Consolidation of learning

When a student first builds new knowledge and understanding, this new learning is fragile. What happens in the brain for this knowledge to become more permanent, easily accessible, and automatically retrievable?

Author/s:

Paul Howard-Jones
Professor, Graduate School of Education, University of Bristol, United Kingdom

Theme/s:

Learning how to learn / Sleep and learning

This report arises from Science of Learning Fellowships funded by the International Brain Research Organization (IBRO) in partnership with the International Bureau of Education (IBE) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). The IBRO/IBE-UNESCO Science of Learning Fellowship aims to support and translate key neuroscience research on learning and the brain to educators, policy makers, and governments.

Executive summary

- *Practice and rehearsal of freshly learnt knowledge* cause it to become automatically accessible. This frees up the brain's limited capacity to pay conscious attention and so be ready for further learning.
- *Testing, applying knowledge in new situations, discussing it with others, or expressing it in new forms* all consolidate our learning by storing it in different ways—making it easier to recall and apply it.
- *Sleep* plays an important role in the processes that consolidate our learning. A good night's sleep helps attend to today's learning but also makes yesterday's learning more permanent.
- Learning is an extended process.

Effective teaching and learning can be considered to involve:

- *engagement* of the learner's attention
- teacher-guided *building* of knowledge and understanding
- *consolidation* of learning through application, practice, and reflection

When a student first builds new knowledge and understanding, when new thought processes and information first appear in their brain, this new learning is fragile. New processes must be rehearsed and practiced to become easily accessible and automatically retrievable. New memories must be "laid down" in long-term memory for them to become more permanent.

Practice prepares the brain for new learning

When we first learn a process, we often have to think through the different stages and attend consciously to a lot of new information to apply what we have just learnt. The effect of this on the brain was seen in a study of adults learning complex mathematics[1]. Activity was shown to be reduced in frontal regions after practicing. These are regions linked to working memory. Working memory is our ability to make the information in our brain conscious—and it is very limited. There were, however, regions where activity increased after practicing. Practice shifts activity from working memory regions (in the front of the brain) to regions more involved with automatic, unconscious processing (away from the front of the brain—see Figure 1). In other words, practice helps consolidate freshly learnt mental processes until we can do them almost without thinking, reducing the burden of fresh learning on working memory. This is important because, when our limited working memory is liberated, it is ready to be occupied by new information and we are ready to move on and learn more.

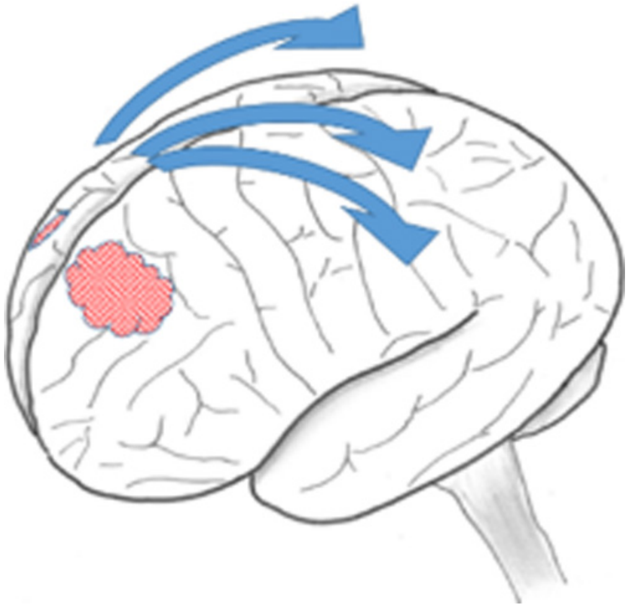

Figure 1. The effects of practice on brain activity can be represented schematically by a shift away from working memory regions in the front of the brain to more distributed regions including those related to automatic processing[1].

