Sleep to Remember

The brain needs sleep before and after learning new things, regardless of the type of memory. Naps can help, but caffeine isn't an effective substitute

Matthew P. Walker

Remember being a student? Faced with a big test the next day, you have to learn something in a hurry—the General Prologue to Chaucer's *Canterbury Tales,* maybe, or two-and-a-half octaves of a difficult scale on the clarinet. After long hours of practice you notice it's the middle of the night. You haven't quite mastered the task. Should you forgo sleep for more practice?

Depending on the stakes, most people would say yes. But based on how our brains work, the answer is probably no. In fact, psychologists have suspected for some time that sleep relates somehow to the development of memory, although the reasons were unclear. Behavioral tests showed that adequate sleep before and after a training session was essential for learning, whether the task was tennis or algebra.

Scientists from many disciplines have confirmed and elaborated those suspicions over the past decade. In view of the collective illumination of much congruent data, most neuroscientists now believe that sleep is integral to learning and memory. However, some subtleties lie beneath this blanket statement: Neither memory nor sleep is simple in terms of structure and function. What's more, the intersections between types of memory and phases of sleep are also governed by sometimes cryptic variables. Despite the inevitable discrepancies that arise in complex fields of study, the preponderance of behavioral, neuroanatomical, physiological, cellular and molecular evidence supports the idea that periods of the sleep cycle actively orchestrate changes in certain categories of memory.

Sleep, Memory

The electrical signature of a sleeping brain is different from that of an awake brain, but equally big differences exist during the various phases of sleep. *Rapid eye movement* (REM) sleep, associated with the most vivid dreaming, produces brain waves (measured with an electroencephalograph) that most resemble the ones found in awake subjects. Across the night, REM sleep alternates with its antithesis, non-REM (NREM) sleep, about every 90 minutes in humans. In primates (including human beings), NREM sleep has four substages. Psychologists refer to the deepest and most electrically distinctive of these substages, NREM 3 and NREM 4, as *slow-wave sleep* (SWS) because of the characteristic low-frequency, high-amplitude brain waves.

Similar to sleep, memory exists in several forms. The most popular classification scheme is based on the distinction between those memories that you can declare verbally and those that you have to show through performance. Psychologists call these categories *declarative* and *nondeclarative* memory, respectively. The former is fact-based and includes answers to questions like "What is the value of Planck's constant?" and "Where did I put my keys?" The annals of neuropathology, brain imaging and modern computer models agree that declarative memory requires a part of the brain called the hippocampus, which lies within the medial temporal lobe. This little structure is a nexus for filing and retrieving information from the neocortex, and it also seems to bind together different perceptual elements of a single event ("Ah, yes. I put the keys down to nab the last doughnut").

In contrast, nondeclarative memory is the "know how" memory, rather than the "know what" memory, and is manifest as an action or behavior. The category is divided further into *procedural* and *implicit* memory. The former is responsible for movements, habits and skills (such as how to ride a bicycle); the latter encompasses less familiar phenomena such as classical conditioning, habituation and priming (also known as the power of suggestion). These different forms of nondeclarative memory depend on somewhat different brain regions. Although a map of these regions must be overly simplistic, neuroscientists consider the core structures for procedural memory to be the striatum, motor cortex and cerebellum; conditioning engages the cerebellum and, for emotional learning, the amygdala; priming involves the neocortex; and habituation is based on reflex pathways in the spinal cord and brainstem.

Although these categories are conveniently separate on paper, real-life memories are rarely so distinct. For example, learning to speak a language

Figure 1. Sleep is critical to cognitive functions, particularly memory. Even during highly choreographed missions aboard the space shuttle, astronauts are instructed to sleep eight hours per night—a difficult feat given the excitement and weightlessness. Recent studies demonstrate that learning requires physical changes in the brain, at least some of which occur during specific phases of the sleep cycle. Here, Mission Specialist Guion Bluford *(left)* and Commander Richard "Dick" Truly *(right)* doze while floating on the middeck of the Challenger in 1983. (Photograph courtesy of NASA.)

