A Quantitative, Theoretical Framework for Understanding Mammalian Sleep

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Recommended with a Commentary by Elisha Moses, Weizmann Institute, Israel.

Scaling and power laws are powerful but limited statistical tools, best used to extract rules that govern an otherwise impenetrable system. Savage and West propose to use allometric scaling to yield a quantitative understanding into the enigma of sleep.The approach has its basis in the original work of West, Brown and Enquist, who explained the scaling of metabolic rate with body size in terms of the power law relation between the energy requirements of a body and the branched, hydrodynamic network of pipes that supply those needs [1]. In this paper a large body of data of body size ranging over six decades for mammals is compared to the total time of the day spent sleeping, and a power law relation is obtained.

The authors go on to check the theory that sleep is used to remedy damage caused to cells during the day. Their main assumption is that the damage accumulated in a cell during the waking hours is related to its metabolic rate. If so, then the time needed for repair of the whole body can be shown to scale differently than the amount of time needed to repair only the damage that the brain has sustained. A number of results for REM and non-REM sleep versus waking times are derived from the theoretical balances and the data, with the main one being that the scaling of the sleep/wake ratio is consistent with the idea that sleep is required for repair to the brain, but not for the body.

While this global type of analysis cannot provide a definite solution to the issue of why we sleep, it does highlight this very fundamental question, and points to an interesting idea that has recently been suggested by Tononi and Cirelli [2]. Basically, these researchers suggest that sleep is the price that an organism pays for the luxury of having synaptic connections that are flexible and can vary the connectivity between neurons. It is well known that the type of problems that a neural network can solve and the efficiency of the computation it performs are fixed by its connectivity matrix, and that the process of learning actually involves changes in these synaptic connections. A stimulus such as a picture that we see or a sensation that we feel will cause changes in the connections in our brain, and we want to keep those memories that are important to us. However, since we are constantly bombarded by multiple stimuli that we do not want to memorize, these connections may be saturated by the end of the day. According to Tononi and Cirelli, an overall reduction in synaptic strength and a readjustment of the connections occurs during the phase of sleep called Slow Wave sleep (characterized by oscillatory activity in the range of 0.5 - 4.5 Hz as measured by electroencephalography, or EEG). This allows us to keep only the salient memories, and be ready for another day of sensory bombardment.

Cirelli and Tononi have some supporting evidence for their hypothesis, although it is still far from being proven. First, they were able to show that genes that are related to changes in synaptic structure and the creation of memory (long term potentiation, or LTP) are up-regulated during waking hours, and barely active during sleep. This may also explain why we have trouble remembering much of what we experience during sleep [3]. They were also able to show that slow wave is locally enhanced during sleep in brain areas where learning has occurred during the previous waking cycle [4].

The Tononi group is also offering insight into sleep using other systems. A study of flies has shown that their periods of rest are reminiscent of what we perceive as sleep in mammals, giving a model genetic system in which regulation of genes in the sleep/wake cycle may now be looked into [5]. A different approach uses a strong magnetic pulse (transcranial magnetic stimulation, or TMS) to excite activity in one area of the human brain, and follows with EEG how that activity spreads to the rest of the brain. The disturbance spreads over a much smaller area and over a shorter time during sleep, indicating that connectivity is highly reduced during sleep [6]. This is an intriguing observation, which may eventually tell us something about how the conscious state of waking is produced from an interacting network of many modules in the brain.

References

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