these are possible; how it is, in other words, that human beings — or any other animal with a brain — are able to seamlessly adapt behavior to changing rules and environments. How is it that distinct populations of brain cells, or neurons, are able to work together to quickly summon an appropriate response? How do we know when it's fitting to play a Patti Smith bass line, and when it's time to explain the complex workings of brain waves?

Earl Miller plays bass at the Tavern at the End of the World in Boston's Charleston neighborhood.

Jason Grow

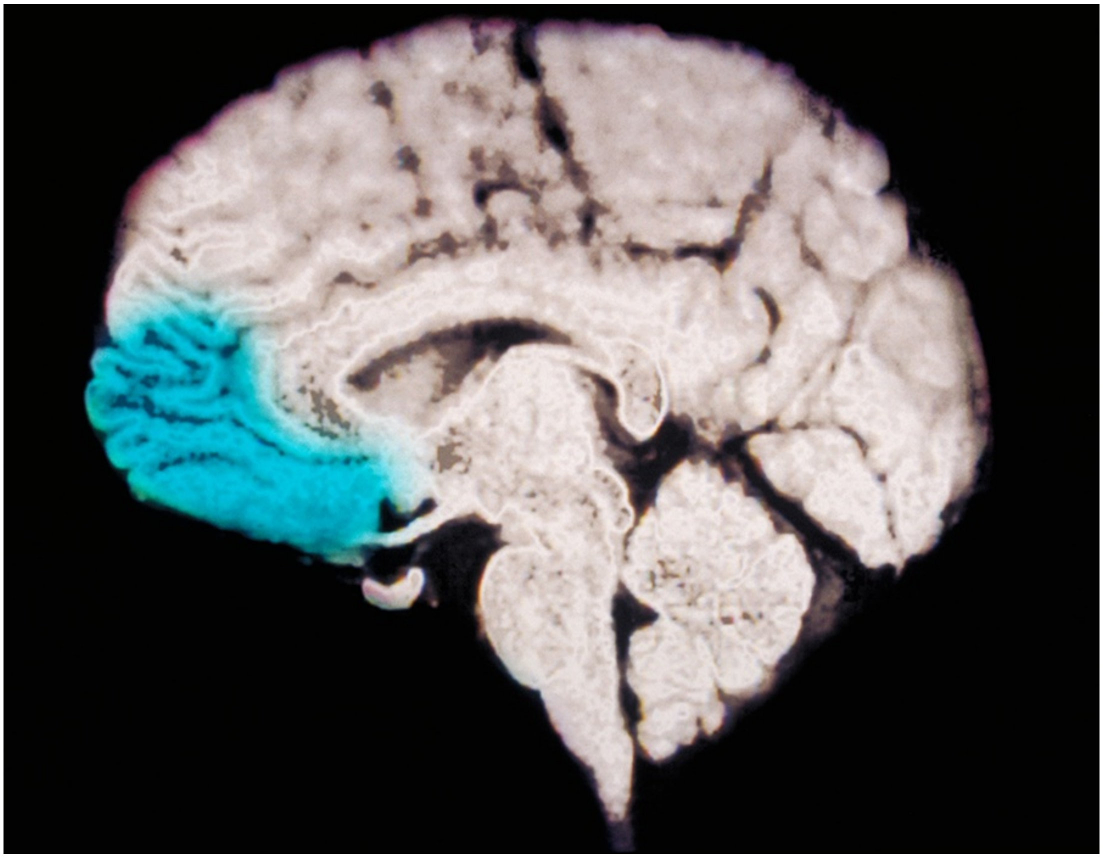
This mental flexibility is so fundamental that it's easy to take it for granted. But there are few functions the brain must perform that are more complex or crucial to survival than recognizing when something has changed and then calling up all the disparate information needed to adapt appropriately.

"Think about what we're doing here," Miller says. "Right now. We're sitting on chairs. We're taking turns talking. This is based on rules. We've learned how to behave in this context we're in right now."

