Memory traces unbound

Karim Nader

Department of Psychology, McGill University, Montreal, Quebec, Canada H3A 1B1

The idea that new memories are initially 'labile' and sensitive to disruption before becoming permanently stored in the wiring of the brain has been dogma for >100 years. Recently, we have revisited the hypothesis that reactivation of a consolidated memory can return it to a labile, sensitive state – in which it can be modified, strengthened, changed or even erased! The data generated from some of the best-described paradigms in memory research, in conjunction with powerful neurobiological technologies, have provided striking support for a very dynamic neurobiological basis of memory, which is beginning to overturn the old dogma.

For >100 years, generations of behavioural paradigms and technologies have been used to address questions about the mechanisms that mediate learning and memory [1–3]. Repeatedly, evidence has been found to suggest that the properties of the memory trace change in a time-dependent manner, such that new memories are initially in a dynamic 'labile' form for a short time [short-term memory (STM)], after which the memory trace is 'fixed' or 'consolidated' into the physical structure of the brain [long-term memory (LTM)] [4–6]. For example, electroconvulsive shock (ECS) is effective in inducing amnesia if presented shortly after training (during STM) but not if given a few hours later (during LTM) [7]. Time-dependent effects such as these are the cornerstone of memory consolidation theory (now called cellular consolidation theory [8]). During the past 40 years, incredible efforts have been made to describe across all levels of analysis the processes that contribute to the transformation of a trace from being labile to being fixed [9,10]. Of note is the finding that the transcription factor Ca^{2+}-response-element-binding protein (CREB), transcription and translation all seem to be universal neuronal requirements for traces to enter LTM [11–15] (Fig. 1a).

Early studies on reconsolidation

In 1968, the view that memories are consolidated over time into a permanent state was challenged by Lewis and colleagues [16]. In agreement with previous studies, when ECS was given 24 h after fear conditioning it was ineffective in generating amnesia. However, if the memory was reactivated before ECS administration, amnesia was observed the following day. Given that amnesia was not produced in the absence of memory reactivation, the memory is defined as being consolidated by that time. Therefore, reactivation of a consolidated memory presumably returned it to a labile state, which initiated another

time-dependent memory process similar to that seen after new learning. This phenomenon is now referred to as reconsolidation [17–19]. Lewis' study defined a paradigm for experimentally differentiating consolidation and reconsolidation: a necessary criterion if an effect is to be attributed to reconsolidation is that the amnesic agent must be
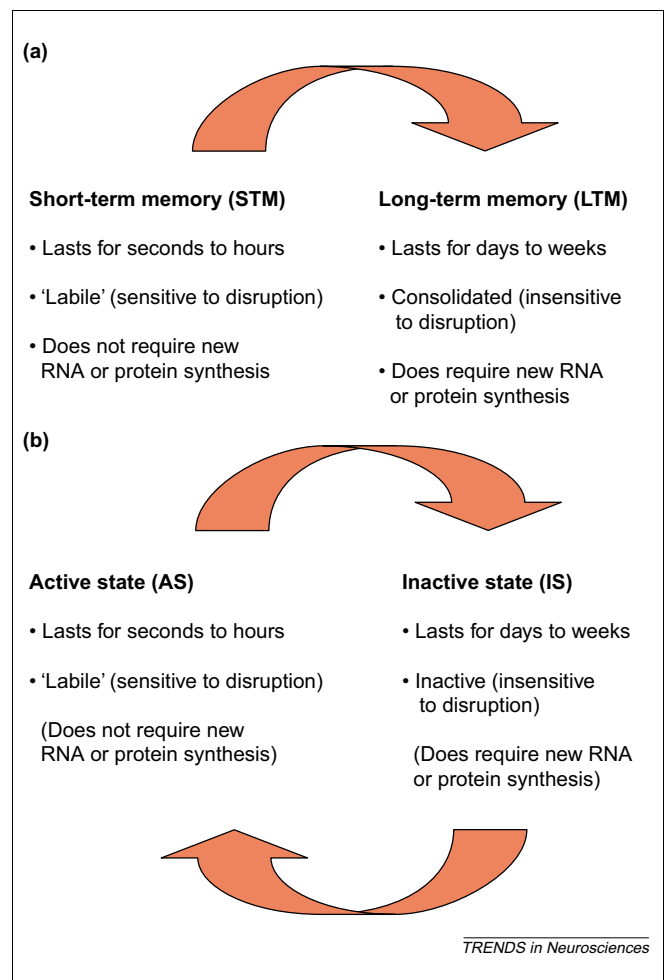

Fig. 1. Two models of memory processing. (a) The traditional consolidation theory, which posits a labile, short-term memory (STM) state and a later, consolidated long-term memory (LTM) state. Once fixed in LTM, the memory is posited to be permanent. Below each memory state is a list that is typically used to describe some of the properties of the two states. (b) The memory model proposed by Lewis [33]. The active state (AS) and inactive state (IS) are analogous to STM and LTM, respectively. The molecular descriptors in brackets were not part of the original model but have been inserted for comparison with (a). New memories enter a labile AS and then with time enter the IS [top red arrow, again similar to (a)]. Reactivation of memories that are in an IS returns them to the AS (bottom red arrow). Both new and reactivated memories require protein-synthesis-dependent mechanisms in order to enter the IS. Contrary to consolidation theory, which cannot explain the reconsolidation data, this model incorporates both the data from consolidation and reconsolidation experiments.

Corresponding author: Karim Nader (nader@hebb.psych.mcgill.ca).

effective only after memory reactivation and not if memory reactivation is omitted. This finding has subsequently been replicated [20,21] and extended in a variety of species, from rodents to the garden slug *Limax* [22], and across appetitive and aversive paradigms [23–25]. However, there have also been some instances where the data could not be replicated, and some negative findings [26–28]. The reasons for these negative findings are not clear. As with all new fields that grapple with understanding the nature of a newly discovered phenomenon, it is possible that slight parametric differences in protocols that are crucial for the phenomenon, and that were not controlled for between labs, could have been a contributing factor. Unfortunately, this line of research was mostly forgotten in neuroscience until recently.

