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HOW THE HUMAN BRAIN LEARNS, MEMORIES AND SHOWS SIMILAR NEURAL PATTERNS TO ITS SOCIAL NETWORK

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At every moment we are confronted with a continuous stream of information and experiences giving us the opportunity to learn. However, how exactly this learning is encoded in the brain and how it becomes part of the existing memory systems is not entirely clear.

Fundamentally, learning is possible through neuroplasticity; i.e., the brain's ability to modify its structures in response to new information and to adapt to new experiences. Neuroplasticity is present differentially throughout the lifespan: it is maximal in early development, especially in sensitive periods, and it is reduced in the elderly population. Specifically, with age there is a progressive degeneration of neuromodulatory systems, like the noradrenergic and the cholinergic circuits, which leads to a reduction in inhibition regulation that renders mental representations unstable and vulnerable to maladaptive plasticity and distortions. This suggests that learning becomes more difficult as age progresses (Voss et al., 2017).

Also important is the role of emotions in learning and memory, since they impact both the allocation of attentional resources and the motivation behind learning. Specifically, emotional stimuli have a pop-out effect, thus facilitating data extraction and making their encoding in long-term memory (LTM) more likely. This memory modulation is mainly possible thanks to the amygdala, which affects encoding, consolidation and retrieval by releasing stress-activated hormones while interacting with the hippocampus, the prefrontal cortex (PFC), and the visual cortex. Thus, higher cognitive functions such as learning and memory are strongly guided by emotions (Tyng et al., 2017).

To explain how learning and memory are encoded in the brain, Richard Semon proposed the existence of memory traces, also called engrams. Engrams are defined as enduring physical or chemical changes happening in the brain after learning. Engram cells are distributed across the whole brain and form a functional network supporting the encoding and retrieval of memories (Tonegawa et al., 2018). Different neuron clusters within the same engram network encode and contribute to different aspect of the memory. This is supported by the observation of the same neurons being active both during encoding and retrieval in several brain regions, such as the hippocampus, amygdala, and hypothalamus, and whose inhibition impairs memory recall (Roy et al., 2022). Importantly, these engram ensembles can be either active or silent, this being an indicator of the memory consolidation stage in which the memory is.

The presence of silent engram cells has been shown in the mPFC, where engrams are formed during encoding through synapse neural tagging (Lesburguères et al., 2011), but are not responsive to natural cueing until later on (Kitamura et al., 2017). In fact, these engrams mature with time, possibly thanks to hippocampal memory replay during sleep that propagates to the neocortex, thus strengthening cortical traces. In fact, during sleep, the coordination of hippocampal sharp-wave ripples, thalamic spindles, and slow cortical oscillations contributes to memory consolidation.

Specifically, during slow wave sleep (SWS) weak synapses are pruned while the ones that are to be strengthened are tagged and later integrated into the existing LTM during REM sleep (Klinzing et al., 2019).

At the same time that cortical engram ensembles mature, hippocampal ones transition to a silent state, indicating that their role in memory retrieval is limited to recent memories (Tonegawa et al., 2018). It has been suggested that this de-maturation is possible thanks to neurogenesis processes. Specifically, the generation of new neurons in the dentate gyrus, and their integration into existing hippocampal circuits, perturbs and weakens the synaptic connections in the existing engram ensembles, thus facilitating the overwrite of old memories by new ones and contributing to memory clearance (Barry & Maguire, 2019).

As neurogenesis aids in weakening hippocampal traces, it seems to also contribute to the occurrence of sharp-wave ripples during sleep, thus facilitating cortical engrams maturation (Terranova et al., 2019). Importantly, it seems that the silent state of hippocampal engrams can be reversed later on, even if this reactivation is possible only thorough optogenetic stimulation and it often leads to incomplete retrieval (Guskjolen et al., 2018).