To pull off tasks like these, the brain uses something called working memory. Cognitive psychologists coined the term in 1960 as they tried to explain the fundamental structure of the human thought process.

You can think of working memory as the brain's conscious mental scratchpad — the chalkboard for attention and decision-making. Try to hold that last sentence in your mind, or memorize a phone number you're about to dial, and you'll have engaged this critical brain system.

Miller has spent the past two decades trying to understand the mechanisms behind working memory, and he believes the key lies in the brain's prefrontal cortex. Insights into this thin layer of neurons at the front of the brain could answer questions that have flummoxed scientists for generations. It might have practical use, too.



The prefrontal cortex, highlighted here in an MRI scan, plays a crucial role in working memory — the brain's chalkboard for attention and decision-making.

Scott Camazine and Sue Trainor/Science Source

Experts have long known that we have a virtually unlimited capacity to store new long-term memories. Yet there's a limit on how much information we can cram into our working memory.

In studying the prefrontal cortex's functions, Miller and others are coming closer to finally explaining this contradiction. And by solving this riddle, we may find ways to get beyond those limits.

Someday, Miller believes, he'll be able to make us all smarter.

**Building the Picture**

Much of what we know about how neurons allow animals to make sense of their surroundings began with experiments performed on the visual cortex of animals by David Hubel and Torsten Wiesel. As postdoctoral students at Baltimore's Johns Hopkins University in the 1960s, they set out to solve a long-standing mystery: What happens in the brain when we see objects and shapes?

Every one of us has about 100 billion neurons, separated by gaps called synapses. Neurons talk to each other by passing signals across these spaces. When one neuron's signal is strong enough, it causes the neuron on the other side of the synapse to fire an electrical spike. When that second neuron fires, it passes messages to all the other neurons it's connected to, which can cause those neurons to fire. This sequential firing of neurons allows us to think, to move — and to see.

Hubel and Wiesel inserted tiny, pin-shaped microelectrodes directly into a cat's visual cortex to measure the activity there. By projecting angled lines onto the surface of the animal's retina, they demonstrated that each neuron in this thin sheet at the back of the head has a distinct function.

Some fired with the greatest intensity in response to lines at specific angles, while others fired at angled lines moving in a specific direction. It is the consecutive firing of these individual, specialized neurons, each responsible for a specific detail in a picture or pattern, they argued, that helps us build complex images in our mind's eye.

*It was as if the brain was on autopilot, primed to notice repetition without any active effort to do so, even when that repetition had no meaning.*

Their work was so impressive within the field that it earned them the Nobel Prize in Physiology or Medicine in 1981.

As it happened, Miller entered college at Kent State University the same year — though back then, Miller dreamed of becoming a doctor.

That quickly changed when he started working in a neuroscience lab.

"The moment I first dropped an electrode into a slice of brain and heard all these neurons firing away like a thunderstorm, I was hooked," Miller recalls.

As a Princeton University graduate student, Miller studied the inferior temporal cortex, a patch of neurons slightly forward of the visual cortex. Scientists had demonstrated this was the region that knits together a unified image from all the complex individual components Hubel and Wiesel identified. Then it starts the "higher level" processing of the outside world.

By the time Miller earned his Ph.D. in 1990, he was asking the questions that would later define his career: What happens in the inferior temporal cortex after a unified picture emerges? How do our brains tell us what it means?

Miller tried to answer those questions while working in the lab of National Institute of Mental Health neuroscientist Bob Desimone. Miller was looking for neurons that fired only when an animal spotted an item it was storing in short-term memory. Miller and Desimone trained animals to hold a single image in mind — such as an apple — and release a lever when that picture reappeared on a screen.

If the animal remembered the first picture it saw and released the lever, a drop of delicious juice would roll down a tube and into its cage.

The pair noticed that certain parts of the animal brain were inherently sensitive to repetition — regardless of whether it translated into a valued juice reward. Some neurons fired when animals saw a second banana or second image of trees. It was as if the brain was on automatic pilot, primed to notice repetition without any active effort to do so, even when that repetition had no meaning.