Erasing fear

Capitalizing on the current knowledge of the locus and mechanisms of fear memory formation, striking support for Lewis' original finding has recently been reported [19]. An auditory fear-conditioning paradigm, which is now well described [29–31], was used in conjunction with targeted inhibition of protein synthesis in the lateral nucleus of the amygdala (LA; a nucleus in which protein synthesis is required for consolidation of auditory fear conditioning [32]). Intra-LA infusions of the protein synthesis inhibitor anisomycin 1 d after fear conditioning had no effect on subsequent tests, defining the trace as being in a consolidated state at this time [19]. However, memory reactivation by presenting the auditory conditioning stimulus (CS) alone before such infusions caused amnesia in subsequent tests, consistent with the findings of Lewis' group. More impressively, just as intra-LA anisomycin infusions after new learning had been shown to impair LTM but not STM [32], the same infusions after reactivation of a consolidated memory impaired behaviour in a post-reactivation long-term memory (PR-LTM) test, but not during a post-reactivation short-term memory (PR-STM) test [19]. These findings, and others, strongly support and extend the original suggestion that reactivation of a consolidated and fixed memory can return it to a labile state that is similar to STM. The theoretical implication of these findings is that 'consolidation theory' might be a myopic view of memory processing that needs to be extended [33] (Fig. 1b). In addition, reconsolidation provides a dynamic mechanism by which memories can be updated and changed.

Reconsolidation across species

In addition to rodents, cellular reconsolidation with targeted infusions has been reported in both the chick [34] and the crab *Chasmagnathus* [35]. These findings are further confirmation that reconsolidation is a basic evolutionarily conserved process. In the crab, a contextual fear-conditioning paradigm was used. Re-exposure to the training context the day after training returned the memory to a state that was sensitive to both cyclohexamide and NMDA-receptor antagonist (MK-801) treatments. Both treatments impaired only PR-LTM and spared PR-STM, as was seen in rats [19]. The deficit was not observed if the animals were placed in a neutral context prior to infusions. The contribution of NMDA to reconsolidation is consistent with a previous report demonstrating that systemic administration of MK-801 blocked reconsolidation of a spatial discrimination task in rats [18]. The implication of NMDA receptors in reconsolidation is very exciting because it suggests that the entire molecular cascade activated by new learning and memory, from NMDA receptors to protein synthesis, could be recapitulated during reconsolidation [36].

Comparison of reconsolidation and consolidation

The findings in chick using one-trial passive avoidance (PA) are the most extensive comparison of consolidation and reconsolidation in a single study. Infusions of anisomycin, or the inhibitor of post-translational glycoprotein fucosylation, 2-deoxygalactose (2-D-gal), into the intermediate medial hyperstriatum ventrale blocked consolidation and reconsolidation [34]. The differences reported were as follows:

(1) on re-testing, the amnesia produced by blockade of reconsolidation (but not consolidation) could 'recover'. Citing other studies in which amnesia resulting from blockade of consolidation for this task recovered [37], the authors concluded that amnesia induced by blockade of both phenomena represented failure to retrieve a memory that is stored in the brain;

(2) reconsolidation was more sensitive to amnesic challenge than was consolidation;

(3) reconsolidation occurred faster than consolidation, a consistent finding across paradigms [38–41].

The finding that reconsolidation occurs more quickly is consistent with the suggestion that reconsolidation does not 'reverse' any of the morphological changes thought to mediate LTM. Rather, reactivation of these processes renders them dependent on protein synthesis if they are eventually to be restabilized [19,42]. It is reasonable to assume that this restabilization process should be completed faster than the construction and stabilization of new synapse formation that is thought to underlie consolidation [43]. Thus, the findings tell us that reconsolidation and consolidation have different characteristics.

Although comparisons between consolidation and reconsolidation are important, direct comparisons between them should be made with caution. This is because the stimuli that are present during consolidation and reconsolidation are different. During a consolidation experiment, a reinforcing stimulus is typically present, whereas in the typical reconsolidation experiment, no reinforcer is presented. Differences in which stimuli are presented during training can significantly affect the characteristics of consolidation [44]. This difference in stimulation conditions between the two phenomena should therefore make their characteristics quantitatively different, a prediction also made by learning theory [43]. This does not necessarily imply that one process is more sensitive to inhibitors of protein synthesis than the other but, rather, that they are different initially and, therefore, that we should expect some differences in their characteristics.

Thus, in studies that have tested for reconsolidation using the same parameters as consolidation and have found no effect [45–47], it is possible that the lack of effect is due to simply not having the correct experimental parameters. For example, systemic inhibition of protein synthesis has been reported to have no effect on reconsolidation of fear conditioning [45]. However, given that reconsolidation occurs faster than consolidation, the negative finding might simply be due to the fact that by the time central protein synthesis in significantly inhibited, reconsolidation is complete. Thus, studies that test whether reconsolidation occurs in a behavioural system must perform parametric tests for both time of infusions and dose of protein synthesis inhibitor. One study has varied memory reactivation with time of infusions of anisomycin into the gustatory cortex [48], providing strong evidence that reconsolidation might not be a global phenomenon (but see the discussion concerning extinction for another alternative interpretation). Thus, parametric differences must be controlled for to be certain of putative boundary conditions for reconsolidation.

