Anesthesiology Graduate Medical Education: Best Approaches for the Learner, Best Approaches for the Teacher

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Educating the next generation of anesthesiologists presents many challenges. In this month's *Anesthesia & Analgesia*, Weidman and Baker[1] review principles of cognitive learning, providing examples pertinent to the field of anesthesiology with a goal of assisting learners and teachers as they confront these educational challenges. Educating the anesthesiologist of the future in the face of a variety of challenges presents an opportunity to improve graduate medical education by applying the principles discussed by Weidman and Baker.

Medical practice as a whole and anesthesia patient care in particular require practitioners to make clinical decisions and problem-solve, often during critical events when time is of the essence and the stakes are high. These decisions can mean the difference between patient survival and demise. A primary goal of graduate medical education is to provide residents and fellows with the necessary background, readily accessible for application when these situations arise; this goal requires that these future clinical anesthesiologists have key material readily accessible and available to be applied effectively and efficiently to crucial clinical decisions. The challenge for educators is to identify and implement optimal educational strategies that will assure that the patient care information is readily available and effectively and efficiently applied by the learners.

There is a variety of key principles of learning presented in the review by Weidman and Baker. To highlight these principles, this editorial focuses on how to enhance learning acquisition to facilitate retrieval of the clinical care information so that it can be applied during clinical scenarios to provide the best patient care.

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Learning is a complex process involving the human memory system with initial steps establishing a basic foundation of knowledge. The brain has a remarkable capacity to store information. This complex process involves initial learning of the material, forgetting, and then remembering with the goal of retrieval of the information and its subsequent clinical application. Studies reveal that after initial learning, only one-third of the content is retained within a day.[a] Residents have significant forgetfulness over a 6- to 7-month period.[2] So how do we apply the learning theories discussed in the review by Weidman and Baker[1] to optimize learning so that this material is not "forgotten," especially when its clinical application is needed?

One of the key aspects of learning is the retrieval process. Some of the processes that enhance learning and thus enable the retrieval process may appear counterintuitive. Some of these principles include varying the conditions of learning rather than having them be constant. It is no coincidence that an effective educational principle included in the review highlights the importance of spacing learning opportunities so that conducting multiple practice sessions will allow for repeated studying and additional opportunities for implementation of the learned techniques.[1] Education is further enhanced by interweaving other learning opportunities that provide better conceptual frameworks that actually increase understanding, although to the learner, this may appear at first to be disruptive. Teachers and students must also recognize that tests, rather than being used solely as a performance metric, can be and should be recognized as learning events. Focusing on testing as a learning aid represents an area that is championed in cognitive psychology and that can be of benefit to the field of anesthesiology. Students who wish to be lifelong learners can gain more educational substance than those who wish to perform and stop learning once they prove their performance ability through passing the test. Interestingly, test-enhanced learning may prove to be most beneficial for novice learners who lack strong associative networks and thus may be particularly valuable for trainees who are in the process of acquiring strong associative networks during training.[3]

The 3 authors of this editorial remember well the principle that guided medical education in the past, that is, "see one,

[a]Ebbinghaus H. über das Gedächtniss. Leipzig 1885. Memory: A Contribution to Experimental Psychology. Ruger HA, Bussenius CE, trans-ed. 1913; section 29 & 34. Available at: http://psychclassics.yorku.ca/Ebbinghaus/. Accessed June 26, 2015.

do one, teach one." However, the past is still present when it comes to graduate medical education. Those entrusted with the future professional lives of clinical anesthesiologists still teach with little educational background to ground their activity. Many of these teachers, for example, walk into the operating room and decide to teach a high-level cognitive topic at the same time the resident is trying to focus on his or her patient's altered physiology. The teachers have not recognized that the distraction of patient care results in cognitive overload, preventing the resident from grasping the depth and breadth of the intended teaching. In other educational settings, the teachers dive into the lesson without a clear understanding of the residents' prior knowledge. All residents are not equal; they enter teaching activities with different backgrounds and different foundational understanding of the anesthesia and medical/surgical patient care that is taking place. These teachers, who do not really understand the educational background of their students, cannot offer, for example, the analogical similarities and differences that may already be known to the resident. Not knowing who the learners are diminishes the educator's ability to capitalize on prior student comprehension. What results is less effective and less efficient teaching and learning.

