Why Is Sleep So Important?

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We spend roughly a third of our life asleep, a state of quiescence associated with a reduced ability to respond to external stimuli. It is this second feature that crucially distinguishes sleep from quiet wake. When we sleep we are "offline", while when we lay on a sofa watching television, for instance, our muscles rest, but our brain remains fully connected with the external world. All animal species carefully studied so far sleep, including fruit flies, honeybees, and octopuses, though we still do not know how much spontaneous activity goes on in their sleeping brains. Furthermore, fruit flies not only sleep many hours a night but, just like mammals and birds, if they are kept awake, their sleep becomes longer and more intense – a process called *sleep homeostasis*. So, sleep seems to serve some essential, universal function, akin to temperature regulation or digestion. What's more, it is a function that requires the brain to work off-line, despite the dangers of being temporarily disconnected from the environment. But what is this function?

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The sleeping brain is almost as active as during wake: neurons fire at comparable rates as in wake, and metabolism is only slightly reduced. Moreover, we all know that every night while we lie asleep, blind, dumb, and almost paralyzed, we are in for a remarkable treat: hours upon hours of free slide shows and movies - a virtual reality made up by your brain that is so powerful it rivals the one in "The Matrix." This is easy to show: have somebody wake you up at random times during the night, whether in REM (REM stands for rapid eye movements) or in non-REM (NREM) sleep and ask what was going through your mind. More often than not, you will find that you were experiencing something: at times mere snapshots and still scenes, at times full-fledged, vivid dreams, especially toward the morning. It is not surprising, then, that unless you wake up immediately, you don't remember anything at all. To the point that, although everybody dreams, many people are convinced they never do. But then, if during sleep the brain does not actually rest, why does it disconnect from the environment, turn on its internal activity, broadcast movies on its private network, but form no new memories?

A good deal of progress has been made recently in understanding why sleep is so important. Recent studies have shown that both acute sleep deprivation (staying awake all night) and chronic sleep restriction (sleeping only a few hours/night for 1-2 weeks) impair many cognitive functions, from vigilance and attention to speech and humor appreciation. We also know that it may take more than one or two days to recover after chronic sleep loss, so oversleeping during the week-end may not be enough, if the accumulated sleep debt is large. There is also strong evidence that sleep need varies significantly among individuals, although why some of us can function well with much less sleep than others remains unclear. Other studies show that a night of sleep benefits the acquisition of new information the next day (new learning *during* sleep, instead, remains largely a dream). Sleep also leads to the consolidation and integration of memories, both declarative memories – those one can recollect consciously, such as lists of words or associations between pictures and places, as well as non-declarative memories such as perceptual and motor skills. These experimental results fit the common observation that after intensive learning, say practicing a piece over and over on the guitar, performance often becomes fluid only after a night of sleep. It is likely that when we learn and repeatedly activate certain brain circuits, many synapses end up strengthening, not only when you play the right notes well, but also when you do it badly, or fumble other notes. The result is that, while by practicing you get better and better on average, your performance remains a bit noisy and variable. After sleep, it is as if the core of what you learned had been preserved, whereas the chaff is eliminated – that is, sleep seems to notch-up the signal-to-noise ratio. Something similar may happen also with declarative memories: in the face of the hundreds of thousands of scenes we encounter in waking life, memory is particularly effective at *gist extraction*, where the details (the noise) may be lost, but the main point of what happened to us (the signal) is preserved. So far, it seems that the memory benefits of sleep, especially for declarative memories, are due primarily to NREM sleep, but in some instances REM sleep or a combination of NREM-REM cycles may also play a role. One should not forget that memories can also consolidate during wake. Moreover, to some extent sleep helps memory consolidation simply because it reduces the interference caused by later memory traces.