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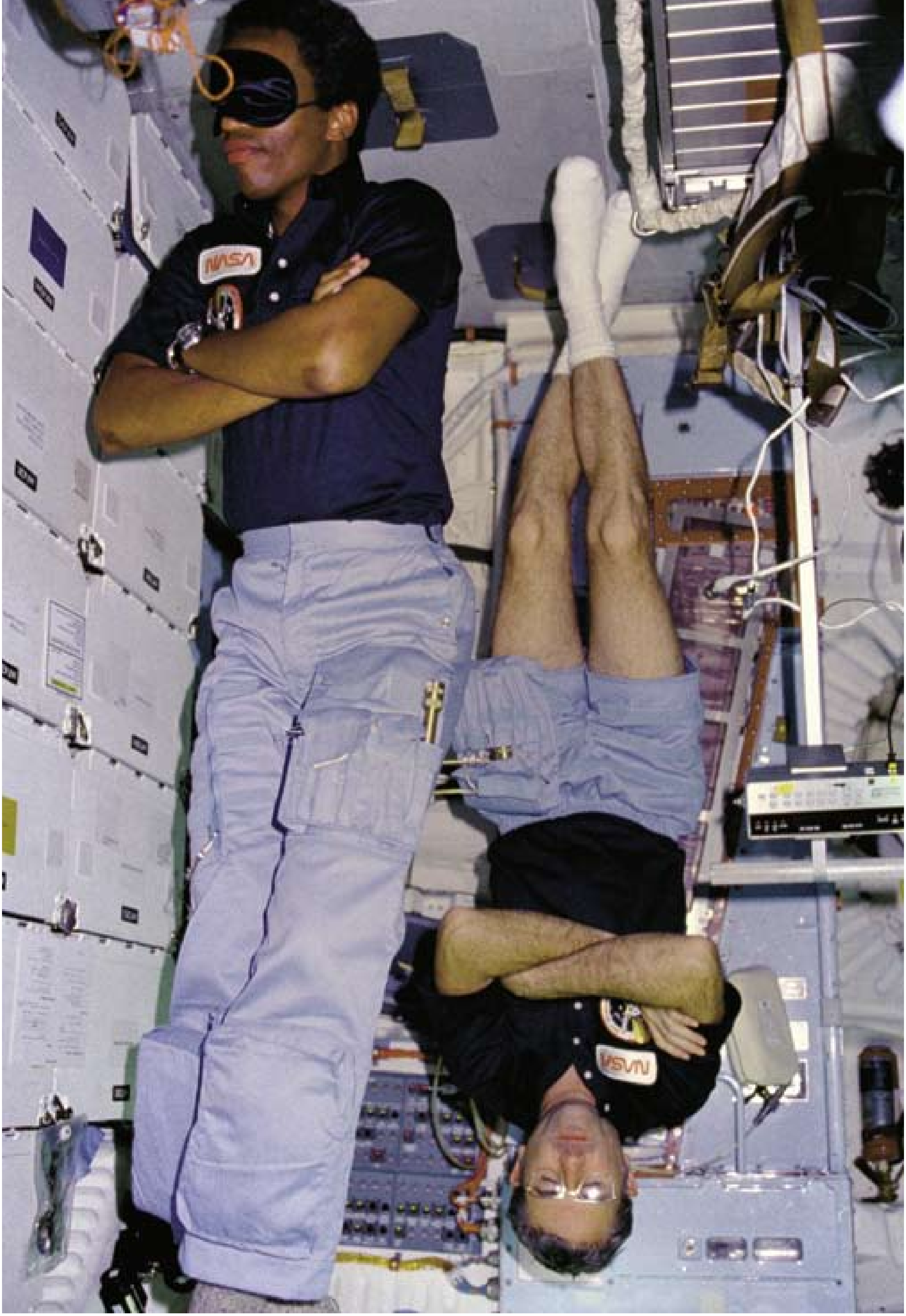
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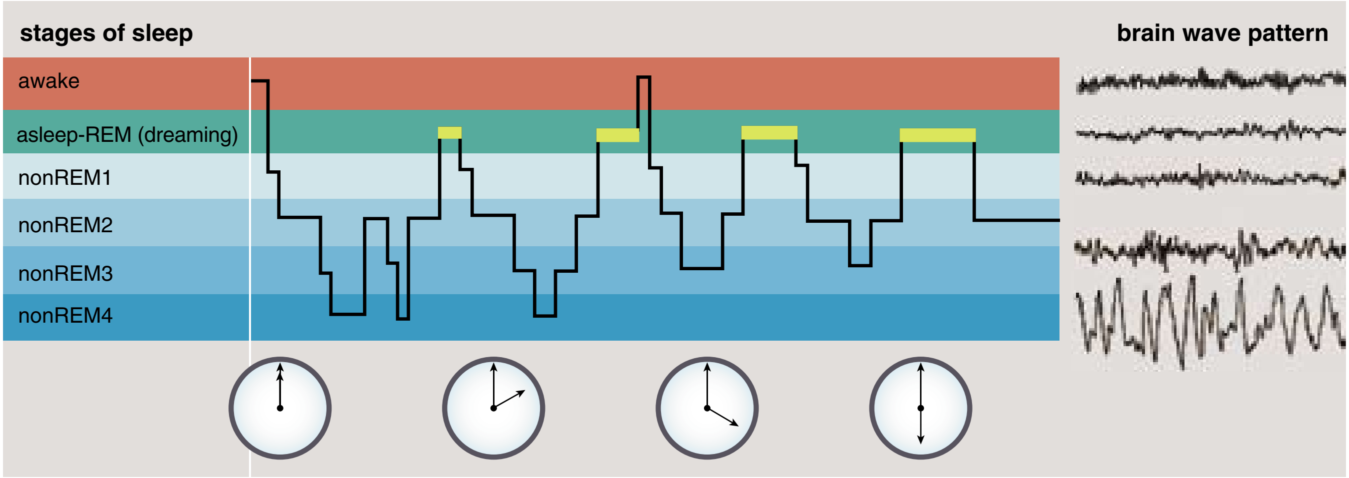

Figure 2. During sleep, a person cycles through periods of electrically distinct brain activity. Rapid eye movement (REM) and non-REM (NREM) sleep alternate about every 90 minutes, although the ratio of NREM to REM sleep shifts as the night progresses (as shown here for a person falling asleep at midnight). NREM stages 3 and 4, which are characterized by high-amplitude, low-frequency waves, predominate during the first half of the night, but stage 2 NREM and REM sleep are more common later.

requires several memory modes, ranging from nondeclarative memory for how to move the mouth and tongue, to memory of grammatical rules and structure (a mix of the conscious and unconscious), to declarative memory for vocabulary.

But regardless of type, all memory appears to go through similar stages on the passage from the first mental glimmer to a permanent record. The steps occur on a continuum, although the exact timing is variable by task, strength of the initial memory, circumstance and individual. Thus, making someone's acquaintance forms an ephemeral representation of that person's name and face within the brain. If that encoded memory is destined for long-term storage, it will go through successive stages to become more stable in a process known as *consolidation*. In classical psychology, a memory is consolidated when, in the absence of mental rehearsal, it becomes sturdy enough to resist disruption from competing new learning, perceptions, thoughts or actions.