These examples point out what we believe should be the obvious; teaching is a profession that requires the educator and the learner to be facile with the principles of learning to assure that the best education will result. The ability to apply principles learned in clinical situations will impact patient care and thus outcome is of paramount importance. We have known for many years that the best curricula are those that use residents' actual clinical experiences and teach medical skills "in real time in existing clinical and educational venues."[4] Just as one would not risk a patient's safety to a neurosurgeon who has never been taught (and thus has not learned) the principles of intracranial surgery, one should not put patients at risk because an anesthesiology resident or fellow was exposed to a clinical teacher who never learned the principles of education. We are all indebted to Weidman and Baker[1] for their superb, timely, and useful review of the principles of cognitive learning; our residents need the best education we can offer, and our patients deserve the best care we can provide.

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REVIEW ARTICLE

CME

The Cognitive Science of Learning: Concepts and Strategies for the Educator and Learner

Joseph Weidman, MD, and Keith Baker, MD, PhD

Education is the fundamental process used to develop and maintain the professional skills of physicians. Medical students, residents, and fellows are expected to learn considerable amounts of information as they progress toward board certification. Established practitioners must continue to learn in an effort to remain up-to-date in their clinical realm. Those responsible for educating these populations endeavor to teach in a manner that is effective, efficient, and durable. The study of learning and performance is a subdivision of the field of cognitive science that focuses on how people interpret and process information and how they eventually develop mastery. A deeper understanding of how individuals learn can empower both educators and learners to be more effective in their endeavors. In this article, we review a number of concepts found in the literature on learning and performance. We address both the theoretical principles and the practical applications of each concept. Cognitive load theory, constructivism, and analogical transfer are concepts particularly beneficial to educators. An understanding of goal orientation, metacognition, retrieval, spaced learning, and deliberate practice will primarily benefit the learner. When these concepts are understood and incorporated into education and study, the effectiveness of learning is significantly improved. (Anesth Analg 2015;121:1586–99)

The first edition of Miller's[1] classic anesthesia textbook was published in 1981 and contained 1535 pages. In the 33 years since the first edition, the book's length has grown to 3312 pages,[2] more than doubling in size. Medical information is growing at a remarkable rate in all fields. The overall length of many residency programs has increased in the past few decades to allow residents more time to attain proficiency with both an increasing set of required skills and an ever-expanding core of knowledge. In 1985, the American Board of Anesthesiology (ABA) published a special article recognizing the continued "growth of the knowledge base of the specialty" and "the incremental variety and complexity" that existed in the clinical arena.[3] Further, the ABA believed that the "opportunities for adequate grounding and experience in the basics of the specialty [were] not keeping pace with the advances of the specialty." As a result, the ABA modified the requirements for residency in anesthesiology to include an obligatory third year of advanced clinical training beginning in 1989. Individual scope of practice is also becoming more subspecialized as a strategy to help clinicians master the expanding body of medical knowledge and develop the specialized skill sets that are required. During this information explosion, physicians continue to be expected to master and recall impressive amounts of information.

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Recent years have also seen significant growth in our understanding of the cognitive science of learning and performance. These advances have led to a deeper understanding of concepts and strategies that can facilitate more effective, efficient, and durable learning. When used in medical education, these methods can help teachers increase their educational effectiveness and help learners develop and maintain mastery of their individual disciplines. It is our belief that patient care, the ultimate goal of the clinician, is enhanced when teaching and learning are improved.

In this article, we review 8 concepts from the literature on learning and performance improvement. These concepts were chosen because they have been empirically shown to influence teaching and learning. These concepts are grouped into those most relevant to educators (cognitive load theory, constructivism, and analogical transfer; Table 1) and those most relevant to learners (goal orientation, metacognition, retrieval, spaced learning, and deliberate practice; Table 2). Despite this grouping, all of the concepts in this article are valuable to both educators and learners. It is also important to note that the study of human learning is a very large field with an immense literature, and our review does not address many important issues. Accordingly, this article is a simple primer for those interested in improving education and, thereby, patient care. We will begin the discussion of each concept with a concrete scenario. These scenarios provide practical examples that relate to the subsequent educational theory discussed below each scenario.