This transition from silent to active engrams in the cortex and vice-versa in the hippocampus is consistent with the theory of system consolidation theory (SCT). This theory posits that while the hippocampus is essential for the initial coding of an experience, its role is time-dependant. In fact, information is progressively transferred to the PFC and integrated within existing LTM systems. At this point, remote memories become hippocampal independent, with the hippocampus containing only a memory index, whose content is distributed throughout the cortex. This theory has received extensive empirical support. For example, a study consisting measuring brain activity during a recognition memory task for material learned 1 month, 1 week, 1 day, and 1 hour prior, showed that while hippocampal activity did not change with time, its functional connectivity with the cortex significantly decreased while the connectivity within the PFC significantly increased. This indicates that with time the hippocampus has less and less influence on remote memories, possibly because the memory is reorganized in the neocortex, ultimately becoming independent from the hippocampus (Tallman et al., 2022).

However, contradicting evidence in patients with temporal lobe damage, showing remote memory loss after hippocampal damage, led to the proposition of the multiple trace theory (MTT), which postulates that the hippocampus is always needed for the retrieval of episodic memories. According to this theory, with each memory reactivation further memory traces are formed in the hippocampus, while traces in the PFC transition to a schema-type state typical of semantic memory. Thus, in order to retrieve vivid and detail-rich memories, the PFC alone is insufficient without the contributions of the hippocampus. An extension of this, the transformation theory, proposes that these qualitatively different traces coexist at the same time, interacting constantly, and that one or the other is reactivated depending on the circumstances (Tonegawa et al., 2018).

So far learning and memory have been talked about in isolation; however, humans are social animals and it is not unconceivable that these cognitive processes are affected by other people and by one's own social network. Social influence on memory and learning is inevitable since humans continuously and reciprocally pass and share information, thus synchronizing their memories, knowledge, and beliefs in order to facilitate communication, collaboration, and collective action (Salminen, 2012). Interestingly, social network topology and characteristics have been demonstrated to shape the brain both at the functional and structural level (Momennejad, 2022). Firstly, its size is associated with higher grey matter density in brain regions related to social and affective processing, since the nourishment of more relationship requires more cognitive effort; while social network diversity is associated with white matter in the mentalization system and in the corpus callosum (Falk & Bassett, 2017).

At the functional level, social proximity has been found to be correlated with cognitive processes similarity, this resemblance progressively reducing with increased social distance (Parkinson et al., 2018). This indicates that close friends tend to process information, interpret the environment, and react to it in a similar way. This allows easier and more satisfactory interactions since the other's behavior is more predictable and more likely to reinforce one's own values and beliefs. This process' similarity is probably due to a combination of similar people being more likely to find each other and form a friendship, and social influence mechanisms in dyads, where members progressively become more cognitively similar.

Differences in brain activity have also been found according to social network features and members' characteristics, particularly in regions related to affective processing and mentalizing. For example, individuals who act as a bridge between sub-groups otherwise unconnected show more recruitment of regions related to mentalization and empathy. Interestingly, activity in these regions is also affected by the person's hierarchic position in the group.

Specifically, in a study, viewing high-status people led to a bigger recruitment of mentalization and valuation network compared to when low-centrality individuals were viewed. This difference in activation was particularly pronounced in higher-status people themselves (Weaverdyck & Parkinson, 2018).

Belonging to a group is crucial since it allows better defence and more resource availability; by consequence, the ability to navigate complex social structures became a matter of survival. The literature shows that these evolutionary pressures have shaped the brain in a way that automatically encodes other people's social status and tracks social ties and third-party relationships among group members in order to respond appropriately (Parkinson et al., 2017). However, since most of the research is correlational, it is unclear to what extent social network features shape brain dynamics or, vice-versa, how much social network is shaped by brain processes.

In conclusion, how learning and memory are encoded is still partly unclear. The literature shows that memories are represented in engram cells distributed throughout the cortex and that this network is constantly reorganized and updated with subsequent learnings. In this context, neurogenesis and neuroplasticity are essential mechanisms; as it is the interaction between the hippocampus and the PFC, especially during sleep, which allows memory consolidation. Importantly, these processes are socially influenced, both by direct and indirect relationships, and by the social network topology.

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