Memory Consolidation: Systems

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The Consolidation of a Memory

At the moment when we perceive an event, the journey of memory storage begins. In a sense, such an event may exist for many years before finally being remembered – where is it, what is it, and how does it manage to persist?

Whereas memory is revealed by an organism's behavior at the time of retrieval, neural substrates of memory storage assume some persistent form during the entire retention interval. The ability to remember an event is made possible by changes in neurons and in networks of neurons – neural plasticity. Yet, these changes are quite unlike when a liquid is poured into a mold and solidifies as plastic or when clay is shaped and fired to form pottery. A memory trace is not a static entity. It does not remain in a fixed state, like a file in a file drawer or on a computer. Rather, further neural changes can transpire during the time period between acquisition and retrieval as a memory is associated with other stored information and potentially becomes more stable.

What is the fate of the neural plasticity first set into motion when an event is experienced? An understanding of the concept of memory consolidation requires understanding the form of memory traces (engrams) both in neural and cognitive terms, as well as specifying how memory traces change over time.

Memory Distinctions

Memory storage and memory retrieval mechanisms are known to differ in fundamental ways according to the type of memory in question. Likewise, memory consolidation proceeds differently for different types of memory.

A long-standing distinction in research on human memory allows for separate mechanisms for short-term storage lasting seconds, perhaps minutes, and long-term storage lasting much longer. Donald Hebb's seminal proposal stated that reverberating neural circuits can keep an experience in mind for a short time, whereas structural changes in neuronal ensembles underlie storage that persists over longer periods. Mental representations of perceptual and conceptual information can be actively maintained through rehearsal. In this sense, short-term storage cannot be defined by a characteristic time span. Rehearsal can continue for an indefinite amount of time. The term immediate memory aptly draws attention to this aspect of memory and is akin to what William James termed primary memory. In contrast, secondary memory refers to information brought back to mind after earlier leaving one's awareness, rather than information kept in mind through rehearsal. The length of the retention interval, short term versus long term, is thus not a suitable way by itself to differentiate between types of memory. Immediate memory (also known as working memory) belongs in a class by itself due to its dependence on the rehearsal of information.

Aside from immediate memory, there are several distinct ways in which behavior comes under the influence of past experience. Of central relevance for major territories of human cognition, declarative memory pertains to memory for complex facts and personally experienced events, and can be distinguished from a diverse set of memory phenomena collectively known as nondeclarative memory. Nondeclarative memory includes skill learning, habit learning, simple forms of conditioning, various types of priming that can be measured in implicit memory tests, and nonassociative forms of learning like habituation and sensitization.

Some of the molecular building blocks of memory storage are common across these different types of memory. Elaborate layers of molecular machinery can require some passage of time so as to complete the process of memory formation. In many cases, neural plasticity induced during learning can be modulated by subsequent events. Release of epinephrine and cortisol, for example, can allow emotional significance to regulate memory strength. Selective gene activation and protein synthesis also play key roles in stabilizing synaptic changes.

These aspects of memory fall in a category called synaptic consolidation. Relevant molecular changes can require minutes to hours. On the other hand, the present discussion focuses on neural mechanisms of systems-level consolidation that are specific to declarative memory and that tend to occur over a much longer timescale.

Consolidating Declarative Memories

Declarative memory concerns the ability to bring back to mind factual and episodic information. Each of us maintains a colossal but changing record of facts and events to access when needed. This information can potentially stay with us for so many years that one might say that declarative memories can last a lifetime. One general principle of memory storage is that cortical networks specialized for processing specific types of information are the very same

networks involved in storing that information as fragments of declarative memories. Those fragments must be linked together in order for any particular declarative memory to exist.

Although we have learned much about the brain mechanisms responsible for declarative memory, and about ways to assess this type of memory using recall and recognition tests, pinpointing the exact neural substrates of any one specific autobiographical event or fact is beyond current technology. Indeed, a declarative memory does not reside in a single location, but rather, it depends on a dynamic network of neurons. Lively controversy surrounds questions about how consolidation operates on such a network, the precise length of time consolidation requires, and whether these memories assume a labile form under special circumstances.