FOR EDUCATORS

Cognitive Load Theory

Cognitive load scenario: *During a busy day in the operating rooms, you supervise a junior resident for his first spinal anesthetic. You provide numerous tips to help the resident with the spinal. You show him how to identify the correct spinal level, how to stabilize the needle when attaching the syringe, and how to slowly inject the isobaric solution. The next day you are working with the*

Table 1. Concepts for the Educator

Description	Relationship to learning
Cognitive load theory: Cognitive load theory maintains that limitations of working memory capacity place a severe limit on human cognitive processing. There are 3 forms of cognitive loads: intrinsic (problem difficulty), germane (learning and development of schema), and extraneous (material that is irrelevant to the problem at hand). Humans are very vulnerable to cognitive overload after which new information cannot be effectively processed or learned.	The bottleneck in cognition can be managed by optimizing germane load (e.g., by providing numerous examples), reducing extraneous load, and reducing intrinsic load by breaking down complex problems into smaller subcomponents.
Constructivism: Constructivism refers to a teaching method that helps learners to create their own understanding of the material through exploration, discussion, and questioning rather than lecturing. The educator probes learners to see whether they are constructing a correct mental model and if not, engages in dialog to help them self-correct their misunderstandings.	Constructivism results in deeper understanding of complex concepts. It ensures that learners create their own understanding of concepts and it affirms, through dialog with the educator, that the learner's understanding is correct.
Analogical transfer refers to using (transferring) the solution of one problem (the analog) to solve a different but related problem. Surface structure is the information that characterizes the particular or circumstantial aspects of the problem. For example, in the addition problem, 2 + 4 = x, the numbers 2 and 4 are surface structure. Deep structure refers to core elements of the problem. The process of addition is the deep structure.	Analogical transfer is a powerful tool, but its application is difficult for most people. Novice learners often use surface structure inappropriately and they often fail to see deep structure. Educators must assist the learner to appreciate the difference between surface and deep structure in problems.

same junior resident and encounter another patient requiring spinal anesthesia. Despite numerous opportunities to take advantage of the tips you provided the day before, you are surprised when the resident does not use any of them. What happened?

Working memory is responsible for actively processing and manipulating information in real time. It is central to the management of complex cognitive tasks such as reasoning and comprehension.[4] Working memory receives inputs from both the sensory systems (sight, touch, and hearing) and long-term memory. It integrates the new information and experiences with what is already understood. The resulting new understanding is then sent back to long-term memory.[5] However, working memory has severe limits on its capacity and is the major bottleneck in the cognitive processing of new information.

Cognitive load theory maintains that it is very easy to overwhelm a learner's limited working memory capacity because of the cognitive processing that is required to work through a new task or understand a new concept. When this happens it is impossible for meaningful learning to occur.[6] The theory posits that working memory is subject to 3 different types of cognitive loads: intrinsic, extraneous, and germane.[7,8] Each of these can be manipulated to enhance learning.

Intrinsic load is the cognitive load related to the inherent difficulty of a task. For example, basic arithmetic has a low intrinsic load, whereas differential equations have a much higher intrinsic load. The intrinsic load associated with a particular task is fixed. Often, the educator can help the learner by breaking down learning tasks into smaller subtasks, each with more manageable intrinsic load.[9] These components can eventually be integrated for a summative understanding of the overall complex construct.

Extraneous load is information that requires cognitive processing, but which is not central to the learning objective. Extraneous load can arise as a consequence of the technique by which information is presented to a learner, or as a result of other irrelevant cognitive activities that occur while thinking. An educator who presents nonessential details when explaining a complex concept to a learner will increase extraneous load and consume the learner's limited working memory that is needed for processing the intrinsic and germane load of the problem (see below). Ironically, the text "see below" in the prior sentence is a form of extraneous load because it interrupts the reader's processing of the text and asks them to look elsewhere in the document to understand the material. To the extent possible, educators should minimize extraneous load when designing instructional methods.[9] By minimizing extraneous load, more of the learner's limited working memory capacity can be devoted to processing elements needed for problem solving, reasoning, decision making, and learning.