But the pair also discovered a second type of firing pattern. When the animal spotted a picture it was *actively* holding in his memory — hoping for a juice reward — not only did different neurons fire, those neurons fired far more intensely.

"Something was switching the volume to make these neurons fire, more or less, depending on the nature of the memory," Miller says. "That got me wondering. Who's turning up or down the volume?"

**Turn It Up**

Scientists have suspected that the prefrontal cortex plays a key role in high-level cognition since the case of Phineas Gage. On Sept. 13, 1848, Gage, who worked in railroad construction, was setting an explosive charge with a tamping iron when the gunpowder detonated, rocketing a metal rod up through the roof of his mouth, into his left frontal lobe and through the top of his skull. The rod landed 75 feet away, coated in pieces of Gage's brain.

Miraculously, Gage survived and could speak, walk and function. But, it was written later, he could no longer stick to plans and lost much of his social grace and restraint. From studying Gage and others like him, neuroscientists surmised that the frontal lobes performed the brain's "executive functions." They run the business of thinking and processing and directing the spotlight of attention. And yet, nearly 150 years after Gage's famous injury, scientists were still trying to understand how the frontal lobe works.

So, when Miller started his own lab at MIT in 1995, he decided to switch his focus to the prefrontal cortex. By then, some of his peers had already shown that clusters of neurons in lab animals would fire repeatedly in the prefrontal cortex during memory exercises. Their results suggested this region houses our working memory.

To Miller, however, this didn't explain how the executive areas of the brain could "turn up the volume" on memories associated with free juice.

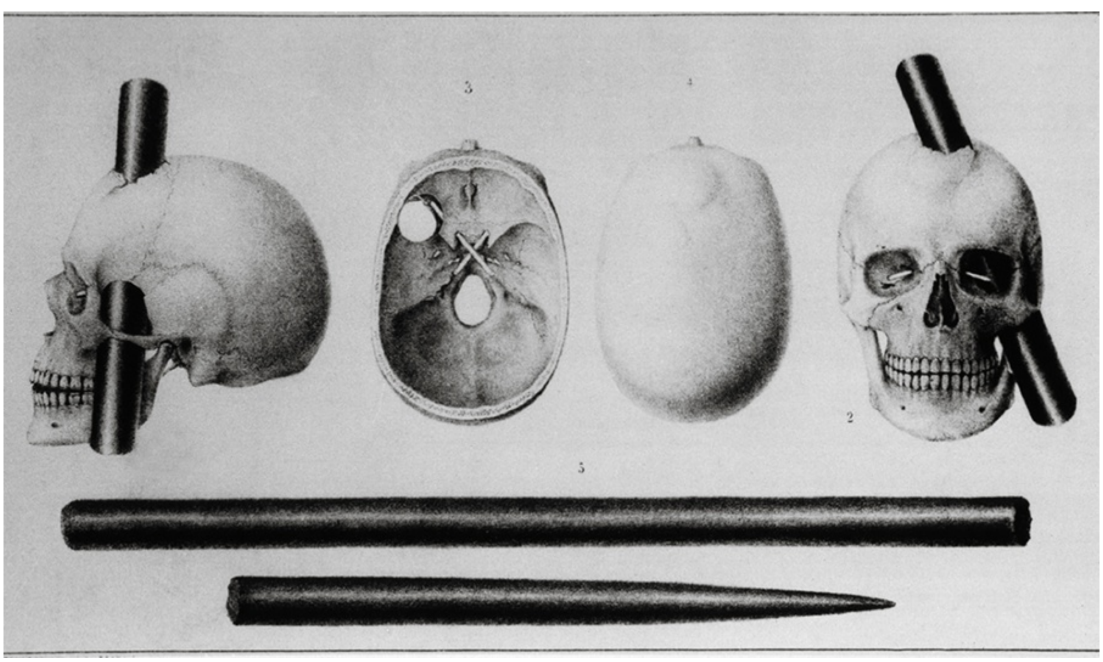
How does the animal know how to do the task? How does the animal know the rules?