Empirical evidence that can be brought to bear on theories of consolidation comes from multiple sources. Neuropsychological studies of patients with amnesia, in particular, suggest that declarative memories can change to become resistant to disruption and that this change is a by-product of consolidation. Critical brain damage in amnesia tends to include midline diencephalic or medial temporal structures, including the hippocampus and adjacent cortical regions, though the distinct memory functions presumably mediated by these different regions are currently unclear. Studies of animal models have also been designed to identify the neuroanatomical basis of this critical contribution to memory.

Evidence from Human Memory Disorders

Memory impairment tends to comprise both anterograde amnesia, a pronounced difficulty in learning new information, and retrograde amnesia, a disruption of the ability to remember information that had been learned prior to the onset of symptoms. In either case, patients experience difficulty remembering factual as well as event information (though dissociations are possible, at least in retrograde amnesia). Some amnesic patients exhibit severe anterograde amnesia and severe retrograde amnesia; some exhibit mild anterograde amnesia and mild retrograde amnesia. Given that neurological insult can produce correlated anterograde and retrograde amnesia in this manner (even though there are important exceptions), standard accounts specified a single mechanism that led to both effects. In particular, a core defect in a protracted consolidation process required for declarative memory storage could result in both types of impairment; new learning would not be normal without consolidation, and old memories would not be retrieved normally if their consolidation had not run its course.

In analyses of retrograde amnesia, it is useful to take into account the age of memories that might be retrieved (i.e., the length of the retention interval) by distinguishing between recent memory and remote memory. Indeed, a prevalent characteristic of retrograde memory impairment, described in 1882 by Theodore Ribot and known as Ribot's law, states that the dissolution of memory is inversely related to the recency of the event. Numerous cases of retrograde amnesia have been described in which the impairment was taken to be limited to recent memories, with preservation of remote memories. Patterns of temporally graded retrograde amnesia have been demonstrated using a variety of tests (**Figure 1**).

Implications of Temporally Graded Retrograde Amnesia

The notion that consolidation progresses over an extended period of time is consonant with evidence from retrograde amnesia, given the following scenario. To the extent that memories were formed recently, consolidation processes would have as yet been insufficient to produce a stabilized cortical memory. These memories become inaccessible in the absence of retrieval mechanisms that depend on hippocampus and related structures. This standard neuroanatomical account of consolidation thus characterizes recent memories as those that depend on both cortical and hippocampal networks.

In contrast, to the extent that an old memory has been subject to sufficient consolidation, it can be retrieved via cortical retrieval mechanisms. Whether hippocampal participation remains critical for some remote memories in some patients, however, is currently controversial.

This standard conceptualization of consolidation is as a process whereby declarative memories outgrow their dependence on corticohippocampal networks to become cortically self-reliant. This metamorphosis may involve increased connectivity among the components of the memory in the cortex; accordingly, the process has sometimes been referred to as cross-cortical consolidation. Cross-cortical consolidation may also involve the formation of new cortical representations that function to represent the gist or higher-order meaning of the memory while simultaneously enhancing the coherence of the set of neocortical storage sites (**Figure 2**).

Testing such speculations about how declarative memory representations change as a result of consolidation will require new sources of neurophysiological and neuroanatomical evidence. Before delving into this sort of evidence, we must examine doubts that have been raised about the evidence from retrograde amnesia.

