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Forum

Learning During Sleep: A Dream Comes True?

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Can information that is processed during sleep influence awake behavior? Recent research demonstrates that learning during sleep is possible, but that sleep-learning invariably produces memory traces that are consciously inaccessible in the awake state. Thus, sleep-learning can likely exert implicit, but not explicit, influences on awake behavior.

Learning while asleep is an ancient dream of mankind, but research has shown that we cannot consciously remember what happens around us while we slept [1,2]. However, a lack of conscious access does not exclude the possibility that we perceive and store happenings unconsciously while we sleep. Indeed, if sleep were to be associated with a complete shut-down of the brain, our chances of survival would have diminished because nightly acoustic, olfactory, and somesthetic stimulation would not be sensed for immediate awakening nor stored for delayed actions such as choosing another sleeping-place. Permanent environmental monitoring and long-term memory formation, even if unconscious, might bear an evolutionary advantage.

Nevertheless, some experimental evidence suggests that nightly events are neither remembered nor recognized the next day (e.g., [1,2]). Such results are consistent with the fact that, during sleep, the average state of the neurochemical milieu of the brain, as well as its functional connectivity, energy metabolism, synaptic plasticity, and gene expression patterns, are not ideal conditions for long-term memory formation. Nevertheless, some of these conditions wax and wane throughout the sleep period. For example, the 1 Hz rhythm of slow-wave activity that is characteristic of deep **NREM sleep** (see Glossary) consists of **up-phases** that are associated with high neuronal activity, and **down-phases** of neuronal silence. Theoretically, up-phases might be conducive to plastic changes associated with learning.

Of course, some plastic changes in memory systems must occur during sleep because information acquired during wakefulness is subsequently strengthened through neural replay during sleep ([3] for a review on the memory functions of sleep). This process, termed memory consolidation, yields better subsequent awake retrieval accuracy [3]. Hence, memory systems are active during sleep. Indeed, the hippocampus, which supports episodic memory formation, is even more active during slow-wave sleep than during wakefulness. The replay of awake-formed memories during sleep can be experimentally triggered by applying auditory cues related to individual awake-learned items. This procedure yields a better retrieval performance for sleep-cued versus non-cued items [3]. The acoustic cueing of memory replay demonstrates that the sleeping brain is capable of processing sounds. In addition, sleeping humans may even process the meaning of spoken words and sentences [4].

Evidence of sensory and semantic processing during sleep raises the question of whether this processing leads to long-term storage that lasts into wakefulness. Recent electroencephalographic recordings of auditory evoked brain responses during sleep evidenced memory storage [5]. Novel noise patterns that repeated in a stream of random auditory noise evoked a distinct electroencephalographic response suggestive of recognition. Moreover, repeated presentation of noise patterns during sleep facilitated the conscious detection of these noise patterns during subsequent wakefulness, but only if the noises were played during **REM sleep** rather than NREM sleep [5].

Glossary

NREM sleep: non-rapid eye movement (NREM) sleep is the stage that is most directly related to physical and mental recovery. It consists of light (N2) and deep (N3) sleep. N2 is characterized by the presence of sleep spindles (brief high-frequency bursts at 12–16 Hz with a duration of 0.5 to 3 s) and *k*-complexes in the electroencephalogram. N3 is dominated by slow oscillating high-amplitude waves (~0.8) and is therefore often referred to as slow-wave sleep. The amount of time spent in NREM sleep decreases across the night.

REM sleep: the rapid eye movement (REM) sleep stage is associated with vivid dreaming. Rapid intermittent movements of the eyes, low muscle tone, and awake-like electroencephalographic activity characterize REM sleep. The amount of time spent in REM sleep increases across the night.

Up- and down-phases: during N3 sleep, neural activity in the neocortex oscillates between a depolarized state that is accompanied by increased neural activity and excitability (the up-phase), and a hyperpolarized state that is associated with neural silence (down-phase). Each up- and down-phase lasts about 0.5 s and occurs in a highly synchronous manner across the neocortex, thereby inducing slow-wave activity in the scalp electroencephalogram.