Recent findings show that consolidation goes beyond simply stabilizing or fixating memories—it enhances them as well. The two processes seem to be distinct: Although stabilization appears to occur over time regardless of brain state, enhancement occurs primarily, if not exclusively, during sleep. This "offline" effect can restore previously lost memories or produce additional learning, both without the need for further practice. In other words, the enhancement phase of memory consolidation is an active process, not merely one of simple maintenance; the brain continues to learn even though it has stopped practicing.

I've chosen in this article to focus primarily on the influence of sleep on encoding and consolidation, but the later stages of memory processing are also important. In them, new patterns of information are integrated with past experiences and knowledge. At about the same time, memories can be reorganized and moved to new anatomical sites in a process called translocation. For declarative memories, this means that the memory trace is no longer exclusive to the hippocampus, but becomes more distributed through portions of the cortex.

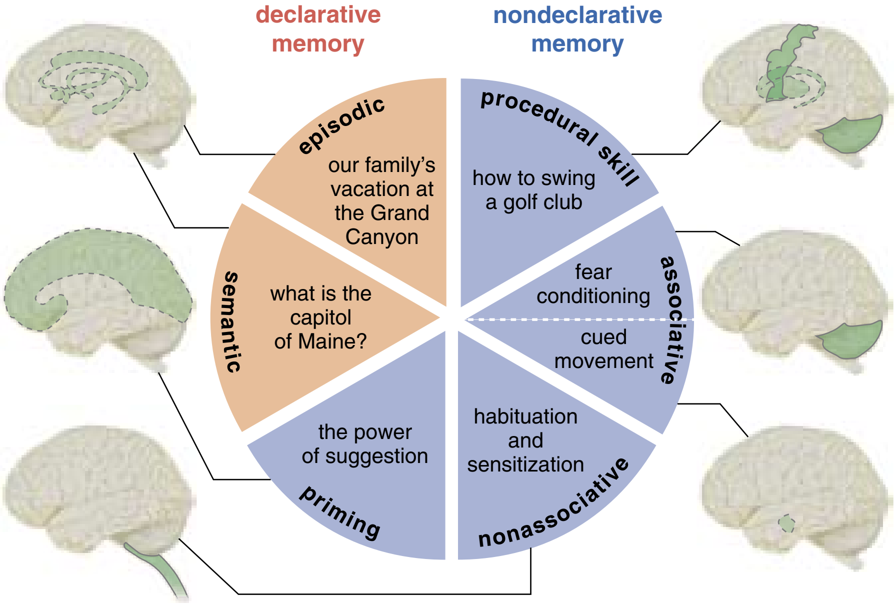

Figure 3. Human memory can be classified several ways. Most schemes distinguish between declarative and nondeclarative memory. The former is consciously accessible and fact-based (knowing *what*), and includes general knowledge (semantic) and autobiographical memory (episodic). In the brain, these categories require the diencephalon and medial temporal lobe, including the hippocampus. Nondeclarative memory is inaccessible to our conscious mind and includes procedural memory for actions, habits and skills (knowing *how*), as well as implicit forms of learning, which depend on various other parts of the brain. For example, learning to swing a golf club requires the striatum, motor cortex and cerebellum; nonassociative learning involves reflex pathways in the spinal cord and elsewhere; priming engages the neocortex; and associative learning requires the amygdala or cerebellum, depending on whether the cued behavior has an emotional or a physical component. (Functional anatomy after Squire and Knowlton 1994.)

Active Memory Enhancement

Many investigators (including myself and my colleagues) have explored the particularly robust link between sleep and procedural learning, the category of memory that includes perceptual and motor skills. In 2002, we published a study detailing the effects of sleep on a finger-tapping task (very similar to learning a piano scale). We told the subjects to press a specific five-button sequence as fast as possible, and then tested them again at 12 and 24 hours after training. The subjects who slept normally during the first 12-hour interval performed the task 20 percent faster and 35 percent more accurately, but an equivalent period awake provided no significant benefit. However, the group that stayed awake for the first 12 hours (and failed to improve during that time) caught up with the other cohort by 24 hours—after they too had a night of sleep. Furthermore, we noted that the amount of overnight improvement correlated with the amount of stage 2 NREM sleep, particularly late in the night. During this period, so-called *sleep spindles*—short, high-frequency bursts of electrical activity—reach peak density. We and other neuroscientists hypothesize that these spindles trigger intracellular events that modify the connections between neurons and may lead to overnight improvements in memory.

When we analyzed the transition-speed profiles for individual subjects (in other words, the time between the first and second button, the second and third button, and so on), we found that the speed of individual key-press transitions within the sequence was unequal. Some transitions seemed easy (fast) and others problematic (slow), as if the subject was parsing the entire sequence into more manageable sub-sequences during the initial training, a phenomenon termed *chunking*. (In a similar fashion, people often chunk a long telephone number into a string of two-or-three-digit numbers for easier memorization). Remarkably, after a night of sleep, the slow, problematic transitions had improved, whereas the fast, easy transitions remained the same. In contrast, people who were trained and retested after eight hours awake did not improve at all. We interpreted these findings to mean that sleep-dependent consolidation unifies or "stitches together" these smaller motor-memory units into one long motor memory program by selectively smoothing out the difficult portions of the sequence. In essence, the sleeping brain appears to work specifically on the most problematic parts of a memory, selectively solving them for the next day. As a consequence, these overnight changes make performance more automated and correspondingly faster.

