From episodic to semantic memory: A computational model

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Abstract

Systems memory consolidation describes the process of transferring and transforming initially hippocampus-dependent declarative memories into stable representations in the neocortex. Experimental evidence indicates that neural replay during sleep is linked to this process. While multiple phenomenological theories of systems consolidation have been proposed, a mechanistic theory on the level of neurons and synapses is missing. Here, we study how episodic memories change over time in a recently suggested computational model for the neuronal basis of systems memory consolidation. We implement the proposed mechanism in artificial neural networks and show that memory transfer in the model facilitates the forgetting of episodic detail in memories and enhances the extraction of semantic generalizations. Moreover, we show that neural replay enhances the speed of consolidation and can in certain situations be necessary for the extraction of semantic memories. The latter appears to be the case specifically for the extraction of semantic content from a rapidly learning hippocampal system.

Keywords: systems memory consolidation; generalization; episodic memory; semantic memory; artificial neural networks

Introduction

Systems memory consolidation transfers declarative memories that initially depend on the hippocampal formation into long-term memory traces in neocortical networks (Dudai, Karni, & Born, 2015). Over the last decades, multiple phenomenological theories of systems memory consolidation have been proposed. While it appears clear that episodic memories undergo a semantization over time, no consensus on why and how this arises has been found as of now, partially because the mechanistic basis for systems consolidation on the level of neurons and synapses is largely unresolved.

Here, we study how episodic memories change over time in a recently suggested computational model for the neuronal basis of systems memory consolidation (Remme, Bergmann, Schreiber, Sprekeler, & Kempter, 2019). The model suggests that systems memory consolidation could arise from Hebbian synaptic plasticity in networks with parallel synaptic pathways

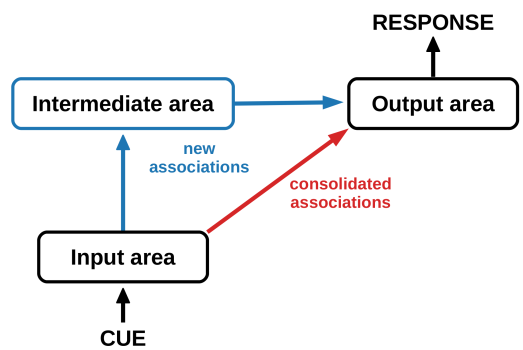

Figure 1: The shortcut motif. Memories – conceptualized as cue-response associations – are initially stored in a multisynaptic pathway (blue) and later consolidated into a parallel shortcut pathway (red).

(see Fig. 1). In the model, memories are initially stored as cue-response associations in a multisynaptic pathway. During consolidation, these associations are reactivated and allow the multisynaptic pathway to act as a teacher for a shortcut pathway. This transfer into shortcut pathways which are widely encountered throughout the brain can be hierarchically iterated to achieve a transfer of memories from the hippocampus to neocortex.

Methods

In the present work, we implement the proposed mechanism in artificial neural networks to study how the characteristics of episodic memories change over time. Given that episodic memories contain details of individual autobiographic events, we conceptualize the formation of an episodic memory in neural networks as overfitting to a single event thereby learning all of its details. Semantic memory on the other hand is abstract and factual knowledge that allows to generalize across experiences and is hence largely independent of any specific event. To model memory consolidation, we simulate the acquisition of new episodic memories during the day by storing their associations in the multisynaptic pathway of the shortcut mechanism. Consolidation during the night is then modelled

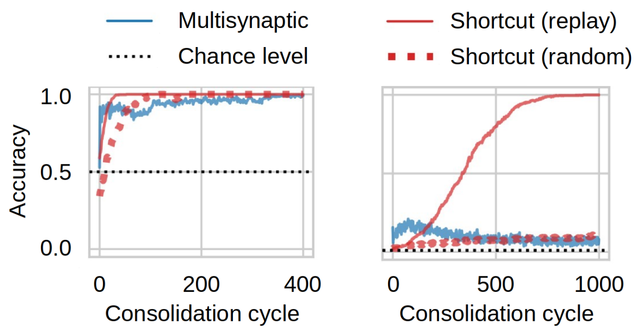

Figure 2: Learning of semantic generalizations from specific experiences. Episodic memories are modelled as random activation patterns with shared statistical regularities. If the environment is simple (left), the regularities can be extracted in both, the multisynaptic (blue line) and shortcut pathway (red lines), and neural replay (dashed line) enhances consolidation speed into the shortcut pathway compared to random reactivations (solid line). If the environment is too complex (right), the multisynaptic pathway cannot learn to generalize and neural replay is necessary for consolidation into the shortcut pathway.

by reactivating these associations and thereby learning them in the parallel shortcut pathway. Memories are therefore transferred from a multi-layer neural network into a two-layer neural network, and hence from a higher capacity learning system to a lower capacity learning system.

Results

We show that in such a model, the transfer of memory associations into the shortcut pathway facilitates the forgetting of random episodic detail in memories and enhances the extraction of semantic generalizations. Moreover, we show that i) the amount of episodic detail that is transferred into the shortcut pathway depends on the speed of learning in the shortcut pathway and ii) that neural replay enhances the speed of consolidation (see Fig. 2, left) and can in certain situations be necessary for the extraction of semantic memories (see Fig. 2, right). The latter appears to be the case specifically for the extraction of semantic content from a rapidly learning hippocampal system. Finally, we hypothesize that the previously suggested hierarchical iteration of the mechanism may provide a mechanistic model for the spatial and temporal gradients of episodic and semantic memories observed in lesion studies (Squire, Genzel, Wixted, & Morris, 2015), which suggest that episodic memory content decreases and semantic memory content increases with distance from the hippocampus.

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References

Dudai, Y., Karni, A., & Born, J. (2015). The Consolidation and Transformation of Memory. *Neuron*, *88*(1), 20–32.

Remme, M., Bergmann, U., Schreiber, S., Sprekeler, H., & Kempter, R. (2019). A circuit mechanism for systems memory consolidation. *Unpublished manuscript*.

Squire, L. R., Genzel, L., Wixted, J. T., & Morris, R. G. (2015). Memory consolidation. *Cold Spring Harbor perspectives in biology*, *7*(8), a021766.