Germane load refers to the aspect of working memory that focuses on making sense of information (learning). Germane load is the part of cognition that leads to recognizing relationships and creating frameworks that represent more generic problem structures. A general framework of a problem and its solution is called a schema. For example, the Seldinger technique (advancing a guidewire into a lumen and then threading a device over the guidewire) is a conceptual schema that can be applied to multiple problems, such as percutaneous vascular access, percutaneous endoscopic gastrostomy tube placement, or endotracheal intubation over a bougie. Formation of schemata is critical in improving a learner's understanding and in developing the ability to apply information to future scenarios. The working memory used to recognize the similarities in deeper structure that exists between related problems is an example of germane load. There is a strain placed on working memory when related examples of a problem are compared and contrasted to reveal similarities and differences between examples. This exercise introduces germane load. This increased demand on working memory is acceptable when the goal is to augment the learner's understanding. Like extraneous load and intrinsic load, the contribution of germane load to the overall cognitive demands of a learning encounter is modifiable by the educator.[7] Instructional design that allows for effective processing of germane load results in more successful formation of schemata. Over time, through effective use of germane load and promotion of schema creation, learning can actually reduce the intrinsic load of a problem by simplifying or encapsulating the concept.[7] When conceptual learning is the goal, it is essential to effectively use germane load to develop a deeper understanding of the material by the learner.[10]

An awareness and understanding of these components of cognitive load theory can help improve an educator's instructional design.[5,11] For example, when the intrinsic load of a learning objective is high, educators who are aware of cognitive load theory can help the learner by dividing the material into smaller components, each having less intrinsic load. In this manner, a savvy educator tasked with teaching about hemodynamics and acute hemorrhage might choose to review stressed blood volume and mean systemic pressure on day 1 and wait until day 2 before discussing the body's reflexive responses to acute hypovolemia. As another example, educators who are unaware of the detrimental effects of unnecessary extrinsic load may choose to use a verbal approach to explain an inherently graphical concept. Unfortunately, this requires the learner to use additional working memory to convert the words to a mental image. The educator who understands cognitive load theory can remove this unnecessary extraneous load by using a visual example to demonstrate the graphical concept.

Multitasking: An Additional Burden Placed on Working Memory

An unappreciated threat to all forms of cognitive load and therefore to education and learning is multitasking. Undertaking >1 task at the same time, or multitasking, is a method that is sometimes used to improve efficiency. In reality, however, it burdens working memory and slows cognitive function. "Multitasking" is a misnomer. In actuality, humans engage in rapid switching from one task to another. This switching process compromises the efficiency of cognitive processes. By trying to attend to multiple tasks at once, multitasking divides the limited capacity of working memory among the tasks, allotting each task less cognitive bandwidth. Rapid switching between tasks also introduces another type of extraneous cognitive load: *switch cost*. Switch cost is the additional cognitive burden necessary to change focus from one subject to another.[12] Switching between even straightforward tasks has been shown to increase reaction time and error rate.[13] Because switching limits the amount of working memory available for processing germane and intrinsic load, multitasking should be avoided in learning environments and in situations that require the timely and accurate completion of a task.

Attempting to complete both physically and mentally demanding tasks concurrently is another form of multitasking. Surprisingly, even modest physical tasks can add to cognitive load. For example, when a subject is required to learn a list of words while concurrently walking along a path (compared with being seated), their ability to later perform simple word recall is significantly reduced.[14] Walking along an oval pathway diminished word recall by 17% for middle-aged adults compared with when these same subjects were seated. As the demands of the physical task intensified (i.e., the geometry of the walking path increases in complexity), performance deteriorated even further (32%).

Automaticity: Easing Cognitive Load and Lowering Demands on Working Memory

Multitasking cannot always be avoided. In the practice of anesthesia, it is often necessary to divide one's attention among multiple demands. Experts in a field are more successful at multitasking than are trainees. The proficiency of experts over novices in multitasking is attributed to automaticity.[15] *Automaticity*, or *automatic processing*, occurs when an input directly prompts the execution of a learned sequence of actions that are stored in long-term memory, bypassing working memory altogether. Because automatic processing does not use working memory, it proceeds without consuming the subject's attention.[16,17] In contrast, *controlled processing* refers to the active management of cognitive tasks that require the subject's attention. Controlled processing uses working memory to accomplish tasks and is therefore subject to working memory capacity limitations. As might be expected, experienced anesthesiologists incorporate much more automatic processing than do novices, thus affording them more available working memory. A novice's reliance on controlled processing for even basic tasks results in a significant reduction in available working memory that negatively impacts multitasking. As a novice gains experience and tasks become more automated, the increased use of automatic processing subsequently increases the amount of available working memory. This working memory can then be used to attend more cognitively demanding tasks.