We further teased apart the process of enhancement by having subjects learn one sequence, then interfering with that motor memory by asking them later to learn a new sequence. In one group, people learned the first sequence, then learned the second 10 minutes later. We retested on each memory after a night of sleep: Only the second memory, learned last, showed significant offline improvements in accuracy. However, when we allowed six hours between learning of the first memory and learning of the second, then tested each after a night of sleep, we saw significant offline improvement for both motor memories, not just the second. These findings suggest several conclusions: First, newly learned motor memories are initially unstable and vulnerable to interference from competing motor memories. Second, the memory gradually becomes more stable and resistant to such competition after several hours awake. Finally, these data demonstrate that following such stabilization across the day, a night of sleep enhances those memories, thereby resulting in improved performance the following day. Thus, it seems that the development of these memories consists of at least three separate stages.

It is important to note that the conclusions we drew from experiments with the motor-memory task are unlikely to be universal. Whereas our task appeared linked to stage 2 NREM, other forms of procedural learning seem to depend on other sleep phases. In 1994

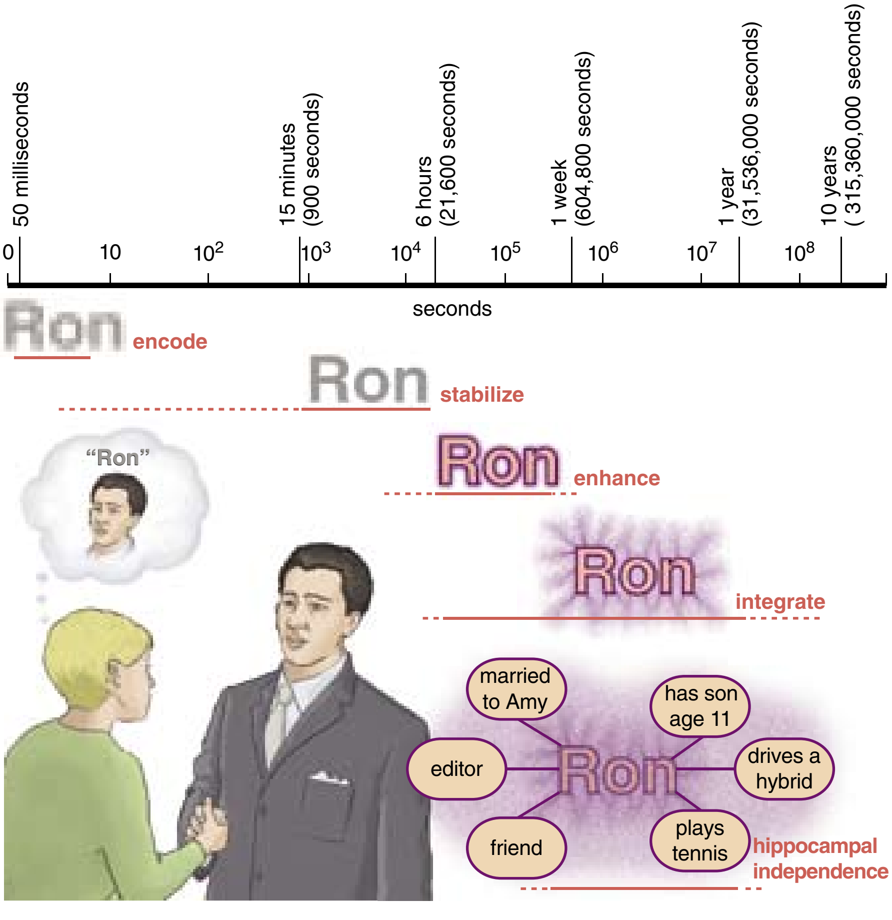

Figure 4. Memory goes through several stages, independent of rehearsal, intent or awareness, on the way from an ephemeral representation to a more permanent state. After its initial encoding, a memory is stabilized and enhanced during the process of consolidation. Many studies show that the latter stage requires sleep. With time, a memory becomes integrated into the fabric of the mind. At some point, a declarative memory no longer depends on the hippocampus but exists in distributed form in the cortex, linked by a web of associations to other, related memories. Solid red lines represent periods of known processing; dotted red lines indicate hypothesized or variable periods of processing. Note the logarithmic time scale.

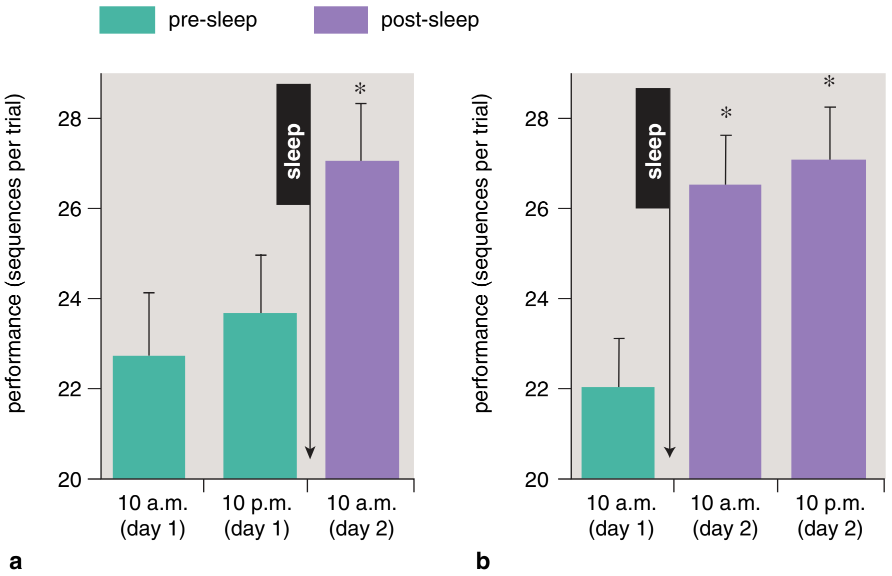

Figure 5. Sleep enhances memory. The author and his colleagues trained subjects on a finger-tapping task (a form of procedural memory) in the morning. All participants improved with practice. Later that day, the author tested half the subjects and found that their performance had not changed *(a, green bar at center)*. However, the other half, which the author tested after normal sleep, improved significantly *(b, purple bar at center)*. A night of sleep subsequently enhanced the memory of the first group *(a, purple bar)*, but the second group did not continue to get better following another 12 hours awake *(b, purple bar at right)*. Asterisks indicate significant differences between initial and later testing; error bars represent standard error.