Transcription versus translation

One of the cardinal rules of consolidation of new memories is that it requires transcription [11,13]. One question concerning reconsolidation has been whether it too would require transcription or whether translation of proteins from dendritic RNAs would be sufficient [42]. This issue was recently addressed using an inducible dominant–negative transgenic mouse in which the function of the transcription factor CREB was compromised in excitatory neurons of the forebrain [49]. Consistent with the findings for consolidation, impairing CREB forebrain neuronal function after reactivation of consolidated auditory or contextual-fear memories caused impairment in PR-LTM but not PR-STM. Again, this deficit was contingent on memory reactivation. These findings suggest that CREB-mediated transcription is necessary for reconsolidation. Additional corroborative evidence that transcription plays a role in reconsolidation comes from studies examining the expression of phosphorylated CREB and two immediate–early genes that are downstream targets of CREB, *Fos* and *zif268* [46,50], after memory reactivation of either consolidated auditory or contextual-fear memories [51,52]. Reactivation of auditory fear memories, which are known to be dependent on the amygdala [29–31], induced an increased phosphorylation of CREB, and expression of *Fos* and *zif268* in the amygdala, without change in the hippocampus. Conversely, reactivation of a consolidated memory for contextual fear, the consolidation of which is known to involve both the amygdala and the hippocampus [29–31], increased *zif268* expression in both these structures. Thus, the pattern of expression is both region and stimulus specific, in a manner predicted by current models of consolidation of auditory and contextual-fear conditioning. Targeted disruption of transcription will be important as a further test of the requirement for transcription in reconsolidation. However, the findings so far strongly support the idea that reconsolidation requires transcription and that there is significant overlap in the molecular cascades implicated in reconsolidation and consolidation. Finally, CREB, which is cast as a universal 'molecular switch' for consolidation, seems to be fulfilling an analogous role in reconsolidation [49].

Reconsolidation and extinction

In the typical reconsolidation experiment, the conditioned stimulus is presented without the reinforcer and the memory trace is challenged. Operationally, this is an extinction trial. Extinction is new learning during which an animal begins to learn that the unconditioned stimulus (US) no longer follows the CS. Reconsolidation, however, is posited to be the re-storage of the underlying memory [16]. Thus, at a conceptual level they are distinct but they might involve similar molecular mechanisms. Protein synthesis, CREB and NMDA receptors have been implicated in reconsolidation [18,19,34,35,49,53]. NMDA receptors and mitogen-activated protein kinase have both been shown to be involved in extinction [48,54,55].

This relationship becomes potentially interesting when one considers two studies that failed to demonstrate the reconsolidation finding [48,56]. One study used conditioned taste aversion and the other used passive avoidance, with central injections of anisomycin into the gustatory cortex and the hippocampus, respectively. In both cases, post-reactivation anisomycin infusions did not cause amnesia. They had the opposite effect, inhibiting extinction such that the experimental animals persisted in responding to the CS, even though it was no longer reinforced. This suggests that the consolidation of extinction learning is also dependent on protein synthesis. There is one telling difference between the studies that blocked extinction and those that blocked reconsolidation [19,34,35,49,53]. In the former, the reactivation test itself caused significant extinction. Conversely, no extinction was observed in the reactivation sessions in the studies reporting a blockade of reconsolidation. Thus, there could be a molecular competition between the two processes, with the dominant process of the reactivation session being the one most affected by protein synthesis inhibition. Gordon made an analogous finding in behavioural studies performed using an active avoidance task. If previously trained animals were briefly returned to the avoidance box and given a non-reinforced CS presentation, behaviour improved on a subsequent test [57]. Conversely, animals that received the same CS treatment but were allowed more time in the apparatus to incorporate the non-reinforced trial demonstrated extinction (decreased responses) the next day. Thus, at a behavioural level there is some support for competition between the two processes. Furthermore, the findings dissociate the behavioural effects of reconsolidation from extinction. If this hypothesis is true, then it will be very exciting to look for the molecular mechanisms that mediate this competition between two very different behavioural phenomena.

Systems reconsolidation

In the hippocampus, consolidation occurs at a second level of analysis that is posited to last in the order of weeks for

rodents and years in humans, called 'systems consolidation' [8]. First described by Scoville and Milner [58], the hypothesis states that the hippocampus plays a time-limited role in memory processing, such that recent memories are hippocampus dependent, whereas older memories are not [59–61]. For the sake of clarity, memories that have become independent of the hippocampus with time are referred to as 'remote' memories.

Hippocampus-dependent memories have recently been demonstrated to undergo both cellular and systems reconsolidation [53] (Fig. 2a,b). Debiec *et al.* used a contextual fear-conditioning paradigm in conjunction with either