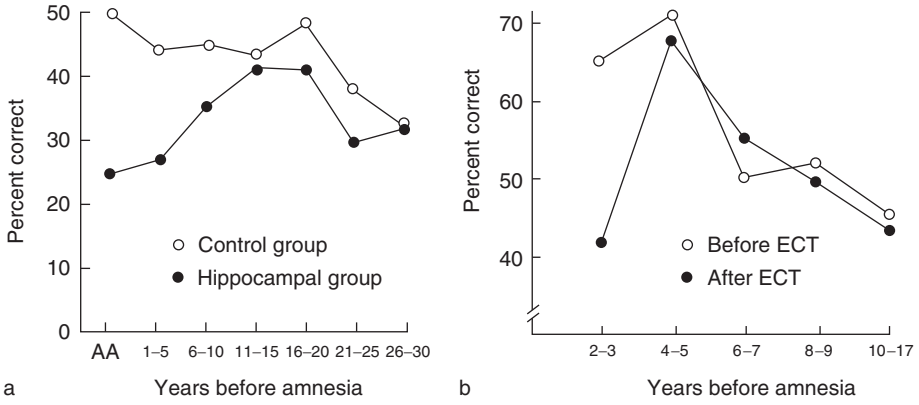

Figure 1 Forgetting curves showing temporally graded retrograde amnesia. (a) Recall was tested using questions about news events that occurred in preceding years (1950–2002) in five patients with damage limited primarily to the hippocampal region and 2–3 control subjects matched to each amnesic patient. The time period labeled AA (anterograde amnesia) represents recall deficits for information acquired after the onset of amnesia. (b) Recognition was tested for TV shows that were broadcast for only one season in preceding years (1957–72) in 16 patients who were given a course of electroconvulsive therapy (ECT) as treatment for depressive illness. Subjects were required to select actual TV show titles presented among fabricated titles, and the guessing rate was 25%. This test is advantageous because TV show titles were learned in a specific year and were unlikely to be rehearsed repeatedly afterwards. ECT was given three times per week and testing occurred before the first treatment and 1 h after the fifth treatment. These memory deficits did not result from medications or depressive illness *per se*. Memory abilities improved within a few weeks after ECT was completed. Adapted from Manns JR, Hopkins RO, and Squire LR (2003) Semantic memory and the human hippocampus. *Neuron* 38: 127–133; and from Squire LR, Slater PC, and Chace PM (1975) Retrograde amnesia: Temporal gradient in very longterm memory following electroconvulsive therapy. *Science* 187: 77–79.

Controversies and Challenges in Studies of Retrograde Amnesia

The extant literature on retrograde amnesia presents a complicated story that does not uniformly support this standard account of consolidation. Temporally graded retrograde amnesia has been observed reliably in patients with closed head injury, Korakoff's syndrome, and other disorders of memory. Observations by Scoville and Milner in 1957 of patient HM, who became amnesic following bilateral medial temporal lobectomy for medically intractable epilepsy, showed retrograde amnesia for autobiographical memory of roughly 2 years in duration. However, an insidious disease onset, as is likely in Korsakoff's syndrome, or factors like epilepsy or certain medications, could lead to apparent retrograde deficits that actually resulted from poor encoding during those years.

Conventional methods for assessing remote memory also have limitations. Whereas tests of anterograde amnesia concern information delivered systematically to the patient under well-controlled conditions, tests of retrograde amnesia tend to probe information acquired under unknown circumstances. When testing memory for historical events or celebrities, for example, it can be difficult to determine the patient's premorbid knowledge. To attempt to overcome this problem, experimenters can learn about important life events from informants or create specialized tests for specific information.

In constructing retrograde tests, it can be helpful to select test items such that various factors are equivalent across time periods. In this way, for example, difficulty might be equated such that an observed forgetting curve would reflect true forgetting rather than greater difficulty for older items. However, equating difficulty may lead to other differences across items, as the most remote items may tend to concern factual rather than episodic knowledge. Interpretations of retrograde gradients thus require careful attention to the makeup of test materials.

Another interpretive limitation results because most people show superior autobiographical retrieval for events from their early adulthood. One explanation is that these years often include people's most momentous experiences and so have a powerful influence on their life story and personality. Events from these times may also be extensively intertwined with other relevant information such that they are not easily lost.

Importantly, many reports of retrograde amnesia have demonstrated impairments not limited to a few years, but spanning one or more decades. Some patients lose essentially their whole life, in that they are unable to retrieve many autobiographical memories from any past time period. In contradistinction to the temporally graded period of retrograde amnesia shown in Figure 1, these patients show no gradient. A process of gradual consolidation does not