"I thought that was the most important thing," Miller says. "I didn't understand why no one was studying it. Context-dependent behavior is what high-level cognition is all about."

In his new lab, Miller designed an experiment that complicated the choice his animals faced. Instead of just showing an animal a picture and training it to respond every time it reappeared, Miller varied the number of possible responses by adding a second cue. In between the first picture and those that followed, he provided a prompt, such as a low tone or a high tone. Then he showed the same picture again, this time next to a second picture. The high tone signified the animal should try to remember and choose that same first picture whenever it reappeared. But the low tone indicated the animal was to remember and choose the second picture, and ignore the first. Correct guesses resulted in the delivery of a tasty food pellet.

Phineas Gage (1823-1860) revolutionized neuroscience after an iron rod pierced the railroad worker's frontal lobe. He recovered physically, but his personality was never the same.

From the collection of Jack and Beverly Wilgus



Various views of the famous wound in the skull of Phineas Gage, (1823-1860), showing the wound and the rod itself. He died of injury related convulsions in 1860. Gage's case helped scientists learn about the functions of different parts of the brain.

Everett Collection/Alamy Stock Photo

Miller predicted he'd detect activity in multiple neurons in the prefrontal cortex every time he changed the rule. These neurons, he believed, somehow turned up or down the "volume" of the neurons he'd recorded in other areas of the brain. Not only was Miller right, but the rule change consistently caused twice as many neurons in the prefrontal cortex to fire than in the more simplistic experiments where the task required the animal to just hold a picture in mind.

"That told us something," he says. Perhaps the prefrontal cortex's primary job wasn't short-term memory at all, but to learn the rules of the game.

In 2001, Miller published a research review that fundamentally shifted the way many viewed the prefrontal cortex. Miller compared the prefrontal cortex to a railroad switch operator, and the rest of the brain to railroad tracks. The switch operator activates some parts of the track and takes others offline. This model would explain how attention works. It explains, for instance, how an animal can focus on a picture while suppressing a noise. And it explained why Phineas Gage had trouble blocking out distractions and focusing on the task at hand.

The theory made intuitive sense. But to some steeped in the specialized-neuron theories of Hubel and Wiesel, Miller's theory seemed preposterous.

"That's impossible!" Miller recalls one prominent neuroscientist declaring after Miller delivered an invited lecture. "We all know that neurons do one thing. Your problem is you can't figure out what these neurons are doing," the researcher told him.

But Miller has continued to accumulate experimental evidence — as have many other labs — gradually winning scientists over to his idea.

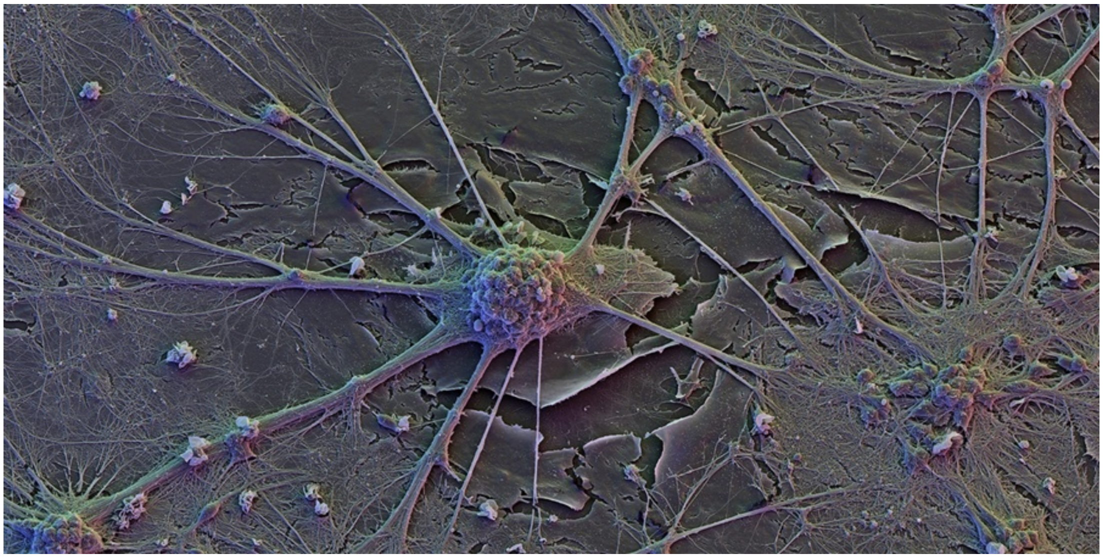
"Neurons are multitaskers," Miller says. "We've shown this over and over again for 20 years."