Avi Karni, Dov Sagi and coworkers at the Weizmann Institute of Science in Rehovot, Israel, demonstrated that subjects who learned to distinguish specific details in a patterned image (a so-called visual-skill task) also improved their performance after sleep (but not after an equivalent period of wakefulness). In that task, the enhancement appeared to depend on REM sleep, since subjects who were deprived of this type of sleep across a night showed no improvements the next day. Subsequently, Robert Stickgold, my frequent collaborator at Harvard, showed that the degree of improvement correlated positively with the time spent in REM sleep and SWS. Steffen Gais and his colleagues in Jan Born's research team at the University of Lübeck in Germany suggest that SWS initiates consolidation, but subsequent REM sleep promotes additional enhancement. Stickgold has since demonstrated that if subjects are deprived of sleep the first night after learning, but then have two recovery nights of sleep before being tested, they still show no improvement on the task. Thus, sleep-dependent memory consolidation instead appears to be an all-or-nothing event: If you don't sleep within the first 24 hours after learning these new memories, they are lost. The prospect is particularly frightening in our 24/7, hurry-up, don't-wait society.

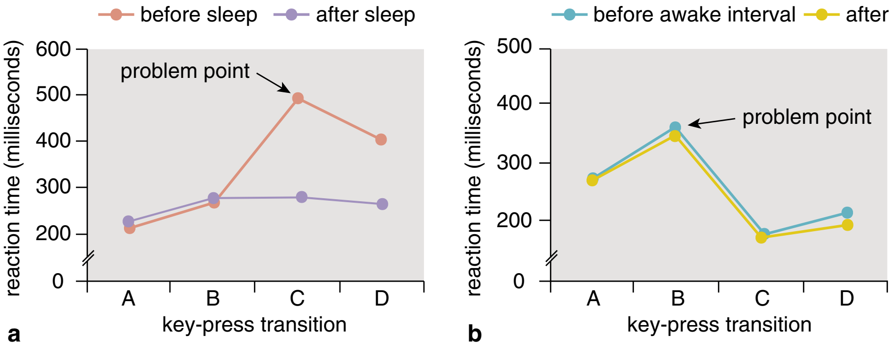

Figure 6. Sleep selectively enhances the most difficult portions of a complex motor task. Subjects learned to tap quickly a sequence of five numbers on a keyboard (for example, 4-1-3-2-4), which contained four unique key-press transitions: *(A)* 4 to 1, *(B)* 1 to 3, *(C)* 3 to 2, and *(D)* 2 to 4. Not all transitions are equally hard: Some are particularly slow, as reflected in greater reaction times, and therefore difficult (labeled as *problem points*). After training, some subjects slept while others remained awake. This figure shows representative performance data from separate individuals, either before and after sleep *(a)* or before and after an equivalent period of wakefulness *(b)*. Following sleep *(a, purple line)*, subjects performed the task more quickly, but the improvement was specific to the slowest, problem-point transition. By contrast, eight hours awake did not improve performance, and the transition profile remained unaltered *(b, yellow line)*.

In Praise of Naps

One twist in this story is that despite the clear importance of nightly sleep for full memory enhancement, short daytime naps yield surprisingly large benefits. We used the finger-tapping task to compare the performance gains of two groups of subjects: One had a 60- to 90-minute midday nap after a morning training session, and the other did not. Later the same day, the group that had napped was significantly (about 16 percent) better at performing these sequences than they had been that morning. In contrast, and as we noted in the earlier study, people who did not nap and remained awake across the day did not improve.

Interestingly, when we tested both of these groups (subjects who did or did not nap) again the next day following a full night of sleep, those subjects who had napped showed only a 7 percent additional increase in performance speed, resulting in a summed total improvement of 23 percent. However, subjects who had not napped were nearly 24 percent faster after sleeping the night. Therefore, by the following day, both groups had improved by approximately the same total amount. These data suggest there may be a limit to how much absolute improvement sleep can trigger across a 24-hour period. Thus, a midday nap changes the time course of when that offline motor memory improvement occurs, but ultimately not the total benefit, as the two groups improved by the same amount after 24 hours.

Daytime naps also appear to improve the learning of a visual skill, although the effects are subtly different. Stickgold, Sara C. Mednick and their colleagues at Harvard have shown that when people rehearse the visual-perceptual task (described earlier) several times across the day, they begin to get worse rather than better. However, if the subjects take a 30- to 60-minute nap among these tests, then the deterioration halts. If they sleep longer—60 to 90 minutes—then performance not only stops declining, but becomes enhanced. Furthermore, these nap-based enhancements didn't occlude the improvement that normally comes with sleep (unlike our results with the motor skill). These results may indicate that certain parts of the brain (those that perform the visual-perceptual task) can fatigue locally, but that short periods of sleep remedy this condition. Further, the data suggest that longer naps, which likely contain SWS and REM sleep, lead to enhancement of memory.

