Optimizing memory capacity in the hippocampus by memory storage in the dentate gyrus and adult neurogenesis

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The hippocampus is required for the formation of episodic memories, but the neural mechanisms underlying memory storage in the hippocampus remain unclear. Currently, the dominant hypothesis is that memory patterns are stored as attractor states in the recurrent CA3 network¹. To minimize interference between similar memories, input patterns to CA3 are thought to be separated by the dentate gyrus (DG)¹. Additionally, several groups have suggested that adult neurogenesis in the DG might improve pattern separation².

Here we show that this scheme is relatively inefficient, and that memory storage in the DG coupled with adult neurogenesis can yield much higher memory capacity than storage in CA3. We therefore propose that episodic memories are more likely to be stored in the DG. Our model assumes that episodic memories are represented as sparse activity patterns in the hippocampus. We estimated the maximum number of memory patterns that share a single neuron to measure the potential of interference among stored memories. Based on data from the rat, our analysis revealed that if memories were stored in CA3, the interference would be much larger than if memories were stored in the DG. Moreover, if neurogenesis in DG is included in the model, the interference is further reduced by roughly an order or magnitude. Using the Willshaw model³, we tested whether the interference among memories is indeed detrimental for cued memory retrieval. We calculated the maximum rate at which CA3 or DG can store memories while maintaining a high retrieval quality. If associations were stored in CA3, the maximum storage rate would be much lower than if associations were stored in the static DG. Furthermore, with the addition of neurogenesis, the DG can store associations at a rate roughly an order of magnitude higher. This increased memory capacity is due to neuronal turnover and comes at the cost of forgetting old memories more quickly, as described previously⁴. Thus, memory storage in the DG would be temporary, consistent with experimental evidence for a time-limited role of the hippocampus in learning and memory.

We further studied the case in which young DG neurons are preferentially recruited to encode episodic memories⁵. While such a mechanism reduces the overlap among memory patterns further, the improvement is small (~25%) – much less significant than the order-of-magnitude improvement introduced by neuronal turnover. Finally, our model allows us to explore when neurogenesis does not improve memory capacity. As an example, an animal with a rat-sized hippocampus, and a much shorter life span or a much lower rate of episodic memory formation would not benefit from neurogenesis. These results suggest that the DG may be specialized for the rapid storage of new associations, leaving CA3 available to process perhaps temporal aspects of episodic memory.

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References