But what are the cellular mechanisms by which sleep benefits learning and memory? Many sleep laboratories are currently trying to address this question. There are two general hypotheses, not mutually exclusive. One is that sleep further reinforces the synaptic connections that had been strengthened in wake during learning, leading to *synaptic consolidation*. This idea is supported by studies performed over the past twenty years, first in rodents and then in humans, which show that patterns of neural activity during sleep often resemble those recorded during wake.

For example, when a rat learns to navigate a maze, different hippocampal neurons fire in different places, in specific sequences. Presumably, each sequence is encoded in memory by strengthening the connections between neurons firing one after the other. During subsequent sleep, especially NREM sleep, these sequences are "replayed" above chance (though neither very often nor very faithfully). It is tempting to assume, as many have, that sleep "replay" may consolidate memories by further potentiating the synaptic connections that had been strengthened in wake. There may also be some *system-level consolidation*, based on evidence that over time memories may be shuttled around in the brain. For example, the hippocampus may provide early storage, after which memories are transferred to connected cortical areas, and sleep may help this transfer.

According to the second idea, the so-called synaptic homeostasis hypothesis (SHY) that we have proposed, sleep may be a time not so much for rehearsal, but for *down-selection*. When the brain sleeps, spontaneous neuronal firing activates many circuits in many different combinations, both new memory traces, which may be particularly prone to reactivation, and old networks of associations. But instead of strengthening whatever synapses are activated the most, which would lead to learning things that never happened, the brain could reverse plasticity rules, and promote the activity-dependent weakening of connections. Indeed, an efficient way to do so would be to implement a selectional, competitive process. For example, synapses that are activated strongly and consistently during sleep would be protected and survive mostly unscathed. They may actually consolidate, in the classic sense of becoming more resistant to decay and interference (though they would not become stronger in absolute terms). By contrast, synapses that are comparatively less activated would be depressed (therefore, consolidated synapses would end up stronger in relative terms). This down-selection process would literally ensure the survival of those circuits that are "fittest," either because they were strengthened repeatedly during wake (the signal, such as the right notes on the guitar), or because they are better integrated with previous, older memories (a new word in a known language). Instead, synapses involved in circuits that were only occasionally strengthened during wake (the noise, such as fumbled notes on the guitar), or fit less with old memories (a new word in an unknown language), would be depressed and possibly eliminated. In this way, synaptic down-selection during sleep would increase signal-to-noise ratios and promote memory consolidation, gist extraction, and the integration of new memories with established knowledge, all while making sure that no false new memories are formed.

SHY's rationale stems from the observation that learning, if it is reflected in the strengthening of synapses, does not come for free. Stronger synapses consume more energy. Also, a net strengthening of synapses is a major source of cellular stress, due to the need to synthesize and deliver cellular constituents ranging from mitochondria to synaptic proteins and lipids. Clearly, learning by strengthening synapses cannot go on indefinitely - day after day - and something must be done. That something, says SHY, is the down-selection of synapses down to a baseline level that is sustainable both in terms of energy consumption and cellular stress. Experiments performed in fruit flies, rodents, and humans, all seem to indicate that the strength of connections among neurons increases during wake and decreases during sleep. For example, when fruit flies spend the day in an environment with plenty of opportunity for interactions with other flies (a "fly mall"), by evening time there are almost 70% more synaptic spines – the little protrusion where an incoming axon makes contact with a dendrite – than there were in the morning, and this is true throughout their brain. The next morning the number of spines goes back to baseline, but only if flies are allowed to sleep. In adolescent mice one sees a similar phenomenon: in the cerebral cortex the number of synaptic spines tends to grow during wake and to decrease during sleep, suggesting that sleep may be critical to maintain a balance in synaptic number at a time when massive synaptogenesis and synaptic pruning occur. If this is the case, chronic disruption of sleep during adolescence could impair the refinement of neural circuits, an idea that ongoing studies are testing.

In short, many recent studies have demonstrated that sleep benefits all aspects of neural plasticity. Currently under investigation are the underlying cellular mechanisms, which should explain why these benefits can only be obtained when the brain is off-line.

Further reading

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