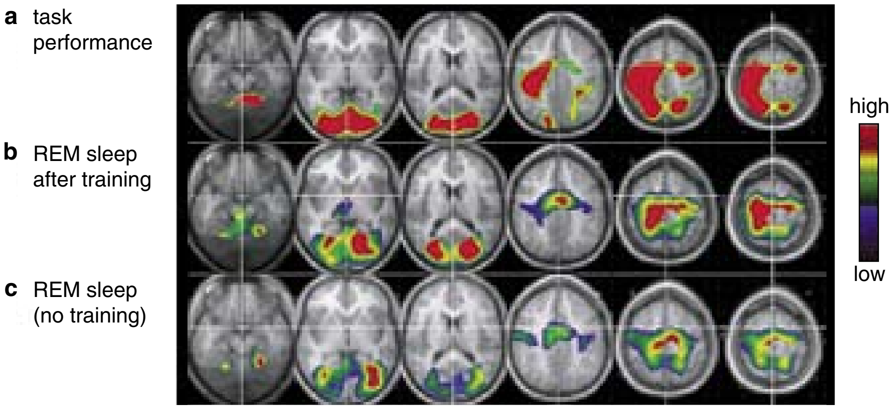

Figure 7. The pattern of brain activity that accompanies learning reappears during the subject's REM sleep that night. These images show brain activity recorded with positron-emission tomography during the performance of a visuomotor task *(a)*, during the REM sleep of subjects who practiced the same task earlier that day *(b)*, and during the REM sleep of untrained subjects *(c)*. In each case, the investigators subtracted baseline activation data from an awake, resting brain. These patterns show that compared to untrained controls, the patterns of brain activity in the REM sleep of trained subjects more closely resembled the activation pattern evoked by the task itself. (From Maquet *et al.* 2000.)

Plastic Brain Changes

To encode new information, the brain must physically change. Neuroscientists call the propensity for this kind of change *plasticity*, and it can operate at the level of individual synapses and cells, between different circuits and even across different brain regions. If, as the behavioral results show, sleep enhances new learning, and if learning requires plasticity, then the consequence of sleep for people who've just formed new memories should include physical changes to the structure of the brain.

Of course, it's devilishly tricky to observe the precise changes that accompany memory formation in the human brain, even when we know where to look. The best noninvasive tools to examine changing patterns of brain activity are positron-emission tomography (PET) and functional magnetic resonance imaging (fMRI). Both techniques measure the metabolic activity of specific brain regions in real time. In the past few years, several research teams, including my own, have used these neuroimaging techniques to observe physical, learning-specific changes in the sleeping brain. These results reinforce the ideas that memory enhancement depends on sleep, and that sleep reshapes memories within out brains.

In 2000, Pierre Maquet from the University of Liege, Belgium, collaborated with scientists at University College London to conduct a study that used PET to see if the sleeping brain subsequently "replays" the same pattern of activity that occurred when a task was originally learned during the day. Indeed, by capturing PET snapshots of subjects' brain activity while they trained on a motor task during the day and then performing scans that night, Maquet did see the reemergence of the motor-learning pattern during REM sleep. This signature REM replay did not appear in untrained subjects. Furthermore, those individuals who learned more during the daytime exhibited more replay during REM sleep. This last detail suggests that the process of learning itself (rather than simply performing the task) dictates the altered physiology during sleep. The more the brain learns, the more it demands from sleep at night.