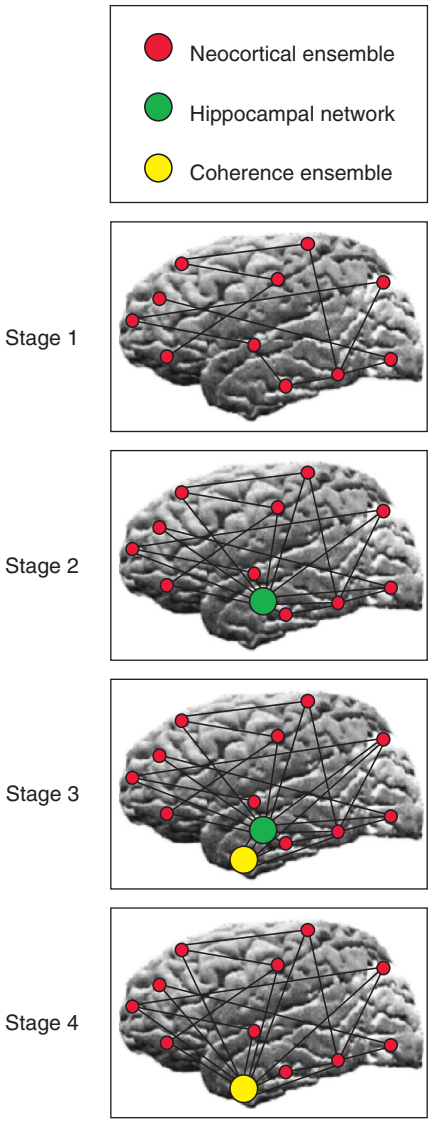

Figure 2 A speculative account of cross-cortical consolidation represented schematically. Initially (stage 1), a fact or event is encoded via representations in multiple cortical regions with binding and cognitive control provided by prefrontal cortex. A selection of neocortical ensembles is figuratively shown in red (allied subcortical networks are omitted). At the same time, high-level features in this dispersed representation involve hippocampal networks (stage 2). These hippocampal networks trigger pattern completion such that the set of dispersed cortical fragments can later be activated together. Over time (stage 3) and with the aid of hippocampal networks, coherence ensembles begin to form in various cortical regions such as medial temporal cortex or other limbic-associated cortex (e.g., entorhinal, perirhinal, parahippocampal, posterior cingulate, and medial prefrontal cortex). These coherence ensembles ultimately become part of the memory representation, taking on a superordinate role. Network connections become strengthened when the memory is retrieved and/or related to other stored information. By this account, a coherence ensemble is a cortical network that functions to maintain cohesiveness among the various parts of a declarative memory, and that ultimately (stage 4) takes over the binding role of the hippocampus. Adapted from Paller KA (2001) Neurocognitive foundations of human memory. In: Medin DL (ed.) *The Psychology of Learning and Motivation*, vol. 40, pp. 121–145. San Diego, CA: Academic Press.

seem to supply a viable explanation for such extensive memory loss. Moreover, dense retrograde impairments have been found in some patients with minimal anterograde amnesia, although this phenomenon is controversial and may be explained in some cases by other factors, such as psychogenic amnesia. Another complication is that retrograde impairments can disproportionately affect episodic versus semantic knowledge. Some patients display poor memory primarily for remote autobiographical information, some primarily for remote factual information.

One theoretical view developed to account for extensive episodic memory loss is known as multiple trace theory. By this view, the hippocampus contributes to episodic memory retrieval for all time periods. This contribution provides episodic retrieval with the contextual detail that supports the ability to approximate re-living a past event. Memories for factual information do not include this contextual detail and become hippocampal-independent after sufficient consolidation. The idea that episodic memories do not become independent of the hippocampus provides an explanation for retrograde amnesia for episodes across all time periods.

Interpretations of these intriguing patterns of retrograde impairment, however, must take into account the fact that retrograde amnesia can arise from several fundamentally different causes. Although consolidation provides a viable explanation for some instances of retrograde amnesia, memories can also be lost when pathology disrupts cortical areas responsible for the storage of this information. Whereas declarative memories are dispersed across multiple cortical regions, some of the multimodal and multidimensional knowledge critical for retrieving certain memories may depend on the integrity of special convergence zones in the brain, perhaps including medial temporal cortex (i.e., entorhinal, perirhinal, and parahippocampal), orbitofrontal cortex, medial prefrontal cortex, parietal cortex, and posterior cingulate cortex. As described above, a new representation formed in one of these regions may become part of the declarative engram by virtue of the consolidation process. Further research is needed to delineate the type of information stored in such regions. Conceivably, decades of retrograde amnesia can arise when storage sites in these critical regions are disrupted, in which case the evidence would have no bearing on specifying the time span of consolidation. Brain damage to some of these regions could conceivably result in extensive retrograde amnesia with minimal anterograde amnesia if the hippocampus and some adjacent medial temporal cortex remained intact.