Our brains evolved to process information

Our neural circuitry evolved to process information rather than just to store and retrieve it. If we want such storage and retrieval to happen effectively, we need to thoroughly process the information. For example, testing is most often used by teachers to evaluate how much their students know, but it has another very important role in learning. Strong evidence from science and education supports testing as a means to improve the learning itself. Being tested on material makes it more likely to be remembered on the final test than simply rereading the material[2], and testing slows the rate of forgetting in the longer term[3]. Testing appears to improve learning for a diverse range of topics, over a wide range of education levels, and for many different age groups[4-8]. Recent neuroimaging research (see Figure 2) suggests that repeatedly retrieving information causes it to be represented in the brain in different ways—essentially connecting it with different meanings, so making it easier to retrieve in the future[9].

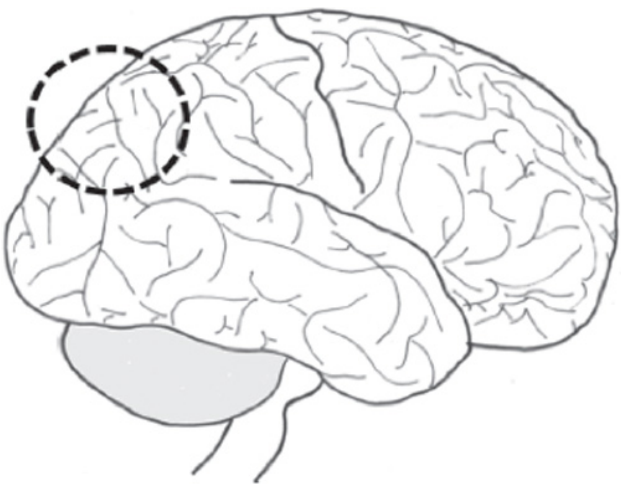

Figure 2. A study of Swedish adults learning Swahili showed brain activation related to their new knowledge took on a greater range of forms after testing. This increased variation was seen in a region of the parietal lobe (shown opposite) thought to act as a "convergence zone" where the different pieces of information that comprise a concept become bound together, supporting

representation and storage of that concept in the brain. Variability here suggests testing is causing the new knowledge to be stored in many different ways. Just as having many different hats can make using a hat easier and more useful, so having many different versions of the new knowledge, linked to different ideas and different associations, makes it easier to find and to use later (Wirebring *et al.*, 2015).

All these types of activity bring about new associations and meanings, producing new versions of the knowledge that make the knowledge more accessible and useful. (See also *Embodiment and movement* in "Building knowledge and understanding.")

Consolidation of memory and the importance of sleep

Research has revealed that sleep plays an important role in making memories more permanent. Sleep is so fundamental to learning that it has been described as "the price we pay for brain plasticity"[10]. While we are awake, memories of what happens during the day are first encoded into representations in the hippocampus. During sleep, these fresh representations are then reactivated and reorganised as longer-lasting memories stored in our cerebral cortex. This is illustrated strikingly by human neuroimaging studies. One of these revealed how the sleeping brain reproduced neural activities that were very similar to those characterising whatever was experienced in the preceding hours of wakefulness[11.]

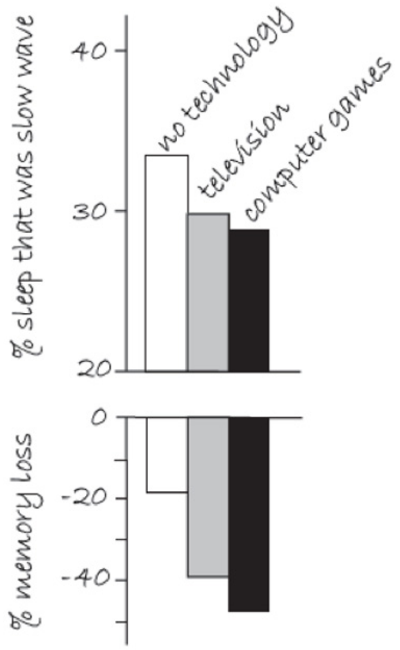

Figure 3. The graph on the left shows the percentage of slow-wave sleep (important for memory consolidation) for three conditions of technology use (basal conditions—no technology, and use of computer or television between 6 and 7 pm), with only the computer game showing a detectable effect. Similarly, in the graph on the right, only the computer game impacted on memory for material studied afterward. (a = statistically significant (p<0.0), N.S. = non-significant) (Dworak *et al.*, 2007).

