

What Can Medical Education Learn From the Neurobiology of Learning?

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Abstract

The last several decades have seen a large increase in knowledge of the underlying biological mechanisms that serve learning and memory. The insights gleaned from neurobiological and cognitive neuroscientific experimentation in humans and in animal models have identified many of the processes at the molecular, cellular, and systems levels that occur during learning and the formation, storage, and recall of memories. Moreover, with the advent of noninvasive technologies to monitor patterns of neural activity during

various forms of human cognition, the efficacy of different strategies for effective teaching can be compared. Considerable insight has also been developed as to how to most effectively engage these processes to facilitate learning, retention, recall, and effective use and application of the learned information. However, this knowledge has not systematically found its way into the medical education process. Thus, there are considerable opportunities for the integration of current knowledge about the biology of learning with educational

strategies and curricular design. By teaching medical students in ways that use this knowledge, there is an opportunity to make medical education easier and more effective. The authors present 10 key aspects of learning that they believe can be incorporated into effective teaching paradigms in multiple ways. They also present recommendations for applying the current knowledge of the neurobiology of learning throughout the medical education continuum.

Over the past 50 years, there has been an explosion in our understanding of the biological basis of learning and memory. Neuroscientists have defined with increasing precision the various molecular signaling pathways within and between neurons that play a role in learning.^{1–5} In addition to those studies that are often carried out with elegant molecular genetic, cell biological, and neurobiological tools and applied to model organisms (e.g., worms, flies, mice), there are equally impressive advances in systems neuroscience to analyze the properties of large-scale neural networks that contribute to learning in the brains of mammals, including those of nonhuman primates and humans.^{6–8} The application of computational and quantitative behavioral approaches combined with functional brain imaging has revealed strategies employed by human brains to acquire, store, and retrieve information in a variety of tasks and settings.^{9,10} Although these gains have provided

many insights and opportunities for understanding the biological basis of learning and memory in both healthy and diseased brains, the application of this knowledge to the pedagogy of education has been limited. The focus of this article is to examine how the principles derived from what has been learned about learning can be best applied to the processes of medical education as a continuum: premedical education, the medical school experience itself, graduate medical education, and the lifelong learning process.

Furthermore, our goal is to apply knowledge of the biological basis of learning and memory to the medical education process for most effectively *guiding* learners to assimilate, comprehend, retain, access, and apply the foundations, principles, reasoning skills, and necessary facts for the most effective delivery of the best possible care to their patients in a humanistic way. Achieving such an ambitious goal will require identifying, and assigning levels of importance to, the biological components of learning for which our understanding is reasonably strong *and* for which there are realistic opportunities for integration into the medical education process. Moreover, such an approach also requires that teachers be made aware of and given access to such

information, and that we evaluate the outcomes associated with this approach.

A Brief Look at the Molecular and Cellular Basis of Learning

There are many types of learning, including various forms of nonassociative and associative learning, perceptual learning, and motor learning.^{11–13} The learning experience is then stored as a persistent representation, moving from a transient working memory stage that has a relatively limited capacity and time frame to a more long-lasting and stable form of memory with larger capacity that is stored for future access.^{14,15} Although memories are generally considered as stable and precise representations of past experiences, they are often anything but that.^{2,13,16} That is, memory is a dynamic process where the information represented is subject to our personal experiences, the context of the learning environment, subsequent events, levels of attention, stress, and other factors.^{17–19} Learning leads to functional and structural changes in the interconnected cellular networks between neurons (synapses) at a variety of sites throughout the central nervous system.^{20–22} For example, some of the earliest observable biological events in learning include changes in the efficiency of chemical synaptic transmission between neurons in areas of the brain known to be

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associated with the formation of new memories.²³ Recent studies have shown that these changes involve a variety of posttranslational modifications of proteins located in proximity to synaptic contacts that can enhance the strength of subsequent signals produced by a presynaptic nerve impulse (action potential) at the postsynaptic neuron. Although there is still discussion of the direct causality of synaptic modifications with respect to the behavioral learning process, considerable evidence supports this relationship in laboratory animals.^{24,25} This type of experimental work provides a direct link between the strength and/or repetition of the information to be learned and the persistence of the changes in the nervous system that accompany such learning. For example, repeated activation of neuronal pathways participating in learning with appropriately spaced trials leads to a cascade of molecular signals that are different and more persistent than those that accompany briefer or fewer trials.^{26–28}