Another explanation for dense retrograde amnesia must also be considered. Cross-cortical consolidation may not be the culprit when retrograde amnesia

across all time periods results from a profound defect in retrieval. Indeed, various sorts of evidence now point to a critical role of the frontal lobes in orchestrating retrieval. Full-blown memories of distinct autobiographical episodes can require extensive memory search. The planning, organization, and evaluation processes required for retrieval can become extremely challenging after frontal brain damage. Also, dissociations in the type of information that can and cannot be retrieved could arise from deficits based on either corrupted storage sites or disabled retrieval.

The interpretation of long periods of remote memory loss must also be informed by evidence for systematic relationships between the length of the retrograde loss and sites of brain damage. More evidence of this sort is needed, but results from postmortem histological analysis for several cases suggest that partial hippocampal damage produces limited retrograde impairment (1–2 years), whereas more extensive damage to the hippocampus and entorhinal cortex produces broader retrograde impairment (15–25 years).

In sum, the literature includes an inconsistent mix of reports of retrograde amnesia that either extends over decades or is limited to a recent period not longer than a few years. In cases of temporally extensive retrograde amnesia, storage and retrieval accounts must be carefully evaluated. Perhaps all old memories in healthy people are subject to steady reorganization. If so, an interesting but untested possibility is that the longer a patient has amnesia, the more dense their retrograde amnesia will be. At any rate, further research will hopefully expand our understanding of the range of retrograde deficits that can be observed and clarify when such memory disorders arise from a consolidation defect.

Problems with Specifying the Age of a Memory

A further theoretical concern haunts the evaluation of all data on remote memory in amnesic patients. How should we conceptualize an episodic memory that is 20 or more years old?

An episodic memory is defined with reference to one specific event that was experienced in a unique spatiotemporal context. If a person is capable of remembering an event from 20 years ago, it can reasonably be assumed that this memory was also retrieved multiple times in the intervening years. Nevertheless, researchers commonly refer to this as a 20-year-old memory. If intervening retrieval influences memory storage, it might be more appropriate to regard the effective retention interval as much shorter than 20 years. Although an individual may recall an event from 20 years ago, the memory itself could be largely based on modifications made more recently. Indeed, past episodes not retrieved and elaborated upon multiple times over many years may be the ones we tend to forget.

Even younger memories are subject to concerns about effects of intervening retrieval. Once we acknowledge that memories are accessed in sleep, which now seems undeniable, we cannot rule out the idea that every instance of remote memory retrieval is a function of storage events at multiple time points.

By the present account of consolidation, each time a memory for an episode is retrieved, there is a possibility that the information in question is associated with other information so as to expand the operative nature and meaning of the memory. Retrieved memories are regularly reevaluated and related to new information in mind at the moment of retrieval, including the context of the new retrieval episode. Moreover, new events can provoke the reinterpretation of past events. Thus, the memory trace should be conceived of as product of memory storage operations engaged during various retrieval experiences. Unless intervening retrieval can be ruled out, it is problematic for the age of an episodic memory to be defined simply on the basis of when the original event occurred.

This reconceptualization of remote memories provides an important point of contact between multiple trace theory and the standard model of consolidation. A recalled episode may be tantamount to a retelling of prior re-tellings of the same story, rather than a replay of an ancient story set in stone long ago.

There are thus two reasons an amnesic patient's retrograde impairment cannot be specified by a simple duration. First, consolidation for various factual and episodic memories may proceed at a different rate depending on the type of information and the ways in which it is retrieved and associated with other information. Second, as underscored by the preceding discussion, specifying a single operative age for a given memory is problematic.

Memory Transformation due to Consolidation

Connections to the cortical storage sites that comprise a declarative memory may be formed via the hippocampus at initial encoding, and then used when that memory is subsequently retrieved. In this way, memories may be subject to continual hippocampal-dependent restructuring for some time. Some remote memories may ultimately reach a state in which any further changes are relatively minimal, even though these memories may retain their episodic quality.