targeted infusions of anisomycin into, or lesions of, the hippocampus. Consistent with previous findings, lesions of the hippocampus 45 days after conditioning had no effect on the subsequent expression of contextual fear conditioning [62,63] (Fig. 2b). However, if the memory is reactivated for as little as 90 s before the lesion, amnesia is observed after the lesion and does not recover with multiple testing protocols or spontaneously. Therefore, memory reactivation of a remote memory causes it to return to a hippocampus-dependent state. Interestingly, this reactivated remote trace remained hippocampus-dependent for only 1–2 d. Thus, although the duration of systems
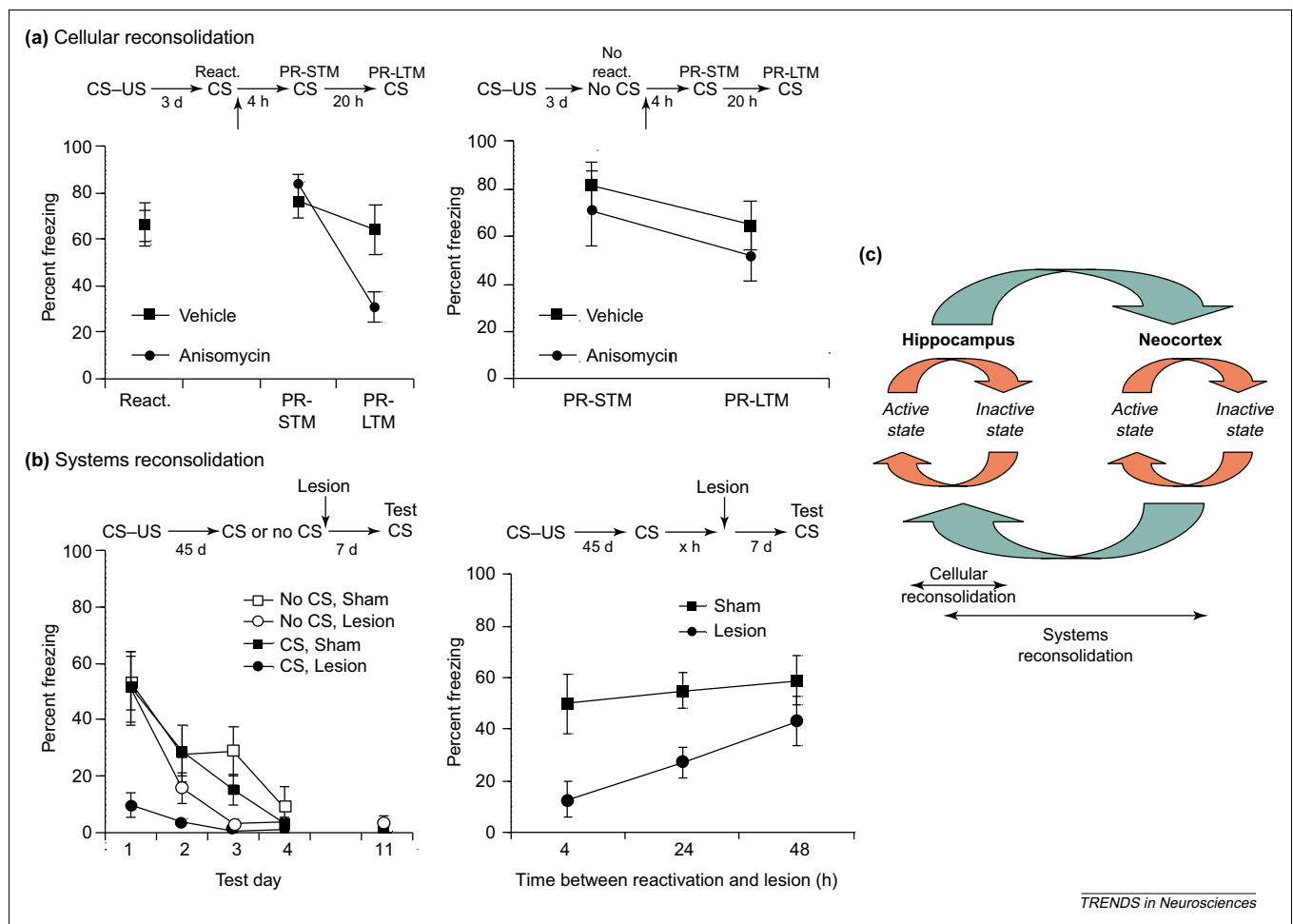

Fig. 2. Cellular and systems reconsolidation in the hippocampus. (a) Cellular reconsolidation. Data from a contextual fear conditioning paradigm that demonstrates cellular reconsolidation. Training [conditioned stimulus–unconditioned stimulus (CS–US)] consisted of eight shock presentations in a conditioning chamber. Three days afterwards, rats were returned to the same conditioning chamber for 90 s to reactivate their memory (left, React.) or not (right, No react.). Immediately afterwards, rats received bilateral infusions of anisomycin or vehicle (artificial cerebrospinal fluid) (vertical arrows). Four hours later they received a post-reactivation short-term memory (PR-STM) test; 20 h after the PR-STM they received a post-reactivation long-term memory (PR-LTM) test. After memory reactivation, anisomycin impaired only PR-LTM but not PR-STM (left). In the absence of memory reactivation, anisomycin had no effect (right). (b) Systems reconsolidation. The same training and reactivation protocols were used as in (a); however, instead of infusions, the hippocampus was lesioned. Forty-five days after conditioning, lesions of the hippocampus (Lesion) immediately after memory reactivation (CS) produced a significant impairment (left). Conversely, the same lesions had no effect when the reactivation session was omitted (No CS), demonstrating that 45 d after conditioning, the memory is independent of the hippocampus. Thus, reactivation of a hippocampus-independent memory returns it to being hippocampus-dependent: an example of systems reconsolidation. Reactivation of the remote memory (right) returned it to being dependent on the hippocampus for <2 d. (c) A functional memory model of the hippocampus, demonstrating both cellular and systems reconsolidation. Cellular reconsolidation in the hippocampus and neocortex is shown with red arrows; systems reconsolidation is shown with green arrows (note the green arrows do not differentiate between the different durations of systems consolidation and reconsolidation). A new hippocampus-dependent memory will undergo cellular consolidation in the hippocampus (top red arrow) and subsequent reconsolidation causes memories to return to a labile state (bottom red arrow) and then to become reconsolidated (top red arrow). Over time, the neocortex becomes competent to mediate the task and no longer needs the hippocampus, at which point it is a remote memory (top green arrow). Reactivation of the remote memory will cause some critical plasticity to return to being hippocampus-dependent (bottom green arrow) and the neocortical trace to return to a labile state (bottom red arrow), which requires hippocampal feedback. Over the next 2 d, cortico–hippocampal interactions will cause the neocortical trace to become hippocampus-independent again (top green arrow) and reconsolidated (top red arrow).