This reactivation of the fresh memories is thought to be achieved during deep sleep, when the brain produces slow waves (less than one per second) of synchronised electrical brain activity. Sleep can improve memory of the context, but the reorganisation also involves extracting and emphasising more the basic "gist" of what happened. This means the memory that is stored is more abstracted from its original context, allowing it to be recalled and used more easily in new situations. So, although we may not be consciously aware of passing from one stage to the next, there are three brain processes to forming a memory.

For humans, the importance of sleep for the consolidation stage has also been demonstrated by researchers interested in children's learning. For example, adolescent sleep often suffers from technology use. In one study, a group of young teenagers was asked to vary their use of technology before immediately doing a "pseudo" homework task that involved memorising facts[12]. On one evening they experienced no technology, on another they watched television between 6 and 7 pm, and on another they played computer games during this period. Only playing computer games, which are more physiologically arousing than TV, significantly reduced slow-wave sleep when the children when to bed a few hours later (see Figure 3). This is the type of sleep that is known to be important for consolidating declarative memory. The next day, only playing computer games significantly reduced what the children could remember of their "homework."

References

1. Delazer, M. *et al.* Learning complex arithmetic – an fMRI study. *Cognitive Brain Research* 18, 76-88 (2003).
2. McDaniel, M. A., Roediger, H. L. & McDermott, K. B. Generalizing test-enhanced learning from the laboratory to the classroom. *Psychon. Bull. Rev.* 14, 200-206, doi:10.3758/bf03194052 (2007).
3. Roediger, H. L. & Karpicke, J. D. Test-enhanced learning – Taking memory tests improves long-term retention. *Psychological Science* 17, 249-255, doi:10.1111/j.1467-9280.2006.01693.x (2006).
4. Rohrer, D. & Pashler, H. Recent research on human learning challenges conventional instructional strategies. *Educational Researcher* 39, 406-412, doi:10.3102/0013189×10374770 (2010).
5. Johnson, C. I. & Mayer, R. E. A testing effect with multimedia learning. *Journal of Educational Psychology* 101, 621-629, doi:10.1037/a0015183 (2009).
6. Campbell, J. & Mayer, R. E. Questioning as an instructional method: Does it affect learning from lectures? *Appl. Cogn. Psychol.* 23, 747-759, doi:10.1002/acp.1513 (2009).
7. McDaniel, M. A., Agarwal, P. K., Huelser, B. J., McDermott, K. B. & Roediger, H. L. Test-enhanced learning in a middle school science classroom: The effects of quiz frequency and placement. *Journal of Educational Psychology* 103, 399-414, doi:10.1037/a0021782 (2011).
8. Karpicke, J. D. & Blunt, J. R. Retrieval practice produces more learning than elaborative studying with concept mapping. *Science* 331, 772-775, doi:10.1126/science.1199327 (2011).
9. Wirebring, L. K. *et al.* Lesser neural pattern similarity across repeated tests is associated with better long-term memory retention. *Journal of Neuroscience* 35, 9595-9602, doi:10.1523/jneurosci.3550-14.2015 (2015).
10. Tononi, G. & Cirelli, C. Sleep and the price of plasticity: From synaptic and cellular homeostasis to memory consolidation and integration. *Neuron* 81, 12-34, doi:10.1016/j.neuron.2013.12.025 (2014).
11. Maquet, P. *et al.* Experience dependent changes in cerebral activation during human REM sleep. *Nature Neuroscience* 3, 831-836 (2000).
12. Dworak, M., Schierl, T., Bruns, T. & Struder, H. K. Impact of singular excessive computer game and television exposure on sleep patterns and memory performance of school-aged children. *Pediatrics* 120, 978-985, doi:10.1542/peds.2007-0476 (2007).