The important neurons, according to Miller's collaborator Stefano Fusi, a theoretical neuroscientist at Columbia University, are the flexible ones. Scientists expect they're the majority in the prefrontal cortex, he explains. Otherwise an animal encountering a complex task would run out of neurons to make sense of it.

**Wave Change**

These days, Miller is taking on another piece of dogma — that neurons primarily communicate by electrical spikes. In recent papers, Miller argues that there's still a lot to learn from the intermittent electrical currents called oscillations, or brain waves.

When we hold an item in working memory, these oscillations move through brain circuits in waves that rise and fall scores of times. These oscillations, he argues, are how the prefrontal cortex — that mental "switch operator" — stores several items on the cusp of our awareness in working memory, so we can pull them into our conscious minds as needed.



Brain cells, or neurons, connect via complex networks in this scanning electron micrograph.

David Scharf/Science Source

The oscillations aren't enough to make the neurons spike. But the brain waves bind together all the neurons in a circuit with every crest, pushing the neurons so close to their firing point that they're primed to respond to just the slightest extra stimulus.

This might help answer a question that has long intrigued scientists: How can the human brain store a virtually unlimited number of long-term memories, yet remain severely limited in the information we can hold in our conscious minds at once?

It's a limit most notably characterized by Princeton cognitive psychologist George Miller (no relation) in a 1956 paper, "The Magical Number Seven, Plus or Minus Two." George Miller, who helped coin the term *working memory*, argued that seven, plus or minus two, is the maximum number of objects most of us can hold in our short-term memory at once. Researchers have since demonstrated the number can vary far more widely and may even be smaller than seven. But no one doubts there are limits.

If working memory is encoded in oscillations, Earl Miller says it would explain these limits, because a single wave can only rise and fall a certain number of times a second.

"That means you have to fit in everything you want to juggle in your current conscious mind," he says. "That's a natural limitation in bandwidth."

Brad Postle, a University of Wisconsin-Madison neuroscientist, says the idea that something other than the spiking of neurons is important has been "kicking around for a while." Postle himself suggested brain waves may play a role in focusing attention. Still, he believes it's significant that Miller is now arguing the point.

"Having it come out of Earl Miller's mouth almost by definition will bring attention to it," says Postle, who authored a widely used neuroscience textbook that includes many of Miller's earlier experiments. "Earl is kind of a rock star. When he says something, a lot more people notice it."

Now, Miller is focusing on new technologies that might actually enhance working memory capacity.

“If we find a way to stretch the cycle, increase amplitude, make it taller or maybe slow the frequency a little bit, maybe we could increase the capacity of working memory,” he says.

So he’s planning on experimenting with a technique that uses electrodes placed on top of the scalp to deliver faint pulses of electricity and record the impact. If these pulses are timed correctly, they could change the shape of the brain waves.

It would be a significant technological feat, but Miller thinks it’ll work. If he’s correct, it could have a profound impact on human performance, literally expanding our brainpower.

*[This article originally appeared in print as "You Attention, Please."]*

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