Hence, it appears that perceptual learning and long-term storage, which call upon neocortical areas, proceed during REM sleep. Another study of sleep-learning [6] explored the feasibility of tone–odor associative learning over many trials, a form of conditioning called trace conditioning that depends on hippocampal processing. The monitoring of sniff responses demonstrated successful sleep-learning because sleeping individuals started to inhale more shallowly in response to a tone after the tone had been repeatedly presented with an unpleasant odor [6]. This conditioning persisted into wakefulness if tones and odors were presented during NREM rather than REM sleep. Hence, NREM sleep may provide favorable conditions for hippocampus-dependent associative learning. A role for NREM in hippocampus-dependent learning, and for REM in hippocampus-independent learning, parallels the suggested roles of NREM and REM sleep in the consolidation of hippocampus-dependent and -independent awake-formed memories, respectively [7].

A more demanding learning task is rapid vocabulary learning because it requires swift relational encoding of new semantic associations between foreign words and the meaning of their translation words. This type of learning draws on the episodic memory system, which is widely believed to depend on conscious awareness of learning and on hippocampal processing of the learning material. Hence, episodic memory formation by way of the hippocampus during the unconsciousness of deep NREM sleep would challenge traditional notions of memory. A recent experiment on vocabulary learning during sleep generated results in support of unconscious episodic memory formation [8]. Fake foreign words (e.g., 'tofer') were played combined with translation words during the slow-wave portion of NREM sleep. Translation words designated either a large or a small object (e.g., 'house' or 'key'). A memory test applied following waking required participants to guess (because they could not consciously remember) whether each foreign word designated a large or small object. The guessing responses of the participants yielded above-chance accuracy for previously sleep-played foreign words. This means that the sleeping brain had formed and stored long-term semantic associations between foreign words and translation words. However, long-term storage was only successful if the associations were formed during up-phases rather than down-phases of slow oscillations. Up-phase-related association formation yielded a mean retrieval accuracy 10% above the chance level of 50%. Hence, the neuronal activity of up-phases likely provided ample conditions for sleep-learning. Functional magnetic resonance imaging revealed that activation in the hippocampus and language areas was associated with correct awake retrieval of sleep-played associations. This finding suggests that the same brain structures that are known to support rapid vocabulary learning in the awake state also support vocabulary learning during sleep.

Although the above results demonstrate that learning during sleep is possible, they also show that sleep-learning invariably produces memory traces that are consciously inaccessible in the waking state. Following sleep-learning, individuals were unable to consciously recall, report, or even recognize the sleep-played information [1,2,9,10]. Instead, the sleep-learned information exerted implicit influences on awake behavior. Specifically, sleep-learning facilitated the awake detection and classification of sounds or words [5,8], guided breathing [6], facilitated the identification of sleep-heard messages [9,10], and induced a preference for brands that were mentioned during sleep [11]. Although sleep-learning produces unconscious memories and small awake retrieval rates, its implicit influence on awake behavior may sometimes have powerful results: exposure of sleeping smokers to cigarette smoke paired with aversive odors during a single night reduced their subsequent awake cigarette consumption by more than 30% over several days. This olfactory aversive conditioning was successful only when applied during sleep, and unsuccessful when applied during wakefulness [12]. It is conceivable that sleep-acquired information circumvents conscious defense mechanisms and therefore disposes an individual more readily towards behavioral change.

The lack of conscious access to sleep-learned information raises doubts about whether sleep-learning would benefit education. Worse, findings even indicate that learning during NREM sleep can generate suppressive memories, in other words memories that impair the subsequent awake-learning of the same information [5]. For example, processing noise patterns during NREM sleep impaired the subsequent conscious learning of these same noise patterns [5]. Inspired by this finding, we are now exploring whether unconscious vocabulary learning during sleep might inhibit ensuing awake learning of the same vocabulary. If it does, this could mean that we process the same information differently during sleep versus wakefulness, although the same memory system is engaged, and that the two related memories compete because their engrams are not fully overlapping.

The reality of perception and learning during deep sleep indicates that the gating of sensory information at the thalamus is not complete and that the main direction of information flow during sleep from hippocampus to neocortex leaves some inverse neocortical–hippocampal information flow that is able to support sleep-learning ([3] for review). Findings also suggest that NREM-associated global synaptic renormalization leaves room for synaptic potentiation [3]. The synapses actively engaged in memory replay and sleep-learning might escape the renormalization process. Finally, traditional memory theories are challenged by hippocampus-mediated, rapid relational learning during the unconsciousness of deep sleep, whereas processing-based memory models (e.g., [13]) accommodate such learning at all levels of consciousness.

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