Automaticity develops through continued practice, although not all tasks can or should be automated. Ideal tasks for automatic processing are those in which there is a consistent relationship between the stimulus and the response. Tasks in which a single input can result in a number of different possible responses are not suitable for automatic processing because the decision regarding which response to use requires higher cognitive processing. As an example, imagine that an anesthesiologist observes a sudden decrease in an intubated patient's oxygen saturation. The anesthesiologist immediately places the patient on 100% oxygen and mentally reviews potential causes of hypoxia. On reflection, the anesthesiologist recognizes that the patient's head was moved for positioning after intubation, correctly identifies a bronchial intubation as the cause of the problem, and adjusts the endotracheal tube's position accordingly. In this example, automaticity was used during the initial response to desaturation. Automaticity triggered the use of 100% oxygen, because there is a strong and consistent relationship between placing the patient on 100% oxygen and improving the saturation. However, subsequent treatment steps differ depending on the root cause of the hypoxia (mucous plug, disconnected circuit, esophageal intubation, etc.). This varied relationship is best managed through controlled processing because the necessary decision making requires higher cognitive processing and the use of working memory. In short, adjusting the endotracheal tube position is not always the correct next step in managing desaturation.

Educators can help learners recognize processes with consistent relationships and encourage extensive practice in those areas. This will result in automaticity that will free working memory for use on more complex task management. This concept was effectively applied to first-year surgical residents who had been randomly assigned to receive training on suturing. The group that received previous training with suturing showed better intraoperative learning of new educational material than did the group that did not receive previous suturing training.[18] This occurred because residents with previous suturing training were able to devote more working memory to understanding what the attending surgeon was teaching during the intraoperative period because the process of suturing had become more automatic.[18] The residents who had not received previous suturing training were less able to attend to the intraoperative teaching because they needed to use precious working memory capacity to perform their suturing task. Thus, automaticity provides a latent opportunity for improvement. In other words, automaticity frees working memory capacity that can be used for more complex thinking, planning, deciding, and learning. As demonstrated by the surgical residents who learned more in the intraoperative setting once their suturing skills were somewhat automated, automaticity can result in better overall performance when the learner takes advantage of it in a manner that enables improvements in learning.[18]

A better understanding of cognitive load theory allows educators to be more effective in teaching. Recognition that working memory acts as a bottleneck for learning is critical. The ability to identify the different types of loads that feed into working memory is useful for educators because it helps them modify their instructional design to minimize unnecessary loads. Further, an appreciation of the detrimental effects of multitasking on cognitive load and the potential benefits of automatic processing allows educators to guide their students toward more efficient and effective learning.

The resident performing the spinal in our initial scenario suffered from cognitive overload. As a novice, his working memory capacity was saturated simply executing the basic steps of placing a spinal. The resident was possibly too cognitively occupied just figuring out which of the numerous vials in the kit contained the local anesthetic for skin anesthesia to internalize the educator's advice. Thus, when the attending was providing important tips, the learner was not able to cognitively process them because his working memory was fully occupied with other more basic tasks. As a result, the learner did not integrate the tips into his schema for how to place a spinal. Previous review of the kit's contents and/or previous rehearsal using a spinal simulator may have yielded a better learning outcome. In an analogous manner, if the educator wants to provide feedback to a learner who is under high cognitive load, the educator should have the learner disengage (stop) from performing the task at hand to allow the learner to completely focus on the educator while the feedback is being provided. This will enhance the learner's ability to cognitively process the feedback in an effective manner.