Whereas consolidation can produce a hippocampal-independent memory, it can also change the representational quality of a memory. In some cases of

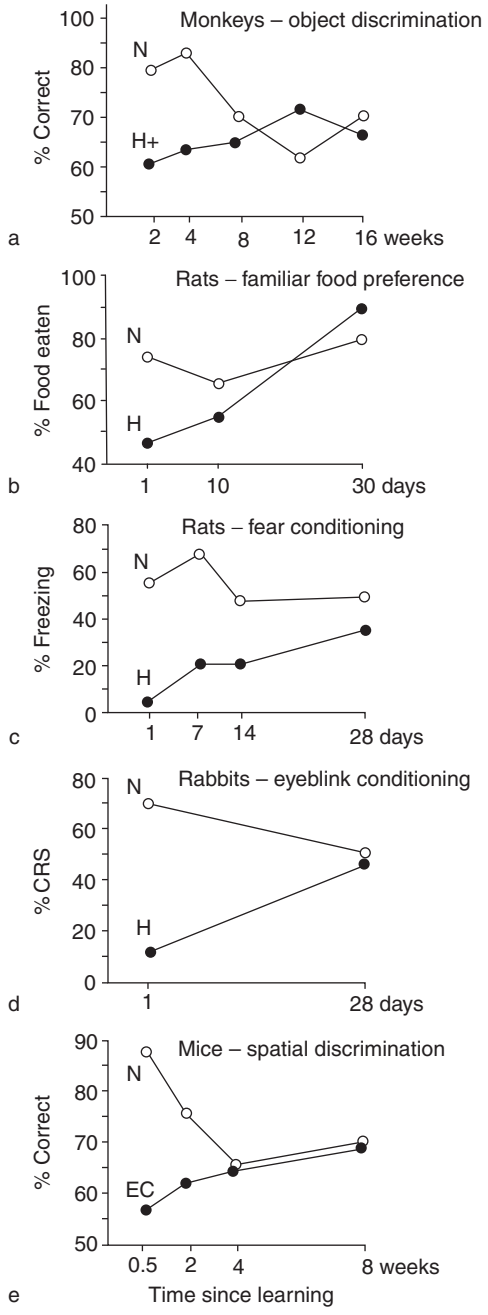

Figure 3 Several demonstrations of temporally graded retrograde amnesia following damage to the hippocampal region. Learning took place at multiple times before surgery. Two groups of animals were tested in each experiment, normal animals (N) and animals with either lesions of the hippocampus (H), lesions of hippocampus plus surrounding cortex (H+), or lesions of entorhinal cortex (EC). Adapted from Eichenbaum H (2002) *The Cognitive Neuroscience of Memory: An Introduction*. New York: Oxford University Press. (a) Retention of 100 object discrimination problems in monkeys. Data from Zola-Morgan SM and Squire LR (1990) The primate hippocampal formation: Evidence for a time-limited role in memory storage. *Science* 250: 288–290. (b) Retention of the social transmission of food preference in rats. Data from Clark RE, Broadbent NJ, Zola SM, and Squire LR (2002) Anterograde amnesia and temporally graded retrograde amnesia for a nonspatial memory task after lesions of hippocampus and subiculum. *Journal of Neuroscience* 22: 4663–4669. (c) Contextual fear conditioning in rats. Data from Kim JJ and Fanselow MS (1992) Modality-specific retrograde amnesia of fear. *Science* 256: 675–677. (d) Trace eyeblink conditioning in rabbits. CRS, chronic restraint stress. Data from Kim JJ, Clark RE, and Thompson RF (1995) Hippocampectomy impairs the memory of recently, but not remotely, acquired trace eyeblink conditioned responses. *Behavioral Neuroscience* 109: 195–203. (e) Retention of maze problems in mice. Data from Cho YH, Beracochea D, and Jaffard R (1993) Extended temporal gradient for the retrograde and anterograde amnesia produced by ibotenate entorhinal cortex lesions in mice. *Journal of Neuroscience* 13: 1759–1766.

repeated retrieval of an event memory, contextual details are lost so that the event itself comes to be represented only abstractly. That is, specific episodic information can become extraneous through a process of decontextualization. Although these memories start out as contextually rich episodic memories, vivid perceptual and contextual details gradually become unavailable – factual information about the event becomes the only part of the memory that can be recalled. In this manner, an episodic memory can be said to have changed into a semantic memory. Decontextualization may produce an enduring semantic memory in conjunction with a shift in memory storage from neocortical/hippocampal to only neocortical.