The functional changes in the effectiveness of communication between individual neurons and networks of neurons are also accompanied by substantial changes in the structural circuitry of the brain,^{5,29} once thought to be hard-wired in adults. In 1982, Francis Crick³⁰ raised the question as to whether the contractile elements within the dendritic processes of neurons might play a role in altering the anatomical connectivity between neurons in a kind of dynamic ballet of the pre- and postsynaptic elements that make and break partners, essentially rewiring the brain on the fly to meet computational demands. Since then, advances in optical imaging technologies in the living brain have demonstrated this process of growth, retraction, and modifying connectivity between neurons.^{31,32} Moreover, the mature brain can generate new neurons.^{33,34} Such neurogenesis occurs in the dentate gyrus of the hippocampus, although the functional implications of these new neurons and their potential contribution to learning and memory formation remain to be determined.^{35,36}

In addition to molecular and cellular approaches to describe the workings of the underlying hardware changes that occur in the brain during learning and

the formation of memories, there has also been considerable progress in higher-order, human-based studies of cognition, including learning and memory, through the application of functional magnetic resonance imaging (fMRI) of the living brain combined with computational modeling to elucidate the strategies and underlying neural processes that subservise these functions in humans.^{37–39} An opportunity and challenge for evaluating differing teaching methods is to use fMRI under highly constrained behavioral regimes in interactive settings to directly observe the neural processing architecture and efficiency of these networks during learning.

Implications for Medical Teaching and Curricular Development

Many features of the biology of learning have been validated using the biologically based technologies described above in animals and in humans, along with behavioral testing. We identify 10 key aspects of learning that we expect can be incorporated into effective teaching paradigms in multiple ways.

Repetition

Teachers have long appreciated the value of *repetition* and revisiting the same topic from multiple perspectives. However, medical curricula often employ compressed coverage over limited time frames of a great amount of material (providing little opportunity for repetition, revisitation, and consolidation with appropriate rest or time away from the material) and avoid perceived “redundancies,” or overlap, between classes or sections. This raises the issue of time management in medical education—try to touch on it all or go deeper on selected topics. Learning theory and the neurobiology of learning and memory suggest that going deeper is more likely to result in better retention and depth of understanding.⁴⁰ With repetition or planned redundancies, many components of the neural processes that are engaged become more efficient (less energy used, more rapid neural execution, off-loading to lower-order pathways leaving higher-order pathways available for additional cognitive processing).^{38,41} There is also considerable evidence for the importance of appropriate spacing of repetitive trials.^{27,42} Whereas this evidence comes

from biological studies in animals that separate the induced molecular and physiological changes over intervals of seconds, such principles also may apply to longer time intervals in humans. Thus, an opportunity and challenge for medical education is the determination and implementation of the best intervals for revisiting material. Indeed, there is strong support from cognitive science for the value of spacing in learning.⁴³ Human cognitive studies using fMRI have demonstrated that enhanced recognition-memory may result from reduction of the process that has been well characterized as neural repetition suppression.⁴³

Reward and reinforcement

Reward is a key component of learning at all stages of life^{44,45} and in all species, including humans. Most parents are familiar with the outcome from rewarding and celebrating a child's successes and “good behaviors.” There is a rich biological understanding of detection of associations, particularly between temporally contemporaneous events. The underlying mechanisms of these associations are known, including the existence of molecular coincidence detectors.⁴⁶ Moreover, the brain's intrinsic reward system plays a major role in *reinforcement* of learned behaviors.⁴⁷ These processes are generally best understood at the level of relatively temporally proximal events such as receiving a reward of praise, money, or food close to the time of the stimulus.^{48,49} However, the realization of accomplishing a goal or the satisfaction of making a successful step toward the goal can be equally rewarding. Interestingly, the neural circuitry of the human brain engages in temporal discounting⁵⁰—that is, the calculation of the relative value of a choice to realize a reward of a certain value in the immediate future versus a reward of a greater value in the more distant future. Such calculations are made by the human brain in real time, often at a level operating below conscious awareness but, nonetheless, having major effects on decision making. Thus, there is value in understanding and applying this information to the structuring of teaching strategies.

Medical students are invariably bright, highly motivated, and eager learners. However, they are rational agents, with tremendous demands on their time and

attention, and must make choices about where to focus their energies and attention most efficiently. Thus, at both the conscious and unconscious levels, their brains are engaging in a continuous process of triaging for the allocation of finite neural resources. Moreover, there are considerable rewards (mostly long-term) ahead of them: passing exams and boards; graduating and earning a medical degree as well as the love, respect, and trust of their families, friends, and the public; a stable and highly respected career; a place in the community; income; happiness; and others. These, of course, are in addition to the more immediate rewards of the satisfaction of understanding medicine and the knowledge that with that understanding comes the ability (and empowerment) to profoundly affect the lives of others in positive ways. The students who derive joy and satisfaction from the more immediate goals of understanding as they proceed through their medical education may have a greater chance of using the brain's capacity to provide reward signals on an ongoing basis, thus effectively facilitating their learning process. Likewise, the curricula and instructors that provide a venue and process to tap into this biologic function may be more successful than those that rely only on sparsely distributed and high-stakes opportunities for reward.