Constructivism

Constructivism scenario: *You are asked to speak to second-year residents about pH management during deep hypothermic circulatory arrest. You work diligently to prepare a lecture reviewing the most recent literature and the theoretical rational behind α-stat and pH-stat management. After the lecture, you leave time for questions. When the residents ask no questions, you feel confident that the presentation was effective. You are surprised and disappointed a few weeks later when you receive your written evaluations. You read comments such as "I found the concepts difficult to understand" and "I felt lost after the first 10 minutes." Why wasn't your presentation as effective as you had hoped? How could you prevent this in future lectures?*

Learners come to an educational encounter preconditioned by their experiences, intuition, and previous understandings. These are the learner's *preconceptions*.[19] Preconceptions that are consistent with the material being taught are called *anchoring conceptions*, and these benefit the learner because they act as a correct foundation on which to build additional understanding. Preconceptions that are inconsistent with a new viewpoint are called *misconceptions* or *alternative conceptions*,[20] and these typically interfere with learning new concepts or information. Misconceptions often represent a faulty foundation that needs correction before new knowledge may be appropriately integrated.

Constructivism is an educational approach that focuses on how learners process knowledge.[21] Constructivism asserts that new knowledge is integrated with a learner's preconceptions in 1 of 2 ways: assimilation or accommodation.[22] *Assimilation* occurs when the learner incorporates new knowledge seamlessly into a preexisting framework of understanding. With assimilation, new information builds on, rather than disrupts, the learner's preconceptions. In contrast, when new information challenges a learner's preconceptions, the learner is required to reframe his or her mental representation through a process called *accommodation*. Accommodation results in cognitive dissonance, which is initially uncomfortable; however, accommodation is the method by which a misunderstanding can ultimately result in learning.

Unfortunately, having a misconception and then being presented with a correct representation of the concept does not guarantee that appropriate accommodation will occur. For example, a learner may correctly recognize the need to restructure a framework on a particular topic, yet incorrectly perform the restructuring. Learners may also mistakenly view new and conflicting information as erroneous, or an exception to the rule, and fail altogether to recognize that it is their own current framework that is incorrect and in need of adjustment.

It is through the use of dialogue that a constructivist educator discerns the learner's preconceptions and works to prevent these maladaptations. The constructivist then customizes the educational experience to help the learner integrate the new information that does not currently fit the learner's preexisting model. An educator who spends time to discover a learner's previous knowledge base and preconceptions will then have information that can be used to deliver optimal teaching and drive better learning. Accurate determination of a student's previous conceptions can be quite difficult without such a discussion. Even experienced teachers often presume their students have a level of understanding that is higher than it actually is.[23]

Constructivist educators frequently use active discovery. Learners build knowledge when they realize that new information conflicts with their current frameworks.[24] Thus, constructivists favor exercises that challenge a learner's current perspective or require the learner to explain their rationale. A recent meta-analysis found that teaching focused on active learning significantly improved performance on standardized tests and decreased failure rates when compared with traditional teaching by lecture.[25] When constructivism was used to teach college physics through student collaboration and an interactive-engagement method, the students exposed to the constructivist method outperformed the students from the traditional method of teaching (lecture) with an effect size of 2.[26] Thus constructivism is a powerful and effective teaching method.[27,28] An example of the constructivist method of teaching is found in Box 1.

In constructivism, the educator, through dialogue, acts as a diagnostician of the learner's preconceptions. If the learner demonstrates anchoring conceptions (i.e., they correctly understand fundamental concepts and their significance), then education is seamless because knowledge is built from a suitable base. However, more commonly, there are misconceptions and the educator assists the learner to recognize these errors through exercises that promote cognitive dissonance. Cognitive dissonance is the mentally uncomfortable state that occurs when a person realizes new information they are being asked to learn actually conflicts with what they already believe to be true. The dissonance causes learners to either change their minds to accept the new information or to reject it, which then allows them to retain their previous belief. Ideally, the conflict between the learner's previous understanding and the new understanding offered by the teacher triggers the process of accommodation that results in correction of the misconception.

The most effective educators are skilled in both diagnosing the learner's misconceptions and, at the same time, crafting a conversation to rectify these misconceptions. The use of questions that require the learner to explain "why" (e.g., "why do you think this patient requires an arterial line?") or ask the learner to compare and contrast related but different things (e.g., "compare and contrast volume-controlled ventilation and pressure-controlled ventilation") are ways for the educator to diagnose the learners' (mis)understandings. Rather than spoon-feeding learners, constructivist educators help learners generate the answers for themselves.[29]

Our constructivism scenario shows that poor educational results sometimes occur with direct delivery (lectures) of complex concepts, especially when such lectures occur without concurrent assessment of the learner's baseline understanding. The educator can act as a diagnostician by providing a pretest that would identify gaps in understanding. Alternatively, the educator can stop and pose a question to the audience during the lecture to check whether the learners are able to generate the correct answers. Anonymous electronic polling can assist constructivist educators to identify learner misconceptions. Incorrect responses can then be debriefed and corrected by the educator during the lecture itself.