consolidation (the first retrograde amnesic gradient) is in the order of weeks [62,63] (up to 45 d in the study of Debiec *et al.*), systems reconsolidation (the second retrograde amnesic gradient) lasts for ~2 d. Furthermore, a third gradient of comparable duration to the second has been reported. The decrease in the length of time for which the hippocampus is necessary after memory reactivation is consistent with an updating role of the structure for neocortical memories, even though the cortical memories are already consolidated. Other interpretations of the findings (in terms of facilitated extinction, new trace formation, state-dependent learning, latent memory, drugs acting as an US to produce competing responses, anatomical damage and/or dysfunction, compromised late waves of protein synthesis required for consolidation, and changes in baseline behaviour) were all considered (with the appropriate controls) and ruled out [53]. Thus, the most parsimonious interpretation of the data is that even remote memories, when triggered with an intact hippocampus, return to a labile hippocampus-dependent state, and that they remain in this state for several days – far shorter than the first consolidation period (Fig. 2c). These findings extend previous work on reconsolidation to another brain system (hippocampus), to a qualitatively distinct memory (contextual representation) and across levels of analysis (systems).

Interestingly, there is some evidence that memories of inhibitory avoidance might behave differently from contextual fear memories [64]. Systemic administration of anisomycin was only effective in blocking reconsolidation if memory reactivation was performed during the first week after training, but not thereafter. It is possible that with increased time after training, the duration of reconsolidation might decrease, such that at later time points reconsolidation is complete by the time inhibition of brain protein synthesis has been significantly reduced. If this and other parametric alternatives are ruled out, and the same reconsolidation gradient is observed, this would be one of the first demonstrations of a boundary condition. This, in turn, would raise the question of why memories for inhibitory avoidance have a time window during which reconsolidation can occur, whereas contextual memories associated with shock always seem to be able to return to a labile state after reactivation.

The qualitative nature of reconsolidation and consolidation

Currently, the issue of whether amnesia is a deficit of storage or retrieval has still not been resolved [9,65]. Thus, although we cannot determine with certainty the qualitative nature of reconsolidation and consolidation, we are in a position to ask whether they are qualitatively similar. If they represent qualitatively similar processes, then they should behave in a qualitatively similar manner in response to different neurobiological challenges across paradigms. However, if they are qualitatively distinct, such that one is a storage process and the other a retrieval process, then they should behave differently in response to the same manipulations. It is clear that when reconsolidation is reported, it is qualitatively extremely similar to consolidation. For example, whether through inhibition

of protein synthesis (in crab, mouse or rat) or decreased CREB function, the same pattern of results is obtained for consolidation and reconsolidation: impaired LTM or PR-LTM and intact STM or PR-STM [19,34,35,49,53]. Furthermore, the use of memory modulators can enhance both new memories and those that are consolidated and reactivated [39,66–68]. Similarly, interference can be obtained between the acquisition of two new tasks or between one new task and a reactivated memory of a second task [38,40,41]. Importantly, all these paradigms show discreet time windows within which the effects are observed. Therefore, for every paradigm that consolidation theory has been built on, there are comparable demonstrations of qualitatively similar results after reactivation of a consolidated memory. Given the discussed similarities, the only logical conclusion based on these data is that reconsolidation and consolidation are qualitatively (but perhaps not quantitatively) the same. Thus, if consolidation is a storage process, then (logically) reconsolidation must be as well.

A final similarity is that there are reports of spontaneous recovery during the first test after amnesia caused by blockade of either reconsolidation [69] or consolidation [70–75]. Thus, whether consolidation and reconsolidation both represent retrieval or storage processes is not yet known.

New learning versus re-storage

One issue that has been at the forefront of discussions on reconsolidation is the role of new learning. For example, perhaps anisomycin prevents the consolidation of new learning occurring during the reactivation session. In turn, it is the blockade of this new learning, as opposed to the re-storage of the original trace, that is responsible for the behavioural deficit. First, we must bear in mind that consolidation theory explicitly predicts that only new information acquired during a session, and not the entire memory, is in a labile state [5]. In the typical reconsolidation experiments, the main source of new learning during the reactivation session is an extinction trial (non-reinforced CS presentation). Extinction normally decreases the response; thus, if anisomycin was blocking extinction, then the anisomycin-treated animals should show an increased response on the test day than do control animals. This is the opposite of what is reported when reconsolidation is blocked.

A second version of the new learning interpretation is that reactivation of the memory causes a second distinct trace to be formed. In turn, anisomycin blocks the consolidation of this new second trace. Two lines of evidence dispute this interpretation. First, this interpretation predicts no impairment on test because animals should have simply retrieved the intact first memory trace and performed at control levels. Second, the first retrograde gradient for a new contextual memory to undergo systems consolidation is on the order of weeks. If reactivation of a remote contextual memory produced a second new memory that underwent systems consolidation anew, then the durations of the first and second retrograde gradients should be the same, because they represent systems consolidation of new

traces. Contrary to this prediction, the second retrograde gradient is < 2 days, whereas the first is in the order of weeks. Thus, the new trace interpretation of reconsolidation does not explain the data.

The last variant of the new learning interpretation is that new learning is always occurring and triggering the entire memory (not just the new component) to undergo consolidation. Because it is impossible to ever have two experiences that are exactly the same, this interpretation is not testable. In addition, acceptance of this position would require rejection of the traditional consolidation theory, which posits that only new information acquired during a session, and not the entire memory, is in a labile state. Last, given that one of the posited functions of reconsolidation is to update memories, the position is easily incorporated into models of reconsolidation.

A note from the past

It has been widely questioned whether reconsolidation occurs in humans, following a study demonstrating that ECS impairs new but not old reactivated memories in humans [28]. However, it should be noted that there are several positive findings of reconsolidation in humans [76,77]. The hypothesis proposed and experimental design used by Rubin were based completely on the findings of Lewis' original reconsolidation experiment. Rubin reasoned that if individuals were forced to focus on the subject of their psychopathologies, this would return the imagery and pathology to an active, labile state that should be sensitive to disruption.

