

PRESS RELEASE

A unified model of memory and perception: how Hebbian learning explains our recall of past events

Physicists and neuroscientists at SISSA discover that two opposite perceptual biases arise from the same brain process. The new research has been published in Neuron.



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A collaboration between SISSA's Physics and Neuroscience groups has taken a step forward in understanding how memories are stored and retrieved in the brain. The study, recently published in *Neuron*, shows that distinct perceptual biases – long thought to arise from separate brain systems – can, in fact, be explained by a single, biologically grounded mechanism.

The research, led by professors Sebastian Goldt and Mathew E. Diamond, and first-authored by Francesca Schönsberg (now a junior research chair at the École Normale Supérieure), brings together theoretical physics, computational modeling, and behavioral neuroscience to bridge decades of fragmented research on perceptual memory. Yukti Chopra and Davide Giana carried out laboratory experiments to provide the empirical data that the model was tested against.



Cracking the code of perceptual memory

Perceptual memory is the ability to extract, store, and use information from the external world – a process that enables us to understand our surroundings by embedding the continuous stream of sensory information into knowledge built on past experience. Scientists have long studied its component processes through different experimental paradigms. For instance, working memory tasks probe how we compare two stimuli presented in sequence, while reference memory tasks involve judging a current stimulus against a fixed internal standard. Despite their common goal of understanding memory, these traditions evolved separately, producing distinct models for each task. “We wanted to see whether these different forms of memory could actually reflect the same underlying neural process,” says Mathew Diamond. “In other words, could a single cortical network account for what appear to be very different behavioral phenomena?”

When perception bends reality

The SISSA team found their unifying thread in perceptual biases – systematic distortions that reveal how the brain’s internal representations diverge from the physical world. If perception were perfectly linear and accurate, it would simply mirror the external environment, leaving little trace of the internal computations that shape our experience. But because perception is subtly biased, these distortions offer a glimpse into how the brain transforms raw input into meaningful representations.

Across sensory modalities, perception of the current stimulus shows two paradoxically opposite tendencies. In some contexts, it is contracted toward the memory of previous stimuli – a “pull” known as contraction bias. In others, perception is repelled away from the recent past – a “push” called repulsion bias. For decades, scientists have debated why the brain should alternate between these seemingly contradictory effects.

A single mechanism behind opposite biases

To tackle this puzzle, the researchers combined computational modeling with behavioral data from both humans and rodents. Their model – a recurrent neural network governed by the biologically plausible rule of Hebbian plasticity (“cells that fire together wire together”) – showed that both contraction and repulsion biases can emerge naturally within the same circuit.

“Instead of assuming that the brain switches between distinct systems, we showed that one network, learning continuously through simple local rules, can produce both effects,” explains Sebastian Goldt. “The key lies in how the network’s synaptic connections adapt over time, encoding traces of recent activity that subtly reshape the representation of new sensory inputs.”

The model was tested against four experimental datasets across three paradigms: working memory, reference memory, and a newly designed one-back task. Without fine-tuning or task-specific parameters, the network reproduced the behavioral data remarkably well. This convergence between model and experiment suggests that the same adaptive mechanism may underlie diverse expressions of perceptual memory.

Reading out the same network in the same way

Perhaps the most surprising finding was that what distinguishes different memory tasks is not the underlying memory storage mechanism but, simply, the way the choice is performed. While network's activity is read out always in the same way, the same recurrent circuit can support very different cognitive demands depending on which aspect of its activity is accessed by downstream processes. In the working-memory paradigm, the network's evolving activity encodes a transient trace of the most recent stimulus, what the network is encoding at the time the second stimulus is delivered, determines whether this is considered stronger or weaker than the previous one. In the reference-memory task, the choice depends instead on how the internal representation varies at the stimulus offset. The same underlying neural mechanism, which, from a theoretical point of view, gives rise to a sliding attractor in the network's dynamics, reproduces both results as well as those obtained in the one-back task – designed by the SISSA team specifically to test the model – each new stimulus becomes the next trial's reference, revealing the network's flexibility in switching between memory roles.

Bridging disciplines to understand the brain

By demonstrating that a single neural circuit governed by local learning rules can account for both contraction and repulsion biases, this work provides a unifying framework for perceptual memory. It challenges the long-standing notion that distinct cognitive effects must arise from separate brain systems and instead suggests that the apparent diversity of perceptual behavior reflects different manifestations of the same adaptive neural dynamics.

"This study exemplifies what makes SISSA unique," says Diamond. "We can combine theoretical physics and computational neuroscience in the same building, with daily interaction between people who approach the same questions from very different angles."

The findings highlight how interdisciplinary collaboration – uniting modeling and experimental neuroscience – can reveal the general principles by which the brain learns from experience, forms stable memories, and adapts flexibly to new situations.

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