Computational models of consolidation have implemented procedures that theoretically could lead to the formation of decontextualized memories. In the Complementary Learning Systems framework, for example, hippocampal networks implement fast links among neocortical components. Memory representation in the neocortex, in contrast, changes more slowly. This scheme keeps neocortical memories safe from interference that would result if networks changed based on each new piece of episodic information. Instead, slow neocortical changes can lead gradually to the buildup of semantic knowledge. The time course of consolidation can then be conceived as a reflection of the time-consuming training of cortical networks by hippocampal networks.

Evidence from Prospective Studies, Neuroimaging, and Sleep Research

Müller and Pilzecker introduced the term consolidation (*Konsolidierung*) in 1900 and proposed that memories could change over time from a fragile, labile form to a fixed form. In 1903, Burnham took up consolidation in the context of the retrograde difficulties experienced by amnesic patients and combined the notion of retrieval and association with the idea of neural reorganization. However, we have only limited opportunities to observe these consolidation-based changes directly. Such opportunities will increase as we (1) begin to understand the physiological changes inscribed in brain networks responsible for

declarative memories and (2) develop ways to overcome the methodological and interpretative limitations discussed above. Prospective studies offer the opportunity to analyze well-controlled memory storage over a certain time period. Instead of relying on memory tests for retrospective information acquired under unknown circumstances, the circumstances of encoding can be controlled such that a range of retention intervals can be systematically examined.

In animal studies of consolidation, a variety of approaches have been used in prospective studies, with lesions created surgically to encompass specific regions (Figure 3). Many of these studies have obtained results supporting the hypothesis that medial temporal damage produces temporally graded retrograde amnesia (although there are also some exceptions). These observations of retrograde amnesia in multiple species and with multiple types of testing procedure also attest to the feasibility of future efforts to delineate the precise causes of retrograde memory impairment, and in this way clarify how these memories are consolidated.

Human neuroimaging has also been used in studies designed to examine how hippocampal contributions to retrieval may change as a function of the time since initial encoding. Interpretations must contend with many of the limitations discussed above. Hippocampal activity for recent and remote memories, in particular, can be engaged due to retrieval processing *per se* and/or due to encoding of the new recollective experiences prompted by the retrieval cues. The possibility of superimposed encoding activity can thus pose difficulties for conclusive interpretations of the role of the hippocampus in recent versus remote memory retrieval in these studies.

Prospective methods have also been used in some neuroimaging studies. In one such study, subjects viewed a series of 320 landscape photographs and were tested up to 90 days later. Brain activations for recognized pictures were examined at four retention intervals (Figure 4). Consolidation apparently led to a change in the anatomical basis of memory storage, in line with predictions based on temporally graded memory deficits due to hippocampal damage. The hippocampal contribution appeared to decrease with time while an anterior medial prefrontal contribution increased with time. Evidence from animal studies