Individuals suffering from obsessive–compulsive disorder (OCD) or hallucinations were given ECS after being prompted to act out their desires or after their hallucination had begun. All 28 patients treated in this way improved dramatically for periods ranging from 3 months to the time of publication of the manuscript, 10 years later. One relapsed, but was treated once using the same approach and recovered. Crucial, however, was the fact that many of the subjects had previously received between 5 and 28 ECS sessions, while anaesthetized, with little benefit. This latter result is analogous to the non-reactivated condition used to test reconsolidation [77].

In a case study, one 30-year-old woman with OCD received 22 ECS treatments in 1 year while 'anaesthetized', but became worse. She was made to act out her compulsion of killing her mother with a butcher's knife and was then administered a single session of ECS while still awake. 'The next day, greatly improved, she went home and spoke kindly to her mother for the first time in years. She asked her mother "Do you love me?" and then kissed her. When the author asked if she still felt like stabbing her mother, she laughed and said, "Oh, she doesn't deserve anything like that"' [76]. She returned home and to work, and remained free of symptoms for the 2 years up to the publication of the study. Thus, the finding that reactivated psychopathologies return to an ECS-sensitive state, when the same treatment is ineffective if given when the individual is anaesthetized, are consistent with reconsolidation occurring in humans.

What we have learned and where we are going

Data from a diverse array of species, a variety of paradigms and different molecular technologies have demonstrated that reconsolidation occurs in multiple brain systems and is qualitatively strikingly similar to consolidation. Already implicated in the reconsolidation process are the usual suspects such as NMDA receptors, CREB, new protein synthesis, *Fos* and *zif286*. It is clear that reconsolidation has not been universally found and that it is still too early to understand which critical variables or systems will dictate when reconsolidation will and will not occur. If the reported negative effects are real, and not due to parametric issues, then we need to use them to build a psychological–functional map of the boundary conditions for this phenomenon. Once we have such a map, we will be in a powerful position to understand, in a deeper sense, the evolutionary advantages that neural systems derive from reconsolidation and why certain types of information undergo reconsolidation, whereas other types do not. The next few years will be extremely exciting as more data from behavioural, physiological and molecular levels of analysis are brought to bear on this exciting issue.

Reconsolidation is poised to reconcile a historical dichotomy between levels of analysis that has existed in memory research for the past 70 years. There can be no doubt at this point that memories are fundamentally dynamic processes, as first explicitly demonstrated by Bartlett [78]. They are not snapshots of events that are passively read out but, rather, are constructive in nature and always changing [79–81]. It is therefore strange that, although memory is dynamic and changing, the dominant memory model proposed to describe it emphasizes fixation. The two views are diametrically opposed. Consolidation theory served scientists exceptionally well in maintaining the idea that we should look for two qualitatively different memory states [9]. Models now exist across levels of analysis to describe the processes engaged during memory storage [10]. Given that consolidation theory ends at memory storage, then it has taken us as far as it can. To move forward to the next level, a conceptual shift from the 'fixed' to the 'dynamic' is required. Reconsolidation, which has been shown to occur in species ranging from slugs to humans, is a mechanism that naturally endows neural systems with dynamic properties and can, thus, bridge the conceptual gulf between current fixed neurobiological models of memory and its dynamic nature. In the same way as consolidation theory was the central axis along which scientists descended through levels of analysis to describe the mechanisms that mediate memory fixation [9], reconsolidation can act as the axis for the next generation of scientists to ascend through the levels of analysis to reconnect with the dynamic properties of the phenomenon we are trying to explain.

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References

1 Ebbinghaus, M. (1885) *Über das Gedächtnis*, p. 1, K. Buehler

2 Müller, G.E. and Pilzecker, A. (1900) Experimentelle beitrage zur lehre vom gedachtnis. *Z. Psychol.* Suppl. 1

3 Ribot, T. (1881) *Les Maladies de la Memoire*, Appleton-Century-Crofts

4 Glickman, S. (1961) Perseverative neural processes and consolidation of the memory trace. *Psychol. Bull.* 58, 218–233

5 McGaugh, J.L. (1966) Time-dependent processes in memory storage. *Science* 153, 1351–1358

6 Hebb, D.O. (1949) *The Organization of Behavior*, Wiley

7 Duncan, C.P. (1949) The retroactive effect of electroconvulsive shock. *J. Comp. Physiol. Psychol.* 42, 32–44

8 Dudai, Y. and Morris, R. (2000) To consolidate or not to consolidate: what are the questions. In *Brain, Perception, memory. Advances in Cognitive Sciences* (Bolhius, J., ed.), pp. 149–162, Oxford University Press

9 McGaugh, J.L. (2000) Memory – a century of consolidation. *Science* 287, 248–251

10 Kandel, E.R. (2001) The molecular biology of memory storage: a dialogue between genes and synapses. *Science* 294, 1030–1038

11 Goelet, P. *et al.* (1986) The long and short of long-term memory – a molecular framework. *Nature* 322, 419–422

12 Flexner, L.B. *et al.* (1965) Memory and cerebral protein synthesis in mice as affected by graded amounts of puromycin. *Exp. Neurol.* 13, 264–272

13 Davis, H.P. and Squire, L.R. (1984) Protein synthesis and memory. A review. *Psychol. Bull.* 96, 518–559

14 Bourtchouladze, R. *et al.* (1994) Deficient long-term memory in mice with a targeted mutation of the cAMP-responsive element-binding protein. *Cell* 79, 59–68

15 Yin, J.C. *et al.* (1994) Induction of a dominant negative CREB transgene specifically blocks long-term memory in *Drosophila*. *Cell* 79, 49–58

16 Misanin, J.R. *et al.* (1968) Retrograde amnesia produced by electroconvulsive shock after reactivation of a consolidated memory trace. *Science* 160, 203–204