Visualization

Visualization is a process well known to surgeons⁵¹ and athletes,^{52,53} among others. The act of visualization engages not only the early and higher-order visual thalamocortical pathways of the human brain but also provides an opportunity for the development and refinement of internal representations of solid and complex objects along with their relative location in space.⁵⁴ Although learning is routinely considered as a process that occurs in response to certain events in the outside world (stimuli that might include semantic information that is taken in by reading or listening to a lecture or watching a procedure, for example), the neuronal networks that assemble the incoming information and construct memories shouldn't "care" about the source (whether externally or internally generated) of the triggering inputs as long as the requisite cellular and circuit signaling processes are accessed. Thus, internal stimuli (e.g., gut contractions,

chronic pain, proprioceptive signals from joints) associated with certain events can be powerful learning signals. Likewise, internally generated activity in the brain from thoughts, visualization, evocation of other memories, and emotions should be able to contribute to the learning process.⁴⁷ Studying, visualization, and rehearsal are likely to contribute to learning. Moreover, with the rich variety of technological innovation currently available to educators, particularly for visualization,^{55,56} these processes can be linked in interactive ways to the learners to allow for the better use of these neural processes and perhaps also can be applied in persons who have not developed these internalization skills sufficiently. Introspection and self-reflection are important components of any such process and can contribute to the strengthening of rehearsed actions or thoughts. In fact, recent neurobiological evidence suggests that networks of "mirror neurons" in the brain may contribute to such processes.⁵⁷

These types of rehearsal/visualization processes also access neural circuits that implement complex decision-making algorithms that have numerous branch points and weighting functions.⁵⁸ Visualization and mental rehearsal are real biological processes with associated patterned activation of neural circuitry in sensory, motor, executive, and decision-making pathways in the brain.⁵⁹ The ability of a learner to successfully employ visualization techniques to enhance learning may depend on the degree of experience of the learner. For example, the amount of practice or experience can affect the degree of improved motor performance gained through mental practice and visualization.⁶⁰ The level of knowledge and expertise of the relatively new learner in a given field (e.g., first-year medical student) may be a limiting factor, and such strategies as visualization may be more effective in later stages of the education process—for example, after having witnessed and participated in procedures.

Active engagement

There is considerable neurobiological evidence that functional changes in neural circuitry that are associated with learning occur best when the learner is actively engaged.⁶¹ Indeed, medical education has moved in this direction over recent decades by reducing time

allotted for traditional large-group lecture venues and giving more time to problem-based learning and small-group interactive discussion formats. Regardless of the success of the other cognitive features embedded in the latter formats, there is little doubt that when there is opportunity for full individual participation, personal accountability, and feedback, these more interactive formats are more likely to foster active learning.

Medicine has long cherished the tradition of the student as teacher. Throughout the medical education process, strategies that create active learning opportunities include learners' having multiple opportunities to assume the role of teacher, learning venues that encourage interaction/questioning between learners and teachers, learners' taking personal responsibility for discovery of information, and feedback to learners of the information they have assembled and its validity. Such opportunities are likely to invoke the neural motivation and reward pathways. These opportunities also invoke another major biological component of the learning process: stress.

Stress

Although the consequences of stress are generally considered undesirable, there is evidence that the molecular signals associated with stress can facilitate synaptic potentiation in brain circuits involved in the formation of memory and also can be behaviorally reinforcing to learning.^{31,62,63} However, particularly high levels of stress can have opposite effects.⁶⁴ The small, interactive teaching format may be judiciously employed to *moderately* engage the stress system on a more regular basis. Such a format provides individual accountability to peers and teachers in a group setting, which gives more insight into the learner's thought processes than would typically occur through objective, brief, answer-based examinations, where the learner's reasoning processes are not shared. These venues create opportunities to engage the physiological stressor pathways at moderate levels while avoiding overactivation for more sensitive individuals.

Fatigue

There is increasing evidence of the importance of rest/sleep for the

consolidation of memories and the enhancement of their representations from working memory stages into a long-term stable form.⁶⁵ This process is referred to in neurophysiological parlance as *replay* and can be monitored in the brains of animals as patterns of neuronal activity that recapitulate the day's events during sleep.⁶⁶ Although there is only so much educators can do to encourage rest/sleep among learners by educating them about these processes, there are potential opportunities for incorporating rest or consolidation times within busy schedules. Moreover, this research suggests that it is important to have appropriate downtime between intense problem-solving sessions or group venues where detailed quantitative reasoning skills are required. Such downtime permits consolidation or reinforcement away from the formal teaching process.