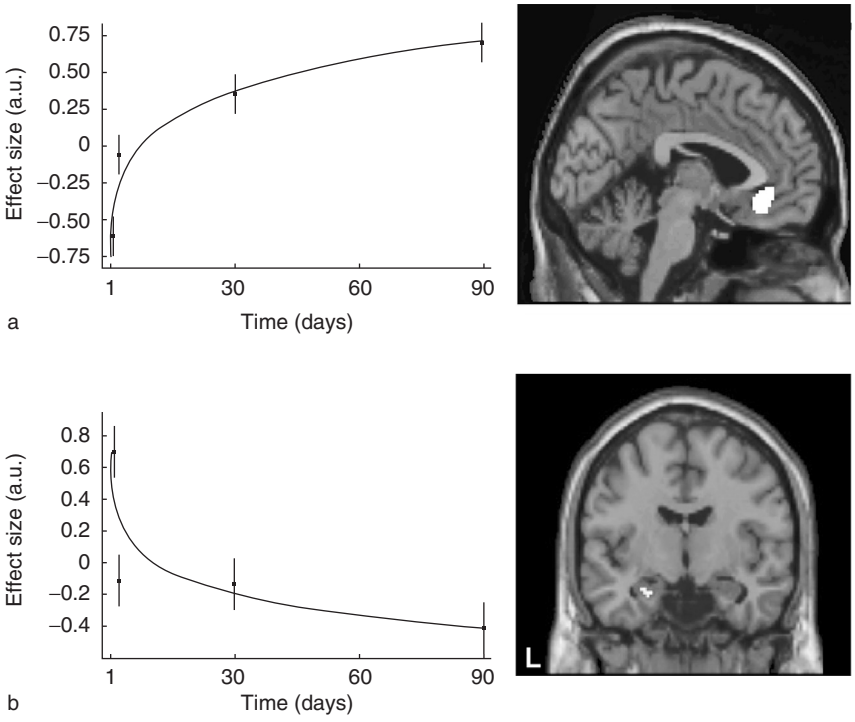

Figure 4 Results from an fMRI experiment in which brain activations for confident recognition responses were compared as a function of whether initial encoding took place 1, 2, 30, or 90 days earlier. (a) A region of ventral prefrontal cortex showed increased activity with increasing study–test delay. (b) Bilateral hippocampal regions showed decreased activity with increasing study–test delay. These findings suggest that hippocampal networks play a temporary role in memory storage, and that this role may be transferred to cortical regions such as medial prefrontal cortex. This experiment also included a rest period about 3 h after encoding, during which polysomnographic recordings were made, and those individuals who exhibited a greater amount of slow-wave sleep during this period tended to demonstrate superior memory for the photographs on later tests. Reproduced from Takashima A, Petersson KM, Rutters F, et al. (2006) Declarative memory consolidation in humans: A prospective functional magnetic resonance imaging study. *Proceedings of the National Academy of Sciences of the United States of America* 103: 756–761. Copyright (2006) National Academy of Sciences, USA.

also supports the idea that this region of prefrontal cortex, which receives information from many other cortical regions, may play a key role in memory reorganization.

Evidence from multiple sources supports the idea that consolidation can occur both during waking and during sleep. Hippocampal and cortical neurons in animals show evidence of memory replay during postacquisition waking and sleep. Plasticity-related gene expression in medial temporal regions is altered systematically during sleep. Hippocampal theta during sleep may also index memory processing, perhaps involving temporal coupling across brain regions. Sleep spindles in cortical electroencephalogram (EEG) recordings at 12–15 Hz become more plentiful after periods of declarative memory encoding during waking, and together with hippocampal sharp wave/ripple EEG patterns may reflect hippocampal–neocortical dialog. Depth EEG recordings have also implicated interactions between hippocampus and medial temporal cortex in memory processing during sleep. Various physiological events that have yet to be deciphered may support memory processing during multiple stages of sleep. Many dreams occur together with eye movements, and these rapid eye movement (REM) periods have some clear ties to memory, perhaps emotional memories in particular. However, some evidence suggests that REM may not be the only time, or even the foremost time, for memory reprocessing. Another stage, slow-wave sleep (SWS), which is prevalent early in the night, may play a vital role in hippocampal–neocortical interactions that promote declarative memory consolidation. During SWS, reduced cholinergic activation and/or cortisol feedback in the hippocampus may promote hippocampal information flow to the neocortex. One possible sign of the processing of declarative memories during SWS is a buildup of slow negative potentials over frontal cortex, and correlations have been observed between SWS and later performance on declarative memory tests for information learned prior to going to sleep. Although many questions remain about memory processing during sleep, this research area will undoubtedly be a source of much new thinking on consolidation in the coming years.

See also: Amnesia: Declarative and Nondeclarative Memory; Cognitive Neuroscience: An Overview; Declarative Memory System: Anatomy; Episodic Memory; Hippocampus and Neural Representations; Hormones and Memory; Memory: Computational Models; Memory Consolidation: Cerebral Cortex; Memory Disorders; Memory Representation; Short Term and Working Memory.

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