17 Spear, N. (1973) Retrieval of memory in animals. *Psychol. Rev.* 80, 163–194

18 Przybyslawski, J. and Sara, S.J. (1997) Reconsolidation of memory after its reactivation. *Behav. Brain Res.* 84, 241–246

19 Nader, K. *et al.* (2000) Fear memories require protein synthesis in the amygdala for reconsolidation after retrieval. *Nature* 406, 722–726

20 DeVietti, T.L. and Holliday, J.H. (1972) Retrograde amnesia produced by electroconvulsive shock after reactivation of a consolidated memory trace: a replication. *Psychon. Sci.* 29, 137–138

21 DeVietti, T.L. and Kirkpatrick, B.R. (1976) The amnesia gradient: inadequate as evidence for a memory consolidation process. *Science* 194, 438–440

22 Sekiguchi, T. *et al.* (1997) Reactivation-dependent changes in memory states in the terrestrial slug Limax flavus. *Learn. Mem.* 4, 356–364

23 Sara, S.J. (2000) Retrieval and reconsolidation: toward a neurobiology of remembering. *Learn. Mem.* 7, 73–84

24 Bucherelli, C. and Tassoni, G. (1992) Engram activation reinstates the susceptibility of consolidated memory traces to retrograde amnesia by functional blockade of parabrachial nuclei. *Behav. Brain Res.* 51, 61–65

25 Land, C. *et al.* (2000) Anomalous properties of hippocampal lesion-induced retrograde amnesia. *Psychobiology* 28, 476–485

26 Gold, P.E. and King, R.A. (1972) Amnesia: tests of the effect of delayed footshock-electroconvulsive shock pairings. *Physiol. Behav.* 8, 797–800

27 Dawson, R.G. and McGaugh, J.L. (1969) Electroconvulsive shock effects on a reactivated memory trace: further examination. *Science* 166, 525–527

28 Squire, L.R. *et al.* (1976) Reactivation of recent or remote memory before electroconvulsive therapy does not produce retrograde amnesia. *Behav. Biol.* 18, 335–343

29 LeDoux, J.E. (2000) Emotion circuits in the brain. *Annu. Rev. Neurosci.* 23, 155–184

30 Davis, M. (1997) Neurobiology of fear responses: the role of the amygdala. *J. Neuropsychiatry Clin. Neurosci.* 9, 382–402

31 Maren, S. and Fanselow, M.S. (1996) The amygdala and fear conditioning: has the nut been cracked? *Neuron* 16, 237–240

32 Schafe, G.E. and LeDoux, J.E. (2000) Memory consolidation of auditory pavlovian fear conditioning requires protein synthesis and protein kinase A in the amygdala. *J. Neurosci.* 20, RC96

33 Lewis, D.J. (1979) Psychobiology of active and inactive memory. *Psychol. Bull.* 86, 1054–1083

34 Anokhin, K.V. *et al.* (2002) Reminder effects – reconsolidation or retrieval deficit? Pharmacological dissection with protein synthesis inhibitors following reminder for a passive-avoidance task in young chicks. *Eur. J. Neurosci.* 15, 1759–1765

35 Pedreira, M.E. *et al.* (2002) Reactivation and reconsolidation of long-term memory in the crab *Chasmagnathus*: protein synthesis requirement and mediation by NMDA-type glutamatergic receptors. *J. Neurosci.* 22, 8305–8311

36 Sara, S.J. (2000) Strengthening the shaky trace through retrieval. *Nat. Rev. Neurosci.* 1, 212–213

37 Radyushkin, K.A. and Anokhin, K.V. (1999) Recovery of memory in chicks after disruption during learning: the reversibility of amnesia induced by protein synthesis inhibitors. *Neurosci. Behav. Physiol.* 29, 31–36

38 Gordon, W.C. and Spear, N.E. (1973) The effects of strychnine on recently acquired and reactivated passive avoidance memories. *Physiol. Behav.* 10, 1071–1075

39 Gordon, W.C. (1977) Susceptibility of a reactivated memory to the effects of strychnine: a time-dependent phenomenon. *Physiol. Behav.* 18, 95–99

40 Gordon, W.C. and Feldman, D.T. (1978) Reactivation-induced interference in a short-term retention paradigm. *Learn. Motiv.* 9, 164–178

41 Gordon, W.C. (1977) Similarities of recently acquired and reactivated memories in interference. *Am. J. Psychol.* 90, 231–242

42 Nader, K. *et al.* (2000) The labile nature of consolidation theory. *Nat. Rev. Neurosci.* 1, 216–219

43 Bailey, C.H. and Kandel, E.R. (1993) Structural changes accompanying memory storage. *Annu. Rev. Physiol.* 55, 397–426

44 Lewis, D.J. (1969) Sources of experimental amnesia. *Psychol. Rev.* 76, 461–472

45 Lattal, K.M. and Abel, T. (2001) Different requirements for protein synthesis in acquisition and extinction of spatial preferences and context-evoked fear. *J. Neurosci.* 21, 5773–5780

46 Taubenfeld, S.M. *et al.* (2001) The consolidation of new but not reactivated memory requires hippocampal C/EBPbeta. *Nat. Neurosci.* 4, 813–818

47 Tronel, S. and Sara, S.J. (2002) Mapping of olfactory memory circuits: region-specific c-fos activation after odor-reward associative learning or after its retrieval. *Learn. Mem.* 9, 105–111

48 Berman, D.E. and Dudai, Y. (2001) Memory extinction, learning anew, and learning the new: dissociations in the molecular machinery of learning in cortex. *Science* 291, 2417–2419

49 Kida, S. *et al.* (2002) CREB required for the stability of new and reactivated fear memories. *Nat. Neurosci.* 5, 348–355