Analogical Transfer

Analogical transfer scenario: *A fourth year medical student is accompanying you in the operating room while you provide anesthesia. She tells you about a liver transplant case that she saw yesterday, mentioning hemodynamic instability and massive transfusion requirements. While she is talking, you notice that your patient has become hypotensive. You quickly scan the work area and realize that the isoflurane has been set too high. Just before correcting the issue, you ask the medical student how she would treat the hypotension. She replies that she would give volume. Why did the medical student reply with this answer? Are there teaching techniques that could help avoid mistakes of this nature?*

Analogical transfer is the process by which the solution to one problem is used (transferred) to solve a new and analogous problem in another situation. The source problem, known as the analog, provides a mental template for the understanding of the new problem. For example, while testing various synthetic compounds for antispasmodic properties, pharmacist Otto Schaumann noticed that one of the drugs, meperidine, caused the tail of a mouse to curve in an S-shape. This physical effect had only ever previously been seen with morphine. Consequently, Schaumann conjectured that meperidine might also share the drug's analgesic effects. Further investigation concluded that meperidine did indeed contain narcotic properties similar to those of morphine.[30]

Analogical transfer appropriately occurs when the deep structure of 2 problems is the same. The surface structure of the problems can be different even when the deep structure is the same. For example, determining the current flow through a simple electric circuit and determining the rate of water flow in a pipe are 2 problems with different surface structures. However, these 2 problems are analogous because they share a common deep structure with Ohm's law. In both cases, flow is directly related to a gradient and is inversely related to a resistance. Once there is recognition by a learner that 2 problems share a common deep structure, the odds of analogical transfer increase significantly.[31]

Low road transfer refers to solving a new problem that shares both surface and deep structure with an analog. An extreme example of low road transfer is learning how to tie the laces of a shoe on the left foot and then applying that to the laces of a shoe on the right foot. Because of the shared surface structure, opportunities for low road transfer are often easily recognized by novices. Conversely, *high road transfer* refers to solving a new problem that shares little or no surface structure with its analog, but does share deep structure. An example of high road transfer is using the physiological principles that explain a decrease in end-tidal carbon dioxide associated with exsanguinating hemorrhage to explain the decrease in end-tidal carbon dioxide associated with spinal or epidural anesthesia. In both cases, reduced pulmonary blood volume and pulmonary blood flow give rise to increased dead space, although the causal (surface) elements differ somewhat. Novices have a difficult time recognizing analogs when surface structures differ, and educators can provide valuable learning opportunities by assisting novices identify opportunities for high road transfer when they exist.

Despite the great importance of analogical transfer, humans are surprisingly poor at using it in problem solving.[32] One study indicated that only 30% of subjects were able to use a previously shown analog to solve a new problem.[33] The difficulty arises in correctly identifying and

Box 1. An Example of a Constructivist Method of Educating

A medical student is observing a mitral valve repair. After the repair has been completed, the surgeon asks that the patient's pacemaker rate be increased from 60 to 90 bpm. The attending anesthesiologist asks the medical student what will happen to the cardiac output when the heart rate is increased. From his classroom experience, the medical student knows that cardiac output is the product of the heart rate and the stroke volume. The student states that increasing the heart rate by 50% will also increase the cardiac output by 50%. When asked for his rationale, the medical student recites the formula. The attending then increases the rate of the cardiac pacemaker, and the student observes that the measured cardiac output hardly changes. When asked to explain the discrepancy between what he proposed would happen and what actually happened, the student reflects and then correctly states that the stroke volume must not be an independent variable as he had assumed, and thus stroke volume may vary as a function of the heart rate.

matching the deep structural elements of both the new problem and the analog.

