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Sleep-dependent memory consolidation and reconsolidation

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Abstract

Molecular, cellular, and systems-level processes convert initial, labile memory representations into more permanent ones, available for continued reactivation and recall over extended periods of time. These processes of memory consolidation and reconsolidation are not all-or-none phenomena, but rather a continuing series of biological adjustments that enhance both the efficiency and utility of stored memories over time. In this chapter, we review the role of sleep in supporting these disparate but related processes.

Keywords: Sleep; Memory; Learning; Consolidation; Reconsolidation; REM; Slow-wave sleep; Visual discrimination; Motor sequence learning

1. Introduction

The question of "sleep-dependent memory consolidation" is a complex one. Each term in the phrase – sleep, dependent, memory, and consolidation – begs for clarification. For a start, the term "memory" covers a wide range of memory types, which differ in the kinds of information stored, the brain structures mediating this storage, and, in humans, whether the information is accessible to conscious awareness. There is no clear consensus at this time on how many such memory systems there are, and how they should be defined, either in terms of information content or brain structures involved in their storage [1]. The most widely accepted taxonomy divides human memories first into declarative and non-declarative, based on their accessibility to conscious recall, and then into finer and finer subdivisions of these basic categories (Fig. 1A) [2].

Similarly, the term "memory consolidation" refers to a poorly defined set of processes which take an initial, unstable memory representation and convert it into a form that is both more stable and more effective. At this time, it is unclear how memories are altered after initial encoding, and no consensus as to which of the processes contributing to this alteration should be included under the umbrella of memory consolidation. When the term was first introduced, it referred to as yet unknown processes which, over a period of minutes to hours, made learning resistant to degradation by, for example, electroconvulsive shock [3–5], but this notion of a single, relatively rapid process of memory consolidation has yielded to one including phases of stabilization, enhancement, and integration, extending over hours to years.

More recently, the concept "memory reconsolidation" has resurfaced to describe yet another aspect of post-encoding memory modification [6]. There is now evidence that when previously stabilized memories are reactivated, either by returning an animal to an earlier learning environment or by having humans briefly perform a previously learned task, the memory is

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destabilized and returns to a labile state in which it is again susceptible to destructive interference. Thus, the terms ‘‘consolidated’’ and ‘‘stabilized’’ must take on a more nuanced meaning, reflecting the *relative* consolidation and stabilization of the memory.

Many of the steps in this consolidation cascade occur preferentially or even exclusively during periods of sleep. Researchers are now focusing on identifying those types of memory, and, for each, the individual steps that show strong sleep-dependent activation. However, again, sleep does not refer to a simple unitary phenomenon, instead representing a complex array of brain states that differ in their physiology, chemistry, and phenomenological experiences. Sleep has been broadly divided into rapid eye movement (REM) sleep and non-REM (NREM) sleep, which alternate across the night, in humans in a 90-min cycle (Fig. 1B). NREM sleep is further subdivided into NREM stages 1–4 [7], which appear to differ in their contribution to sleep-dependent memory consolidation [8].

Before describing these systems of memory consolidation in greater detail, we would like to offer an overview of our perspective on memory consolidation and reconsolidation. First, all of these processes occur over time automatically, outside of awareness and without intent. Thus, they are specifically different from changes that result from conscious reminiscing or intentional rehearsal. In this respect, they are no different from molecular cascades triggered by an initial biochemical event, but while molecular cascades are normally restricted to a single cell, the cascade of events characterizing memory consolidation range from intracellular gene inductions to brain-wide, system-level reorganizations of memories representations.

Second, while these processes occur automatically, they are, nevertheless, modulated by other factors. Again, this is not different from what is seen with intracellular molecular cascades, but the greatly extended time course allows for different forms of modulation. As a result, the multiple components of memory consolidation and reconsolidation form a coherent whole, which functions to optimally integrate initially encoded memories into an organism’s existing informational networks, and which continues to refine and remodel these memories following reactivation, during wake and sleep. In short, memories do not simply form in the brain; they evolve.

For the purposes of this review, we use the term memory consolidation to refer to all post-encoding memory processing that is automatic and which occurs without intent or awareness under the rubric of ‘‘memory consolidation,’’ while those that require either

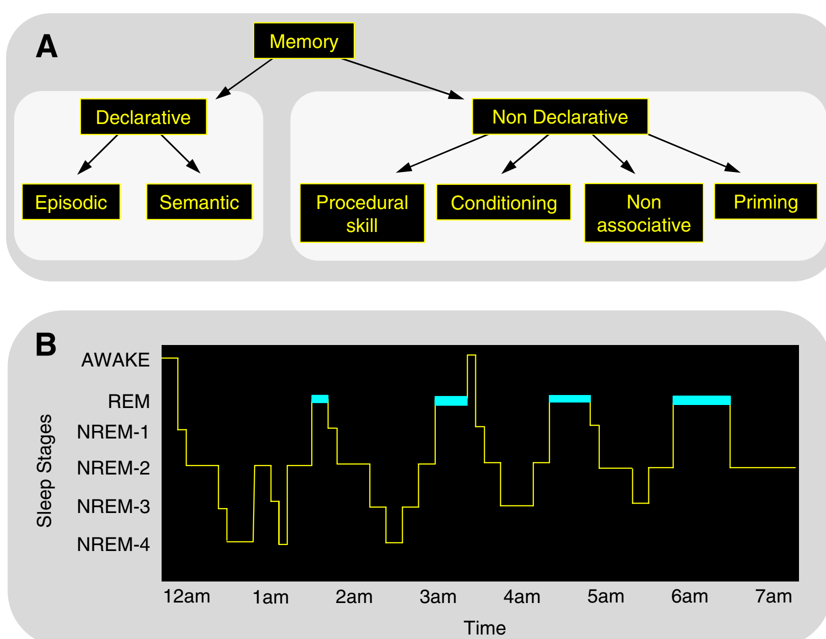

Fig. 1. Forms of memory and stages of sleep. Neither memory (A) nor sleep (B) represents a homogeneous phenomenon. (A) Declarative memory includes consciously accessible memories of fact-based information (i.e., knowing ‘‘what’’), and contains several subcategories, including episodic memory (memory for events in one’s past) and semantic memory (memory for general knowledge) [110]. In contrast, non-declarative memory includes all non-conscious memories, and includes subcategories such as conditioning, implicit memory and procedural memory (i.e., knowing ‘‘how’’). (B) In mammals, sleep is divided into REM and NREM sleep, and in primates and felines, NREM sleep has been divided into sub-stages 1–4, corresponding to increasingly deeper states of sleep [7]. The deepest NREM stages, stages 3 and 4, are collectively referred to as slow wave sleep (SWS), based on a prevalence of low frequency (0.5–4 Hz) cortical oscillations. Dramatic changes in brain electrophysiology, neurochemistry and functional anatomy occur across these sleep stages, making them biologically distinct from the waking brain, and dissociable from one another. For example, SWS is characterized by a diminution in cholinergic activity and REM sleep by a suppression of release of norepinephrine from the locus coeruleus and serotonin from the raphe nucleus. (Reproduced with permission from [8]).