50 Guzowski, J.F. (2002) Insights into immediate-early gene function in hippocampal memory consolidation using antisense oligonucleotide and fluorescent imaging approaches. *Hippocampus* 12, 86–104

51 Hall, J. *et al.* (2001) Cellular imaging of zif268 expression in the hippocampus and amygdala during contextual and cued fear memory 51retrieval: selective activation of hippocampal CA1 neurons during the recall of contextual memories. *J. Neurosci.* 21, 2186–2193

52 Hall, J. *et al.* (2001) Fear memory retrieval induces CREB phosphorylation and Fos expression within the amygdala. *Eur. J. Neurosci.* 13, 1453–1458

53 Debiec, J. *et al.* (2002) Cellular and systems reconsolidation in the hippocampus. *Neuron* 36, 527–538

54 Falls, W.A. *et al.* (1992) Extinction of fear-potentiated startle: blockade by infusion of an NMDA antagonist into the amygdala. *J. Neurosci.* 12, 854–863

55 Lu, K.T. *et al.* (2001) Mitogen-activated protein kinase cascade in the

basolateral nucleus of amygdala is involved in extinction of fear-potentiated startle. *J. Neurosci.* 21, RC162

56 Vianna, M.R. *et al.* (2001) Retrieval of memory for fear-motivated training initiates extinction requiring protein synthesis in the rat hippocampus. *Proc. Natl. Acad. Sci. U. S. A.* 98, 12251–12254

57 Gordon, W.C. (1981) Mechanisms of cue-induced retention enhancements. In *Information Processing in Animals: Memory Mechanisms* (Spear, N.E. and Kleim, J.A., eds) pp. 319–339, Erlbaum

58 Scoville, W.B. and Milner, B. (1957) Loss of recent memory after bilateral hippocampal lesions. *J. Neurol. Psychiatr.* 20, 11–21

59 Anagnostaras, S.G. *et al.* (2001) Hippocampus and contextual fear conditioning: recent controversies and advances. *Hippocampus* 11, 8–17

60 Eichenbaum, H. *et al.* (1994) Two functional components of the hippocampal memory system. *Behav. Brain Sci.* 17, 449–518

61 Squire, L.R. and Alvarez, P. (1995) Retrograde amnesia and memory consolidation: a neurobiological perspective. *Curr. Opin. Neurobiol.* 5, 169–177

62 Kim, J.J. and Fanselow, M.S. (1992) Modality-specific retrograde amnesia of fear. *Science* 256, 675–677

63 Anagnostaras, S.G. *et al.* (1999) Temporally graded retrograde amnesia of contextual fear after hippocampal damage in rats: within-subjects examination. *J. Neurosci.* 19, 1106–1114

64 Milekic, M.H. and Alberini, C.M. Temporally graded requirement for protein synthesis following memory reactivation. *Neuron* 36, 521–524

65 Miller, R.R. and Matzel, L.D. (2000) Memory involves far more than 'consolidation'. *Nat. Rev. Neurosci.* 1, 214–216

66 Gordon, W.C. and Spear, N.E. (1973) Effect of reactivation of a previously acquired memory on the interaction between memories in the rat. *J. Exp. Psychol.* 99, 349–355

67 Rodriguez, W.A. *et al.* (1993) Post-reactivation cocaine administration facilitates later acquisition of an avoidance response in rats. *Behav. Brain Res.* 59, 125–129

68 Horne, C.A. *et al.* (1997) Time-dependent effects of fructose on the modulation of a reactivated memory. *Prog. Neuropsychopharmacol. Biol. Psychiatry* 21, 649–658

69 Mactutus, C.F. *et al.* (1979) Retrograde amnesia for old (reactivated) memory: some anomalous characteristics. *Science* 204, 1319–1320

70 Young, A.G. and Galluscio, E.H. (1971) Recovery from ECS-produced amnesia. *Psychon. Sci.* 22, 149–151

71 Serota, R.G. (1971) Acetoxycycloheximide and transient amnesia in the rat. *Proc. Natl. Acad. Sci. U. S. A.* 68, 1249–1250

72 Quartermain, D. and McEwen, B.S. (1970) Temporal characteristics of amnesia induced by protein synthesis inhibitor: determination by shock level. *Nature* 228, 677–678

73 Kohlenberg, R. and Trabasso, T.O.M. (1968) Recovery of a conditioned emotional response after one or two electroconvulsive shocks. *J. Comp. Physiol. Psychol.* 65, 270–273

74 Flexner, L.B. *et al.* (1966) Stages of memory in mice treated with acetoxycycloheximide before or immediately after learning. *Proc. Natl. Acad. Sci. U. S. A.* 56, 730–735

75 Cooper, R.M. and Koppenaal, R.J. (1964) Suppression and recovery of a one-trial avoidance response after a single ECS. *Psychon. Sci.* 1, 303–304

76 Rubin, R.D. *et al.* (1969) New application of ECT. *Advances in Behavior Therapy, 1968* (Rubin, R.D., Franks, C., *et al.* eds), pp. 37–44, Academic Press

77 Rubin, R.D. (1976) Clinical use of retrograde amnesia produced by electroconvulsive shock: a conditioning hypothesis. *Can. Psychiatr. Assoc. J.* 21, 87–90

78 Bartlett, F.C. (1932) *Remembering*, Cambridge University Press

79 Tulving, E. and Thomson, D.M. (1973) Encoding specificity and retrieval processes in episodic memory. *Psychol. Rev.* 80, 359–380

80 Loftus, E.F. and Yuille, J.C. (1984) Departures from reality in human perception and memory. In *Memory Consolidation: Psychobiology of Cognition* (Weingartner, H. and Parker, E.S., eds) pp. 163–184, Lawrence Erlbaum Associates

81 Schacter, D.L. (1999) The seven sins of memory. Insights from psychology and cognitive neuroscience. *Am. Psychol.* 54, 182–203