Multitasking

A common descriptor of the current generation of medical learners is *multitasking*. For example, they text while reading, or engage in other forms of electronic communication while in class or even when interacting with patients. The data are clear on the subject of cognitive distractions while performing physical activities like driving a car: It's not just the physical act of managing a cell phone that diminishes driving performance but also the cognitive competition between attending to the conversation and the driving that further degrades performance.⁶⁷ Moreover, while trying to discuss or, more importantly, to stimulate a learner to consider a body of evidence about a biological process, disease mechanism, or planned course of therapy, the engagement of additional information streams, particularly those unrelated to the topic, diminishes the likelihood of achieving optimal learning and, subsequently, full and deep understanding.

Thus, it is important that educational methods *integrate* multimodal information relevant to the topic; this encourages engagement of relevant converging informational mechanisms by enhancing rather than dispersing attention. Reinforcement of concepts and facts in a temporally proximal domain through varied media engages processes that facilitate abstraction and the

construction of integrated frameworks of knowledge for the synthesis and future accessibility of information for recall and implementation. The same technologies that enable multitasking during learning can be used to enable and tap into the intrinsic neural processes that enhance the learning process.

Individual learning styles

It is well appreciated that there are many different types of learners and learning strategies.⁶⁸ Individuals have various types of intelligence and show differences in the types of learning that they employ best. Some are particularly adept at integrating lecture material, others are better at obtaining the material independently through reading, and others benefit from various forms of visualization and/or interactive use of the material. The neural responses of these different individuals also show variability, and that is the rationale for embracing multiple learning styles to provide opportunities for all learners to be most effectively reached, to provide opportunities for positive feedback and successes, and to reinforce information with multimodal convergent strategies, even for those who excel equally with all approaches.

Active involvement

There is considerable support for *active involvement* when learning skills and concepts. Laboratory and simulation environments are rich venues for the learning process and for storing information into memories based on those experiences. In other words, doing is learning. And success at doing/learning builds confidence, as has been shown by recent neurobiological studies of human performance during episodic retrieval of remembered information.⁹

Revisiting information/concepts through multimedia/sensory processes

Sensory processing is used for detecting, decoding, and analyzing outside information and for developing internally generated representations of information to learn and to consolidate information. Moreover, these processes use unisensory as well as multisensory integration areas of the brain, with individual variations in the relative contributions of these modalities. Multiple teaching approaches addressing the same information using different sensory processes are likely to

enhance the learning process, potentially bringing more neural hardware to bear to process and store information.

Where Do We Go From Here?

Although there is considerable information available about the processes that mediate the changes in the brain that manifest as learning and memory, much remains to be learned and, more importantly, there is a need to systematically apply the principles to optimize learning in real-world settings within the medical education continuum.

There is clearly already a wealth of data on the biological basis of learning. It is challenging enough for researchers in the field to keep up with the literature, let alone keep up with those who specialize in other areas of science or medicine and who are dedicated educators in their particular areas of expertise. Thus, there is a large gap in the dissemination of the accepted and relevant information from the biology of learning community to the education community. The organization of task forces or consensus conferences to develop consensus on the accepted principles followed by interactive task forces to bring together educators with learning biologists would prime the effort to narrow that gap. A national organization such as the Association of American Medical Colleges and/or private foundations could support such an effort. It is likely that the greatest challenges (and opportunities) will be to identify implementation plans and to design experimental work to evaluate these new approaches. For example, current technology⁶⁹ makes possible interactive functional brain imaging of groups at a single site or at multiple sites, which would permit individual and group behavioral studies, including investigations of learning and social cognition. Neurobiological assays could be done of the impact of various learning/teaching approaches; coupled with conventional and enhanced computationally based behavioral analysis, such assays could be employed to track outcomes and provide feedback.

If educators take the time to explain to students why certain teaching approaches will be used, the students may understand and accept the approaches and develop a mutually respectful relationship with their instructors. That

relationship may also serve as a reward system for learning enhancement. By appealing not only to students' capacity to derive pleasure from learning about medicine but also to their intellectual capacity for understanding the rationale for the educational process selected by the instructor (based on various principles, including those derived from the neurobiology principles of learning), real motivation can be engendered. Moreover, as physicians in training learn teaching methods based on these principles, they become more effective communicators and enhance their patients' success at learning the information they need for managing their own health and treatments as well.

Recommendations for Medical Educators

- Apply the current knowledge of the neurobiology of learning to the lifelong education of health care professionals.
- Base faculty development practices on current knowledge of the neurobiology of learning.
- Share with the learner the underlying neurobiological principles that shape the pedagogy of the learning experience.
- Establish a toolbox of evidence-based practices for medical education that applies current knowledge of the neurobiology of learning.
- Develop a shared research agenda between neurobiologists and medical educators.

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