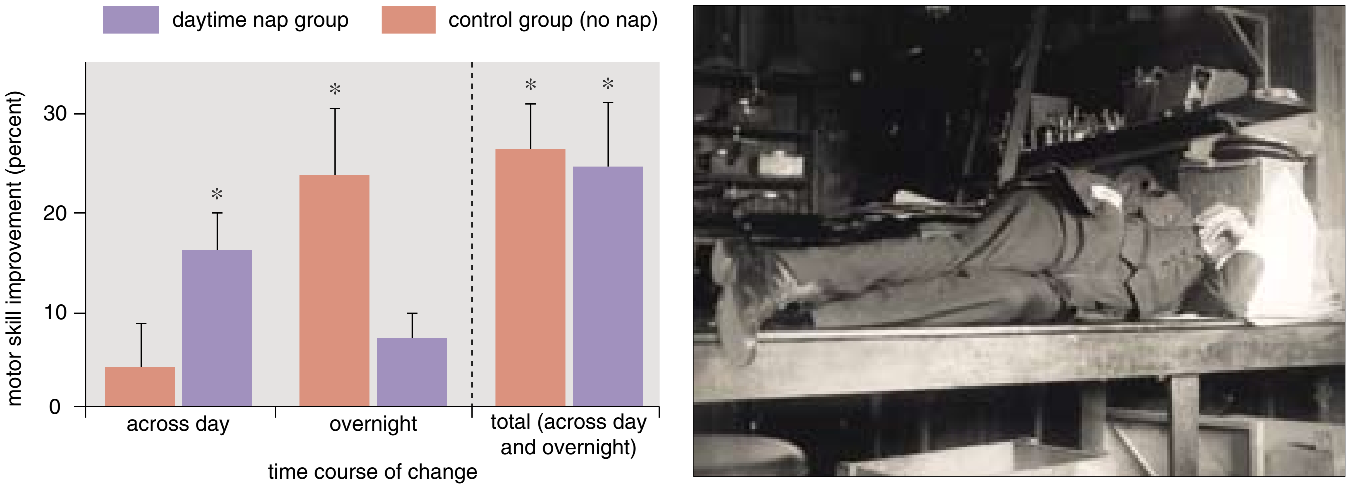

Figure 8. Daytime naps can fill much the same role in memory enhancement as a full night's sleep, although adding a nap to a night's sleep doesn't offer any greater benefit than a night of sleep alone. In this experiment, subjects practiced a motor skill task in the morning and either napped (60 to 90 minutes) at midday or remained awake until evening. When retested later the same day, subjects who had napped *(purple)* were significantly faster (16 percent), but the performance of controls *(red)* was unchanged. After a full night of sleep, the performance speed of subjects in the nap group only increased by an additional 7 percent, but the control group sped up by 24 percent. Therefore, within 24 hours, both groups averaged the same total amount of delayed learning. Several famously creative thinkers throughout history have been dedicated nappers, including Leonardo DaVinci, Salvador Dali, Buckminster Fuller and Thomas Edison (shown here asleep on a laboratory bench in 1911). Asterisks indicate significant performance differences between training and testing. (Photograph courtesy of the National Park Service, Edison Historical Site.)

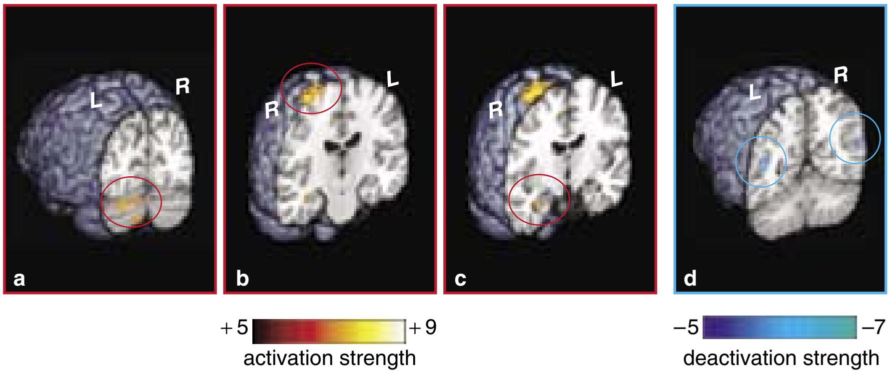

Figure 9. Physical changes in the brain accompany sleep-dependent learning. The author used functional magnetic-resonance imaging to compare patterns of brain activity between subjects who had either slept or remained awake after training on a test of motor-skill memory. Following sleep, the left cerebellum *(a)*, the right primary motor cortex *(b)* and the right hippocampus *(c)* were more active. Several regions also showed *less* activity post-sleep, including the left and right parietal lobes *(d)* and other areas responsible for emotion and motivation *(not shown)*.

My laboratory used a different experimental design to examine sleep-dependent plasticity by comparing patterns of brain activation during memory recall, either after a night of sleep or following the same period of wakefulness. Our hypothesis was that if memory had improved the next day, then these performance enhancements must be accompanied by specific changes within the brain and would be evident from the pattern of "where" the memory was being recalled after sleep, as shown in the MRI activation images. Our quarry: sleep-dependent restructuring of the neural representation of memory.

We again used the finger-tapping task, in which two groups are trained and then both are tested 12 hours later. One of them sleeps through the night, and the other remains awake across the day. During the testing phase, we examined brain activity with fMRI. After controlling for individual differences and circadian fluctuations in metabolism, we identified several regions that differed between groups. The sleepers' brains showed more intense activity and a larger active area in the right primary motor cortex and left cerebellum, changes consistent with improving the accuracy and speed of movement. The medial prefrontal lobe and hippocampus were also more active, consistent with the fact that these brain regions can help to order the sequence of movements.

Some areas of the sleepers' brains were less active, including the left and right parietal cortices and the extended limbic system. The former could reflect a reduced need for conscious monitoring as a result of improved task automation; the latter could indicate a lessened emotional burden of the task. Taken together, these data showed that sleep-dependent motor learning coincided with large-scale restructuring of the memory representation within the brain overnight. We think these changes enable subjects to return the next day and perform the task faster, more accurately and more automatically following sleep.

Memory Modifiers

Although not all studies of human behavior support the link between declarative learning and sleep, many do. For example, some studies that used a verbal memory task reported no change in the architecture of the sleeping brain after training, but others found the opposite: significantly more REM sleep among subjects who had intensive training in a foreign-language earlier that day. In the latter experiment, the more an individual learned, the greater her increase in REM sleep (a result similar to Maquet's study of the motor-learning task). Still, the findings are not in perfect agreement (like many in science), and some open questions remain, including the degree of sleep alteration after training on declarative tasks and the degree of learning impairment that follows selective sleep deprivation.

Recent papers by Born and his colleagues show that subjects who learned certain word pairs performed better after early sleep—the part of the night largely devoted to SWS—and their brainwaves showed more frequent sleep spindles during this period than did those of controls. However, earlier studies with similar tasks had reported no connection to sleep. The discrepancy may reflect subtle details of how memory works. Whereas previous experiments used unrelated words, such as dog–leaf, Born used related pairs, such as dog–bone. The former task required subjects to form and retain completely novel associations (dog–leaf), but Born's task called for the strengthening or tagging of well-formed associations (dog–bone) for subsequent recall. Thus, it's possible that sleep is not an absolute requirement for the consolidation of declarative memory, but it could be necessary for specific tasks, such as those that play on semantic associations.

In addition, emotion can affect declarative memory, and my colleagues and I recently showed that sleep also enhances emotionally charged declarative memories more than neutral ones. We first presented to subjects a mixture of emotionally evocative and neutral pictures. Half of the group remained awake for 12 hours, half slept. At the end of this period, we tested the subjects on whether they recalled ever seeing the images. Generally, people who had slept scored better across the board. However, the breakdown by group and image type was remarkable: Among the sleepers, recognition of emotional images improved by 42 percent relative to the awake group. Without sleep, the subjects' recall of emotional scenes was not significantly different from that of neutral images. These data indicate that sleep, rather than time *per se,* selectively helps to consolidate this form of emotional memory. This type of consolidation may be related to REM sleep late in the night: The brain structures that light up at that time, together with the neurochemicals released, are the same ones that support emotional memories.

