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Research Focus

To sleep, perchance to gain creative insight?

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The development of mathematical insight, the knack for discovering novel solutions to mathematical problems, might be one of the most erudite forms of learning that we can hope to achieve. However, Wagner and his colleague now report that a night of sleep after being exposed to a class of mathematical problems more than doubles the likelihood of discovering just such a novel solution.

The neuroscience community is long past the days when we conceived of the sleeping brain as simply dormant. Indeed, we have just recently celebrated the 50th anniversary of the discovery of REM (rapid eye movement) and non-REM sleep states. Half a century on, we are getting ever closer to unraveling the secrets of the sleeping brain and dreaming mind.

A prominent finding in the field is that sleep, and certain stages of sleep, are particularly important in memory processing. More specifically, sleep has been consistently implicated in the ongoing process of consolidation of certain forms of memory, resulting in delayed learning without the need for further practice or task engagement [1,2]. These findings of sleep-dependent learning are now strongly supported by cellular and molecular evidence of sleep-dependent plasticity across a broad range of phylogeny [3].

Yet memory consolidation is only one of many cognitive virtues possessed by the human brain. Another is creativity – perhaps the most defining of all human mental characteristics. Creativity has enjoyed a variety of definitions and constructs, but central to its meaning is the ability to take existing pieces of information and combine them in novel ways that lead to greater understanding and suggest new behaviors and responses.

Problem solving and sleep

The link between creative problem solving and sleep, especially dreaming, has long been a topic of intense speculation. From the dreams of August Kekulé that led to the conception of a simple structure for benzene [4] and Dmitry Mendeleyev that initiated the creation of the periodic table of elements [5], to the late-night dreaming of Otto Loewi, which inspired the experimental demonstration of neurochemical transmission [6], examples of creativity occurring during sleep are not uncommon.

Quantitative data have demonstrated that problem solving ability, as measured using tests of fluid thinking, is more effective following a 3.5-hr interval containing high proportions of REM sleep than following 3.5 hr of non-rapid eye movement (NREM) sleep or waking [7]. A more recent report has measured performance on a test of cognitive flexibility using anagram word puzzles following REM and NREM awakenings [8]. REM awakenings provided a significant, 32% increase in the number of anagrams solved compared with NREM awakenings. Furthermore, correlations of individual performance profiles suggest that REM sleep could offer a different mode of problem solving compared with waking performance and NREM. Similarly, a study of semantic priming has demonstrated that, in contrast to the situation in waking, performance following REM sleep awakenings shows a greater priming effect by weakly related words than by strong primes, whereas strong priming exceeds weak priming following NREM sleep awakenings [9]. This again indicates the highly associative properties of the brain in REM sleep. Even the study of mental activity (dreaming) during REM sleep has demonstrated that it is not a concrete episodic replay of daytime experiences or concerns but, instead, there is a much more associative process of semantic integration during sleep [10]. Although the concept of such fluid thinking during REM sleep remains controversial [11], these data support the hypothesis that REM sleep dreaming can facilitate more flexible cognitive skills [12], and offer further insights into the hyperassociative and creative processes that have been assigned to the REM-sleep state [6,13].

‘Sleep on it’

However, direct proof that ‘sleeping on a problem’ can result in creative solutions has, until now, been lacking. Wagner and colleagues have recently provided just such evidence [14]. Using a mathematical ‘Number Reduction Task’ [15], they have elegantly demonstrated sleep-dependent creative insight. In the task (see Fig. 1), subjects analyze an 8-digit string of 1’s, 4’s and 9’s, from left to right. They start by determining the appropriate

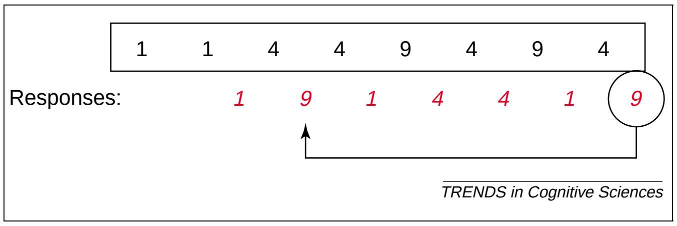

Figure 1. Test sequence used in Wagner *et al.*’s study (top) and correct responses (bottom). See text for details of task. Note that the last three response digits (‘4-1-9’) mirror the second, third and fourth (‘9-1-4’). Thus, the short cut to the solution is to stop at the second digit. Based on data from [14].

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response to the first two digits in the test sequence, and then use that response, together with the next digit in the test sequence, to produce the next response, and so on. In determining each response, they use two rules: (a) *If two digits are the same, respond with that digit*. Thus, starting from the left, the first two digits are both '1', and hence the response (shown below and to the right of the second digit) is also '1'. (b) *If two digits are different, respond with the remaining digit*. Having produced the response '1', this response and the next digit ('4') differ, so the next response is 'the remaining digit', or '9'. This response and the next digit, '4' also differ ('9' and '4') and so the next response is the remaining digit, '1'. The analysis is continued to the end, and the final response, '9' in this case, is the solution to the problem. This final response is then entered as the answer the problem.

At training, subjects completed three blocks of 30 trials each. Then, after periods of either waking or sleep, they returned for an additional 10 blocks, or 300 trials. When retesting occurred after one night of sleep, a subgroup of the subjects solved the task, using this 'standard' procedure, 16.5% faster. By contrast, subjects who did not sleep prior to retesting averaged less than a 6% improvement [14]. The sleep-dependent improvement on this complex cognitive mathematical task is strikingly similar in magnitude to the 15–20% sleep-dependent improvements previously reported on procedural tasks in both the visual [16] and motor [17] domains.

But this is not the beauty of the study. For hidden in the construction of the task is a much simpler way to solve the problem. On every trial, it was arranged that the last three response digits (e.g. '4-1-9' in Figure 1) are the mirror image of the preceding three (i.e. '9-1-4'). As a result, the second response digit always provides the answer to the problem, and an insightful subject can stop after producing the second response digit. Indeed, subjects who discovered this short cut subsequently reduced their average solution time by over 70%. And, to the author's delight, 59% of the subjects who slept for a night between training and retesting discovered the short cut the following morning. By contrast, no more than 25% of subjects in any of four different control groups who did not have a night's sleep had this insight. Thus, 'sleeping on the problem' in this case more than doubled the likelihood of solving it.

Short cut or speed-up?

There are three striking aspects of these findings that should provoke further thought and study. First, subjects were not informed that there was a simpler method of solving the problem. So unlike the classic image of sleeping on a problem, subjects did not go to bed knowing there was a problem to solve. Indeed, the second striking aspect was that few if any subjects awoke with awareness of the short cut, as one often wakes up with the solution to a problem, or a decision about a future action, clear in one's mind. Instead, subjects only discovered and implemented the short cut after an additional 135 trials (on average). And third, perhaps most intriguingly, subjects who benefited from sleeping by subsequently finding the short cut did not show the initial 16% increase in speed seen in the 40% of subjects who failed to discover the short cut, instead showing only a 2% increase. This would suggesting that the sleeping brain can only process the information initially learned one way or the other, either to enhance speed (a simple strengthening of the acquired skill) or to investigate the possibility of alternative solutions (a search for new, creative associations). It is disappointing that the sleep data were not analyzed for differences between these two groups. It would have been exciting if, for example, those who developed insight the next morning showed more REM sleep than those who didn't.

So, with apologies to politicians, the question seems to be, what did the brain know, and when did it know it? Hopefully, this study will encourage a series of investigations that will provide further insights into these sleep-dependent processes.

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