Taken together, these and other studies suggest that sleep plays an important but nuanced role in conscious learning. Although the contribution of REM sleep to simple, emotion-free declarative tasks is not settled, a substantial body of evidence indicates that SWS and REM sleep contribute (respectively) to the consolidation of complex and emotionally salient declarative memories—particularly those memories that link to networks of preexisting associations.

Caffeine Is No Substitute

So far, I've discussed the need of sleep after learning for memory consolidation. But what about sleep *before* learning? Not surprisingly, a sleepless night also hampers the process of encoding novel information. For example, being awake

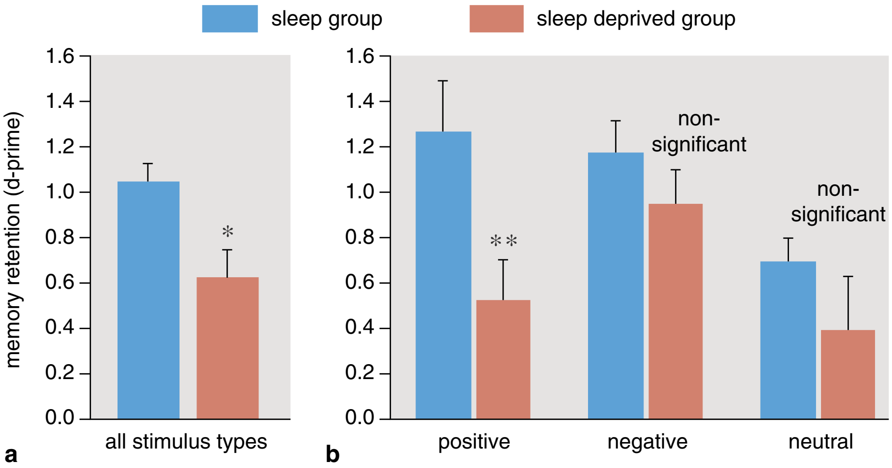

Figure 10. Sleep deprivation exerts variable consequences on declarative memory depending on the emotional significance of the memory. The author found that on average, 36 hours without sleep resulted in a 40 percent decline in the ability to form new memories *(a)*. However, when he segregated the data according to the emotional tenor of each item in the test, he found that the deficit was most pronounced for positive and, to a lesser extent, neutral associations; recall of those memories with a negative association were impaired the least as a result of sleep deprivation *(b)*. Asterisk indicates statistical significance ($p \leq 0.05$); double asterisk indicates high significance ($p \leq 0.01$).

for 36 hours robs people of much of their ability to perform a test of "temporal" memory (remembering when things occurred) and, interestingly, cripples their insight into how well they actually performed the task, according to a study by Yvonne Harrison and James A. Horne at Loughborough University in the United Kingdom. This bodes ill for the success of people who need to acquire and analyze new information while sleep deprived, such as physicians or soldiers. They may think that they're doing just fine on little sleep, but because their ability to judge is compromised, they are more likely to be wrong. Harrison and Horne also showed that caffeine, while increasing general alertness, did not mend the performance deficits.

However, not all forms of declarative memory are affected equally by sleep deprivation. My lab recently looked at the influence of emotion on verbal learning in subjects who had slept normally or not at all for 36 hours prior to learning. After we presented pairs of words that had positive (happy, love, sunlight), negative (cancer, grief, jail) or neutral associations, the participants slept as they wished for two nights and then returned; we surprised them at that point with an unexpected test of word recognition.

The data showed that subjects who were sleep-deprived before learning remembered 40 percent less than controls—a striking impairment—but this deficit was not the same in each emotional category. Rested subjects had better recall of positive and negative stimuli than of neutral stimuli, a finding that agrees with the hypothesis that emotion improves learning. By contrast, the sleep-deprived subjects were severely compromised in remembering positive and, to a lesser extent, neutral stimuli (almost a 60 percent decrement for positive associations). Furthermore, negative emotional memories were somewhat more resistant to the effects of sleep deprivation; the groups were not significantly different in their recollection of negative word pairs.

The take-home message from these studies is that sleep before learning is critical for the brain to be able to lay down new memories. Without it, the initial coding of information suffers dramatically, resulting in memories that do not persist in the long term. Furthermore, the impact of inadequate sleep may be different for different types of information, specifically positive forms of learning, meaning it's harder to remember the happy events of the day without a good night's rest.

Dreams Becoming Reality

The publication rate in the field of sleep and memory has doubled in each of the past two decades—a rate that eclipses the growth of research in either sleep or memory alone. These reports, from cellular and molecular studies in animals to behavioral studies in humans, provide converging evidence that pretraining sleep prepares the brain for learning, and posttraining sleep triggers memory consolidation through neural plasticity, leading to enhanced recall the next day.

Two principal questions promise to dominate this field in the future: What is it about sleep—brain chemistry, regional brain activation, electrical oscillations—that triggers changes in individual synapses, cells and circuits? And, what is the role of sleep in postconsolidation processes, such as integrating memories, and even erasing them? Neuroscientists need to work across disciplines to answer these questions, but with the current growth of the field, I expect that important advances will continue to emerge. Treatments for disorders of memory (and perhaps even the enhancement of normal function) may not be a dream of the distant future, but reality in our time.

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