Surface structure can complicate the process in 2 ways. First, when the surface structure of a new problem differs from an appropriate analog, then the analog may fail to be recognized as a solution to the new problem. For example, hypovolemic shock is characterized by hypotension, a small and underfilled heart and a low central venous pressure (CVP). This constellation is easily recognized and volume infusion is the therapy of choice. In contrast, intra-abdominal hypertension (abdominal compartment syndrome) is characterized by hypotension, a small and underfilled heart and a high CVP. The high CVP may lead the learner to believe that the heart is full when in fact it is compressed and underfilled. In this case, the difference in surface structure (low versus high CVP) may result in a learner missing the common deep structure of these 2 forms of shock (an underfilled heart), which may cause the learner to avoid giving the needed volume therapy because of the high CVP.

The second way surface structure can complicate transfer is when a new problem's surface structure is the same as a possible analog, but the deep structure is different. In this situation, the analog may be incorrectly applied to the similar-appearing new problem. This process of identifying an analog and then using it inappropriately to solve a problem is known as *negative transfer*. Negative transfer is high when surface elements are similar.[34] For example, a hypotensive, hypovolemic, and tachycardic patient should be treated with volume to increase venous return, cardiac output, and arterial blood pressure. In response to this fluid infusion, the heart rate is expected to decrease. If a learner somehow thought that directly reducing the tachycardia would help treat the hypotension and did not appreciate that the tachycardia was reflexive and resulted from the primary problem of hypotension and hypovolemia, then the learner may incorrectly use a β-blocker to slow the heart rate. The learner would have recognized that in certain cases the resolution of hypotension is associated with resolution of the tachycardia (surface structure), but failed to understand the deeper structure of the problem, resulting in negative transfer. Of note, learners who can successfully identify and incorporate analogs when they do exist (*positive transfer*) are also better at avoiding negative transfer.[34]

Educators can improve the learners' successful use of analogical transfer by helping them develop schemata for problems that share similar deep structure. A schema acts as the abstract representation of a deep structure that is common to multiple problems and is useful in helping a learner to recognize opportunities for transfer. For example, the term "full stomach" can be viewed as a construct or a schema that means anything that predisposes the patient to aspiration. There are many examples that fit this abstract concept of "risk of aspiration" such as recent ingestion of a meal, severe reflux disease, achalasia, pregnancy, bowel obstruction, emergency surgery, etc. The benefit of a schema is that it functions as an analog already stripped of its surface elements. By developing schemata, learners decrease the likelihood of negative transfer and establish a repository of analogs that promote the probability of successful positive transfer.[35]

Educators who teach with more generic representations of a problem help learners create accurate schemata. Teaching with concrete examples has been shown to be less effective at promoting analogical transfer than teaching with abstract examples.[36] However, concrete examples tend to be more engaging for learners. Thus, presenting a concrete problem followed by a generic example may be an optimal instructional design to encourage transfer. If educators choose to use concrete examples exclusively, then offering multiple examples of the same type of problem with varied surface elements will help learners identify common deep structures and thereby create schemata. Concerns have been raised that the use of abstract teaching might compromise learning because it detracts from the authenticity of the educational experience. However, a recent study of third-year medical students indicated that differences in instructional authenticity (i.e., use of paper-based cases versus live standardized patients) did not affect subsequent clinical performance.[37] Interestingly, the authors felt that perhaps any advantage gleaned from increased authenticity might have been mitigated by drawbacks introduced from the increased cognitive load of a more complex instructional format.

Novice learners typically focus on surface structure and miss the deep structure. This makes analogical transfer difficult for the novice. When a novice makes an error in transfer, it is important for the educator to explain why the error is incorrect as opposed to simply telling the learner what to do without offering an explanation. Part of the educator's role is to assist the learner recognize common deep structure. This explanation will promote deeper learning that will help with subsequent transfer (effect sizes of 0.9–1.6).[38]

Verbalization of a problem's structure by the learner can also help promote successful analogical transfer because it assists in schema formation. When learners are required to explain how they arrived at a solution (a form of constructivism), they increase the likelihood of future positive transfer.[32] As the complexity of a problem increases, learners often have more difficulty articulating their thought processes, even if they are able to correctly solve the problem.[39] If a learner cannot express how the solution to a problem is determined, analogical transfer between that problem and similar problems will not happen. Explicit awareness of the deep structure of an analog is requisite for successful analogical transfer to occur.

In our initial scenario, the medical student exhibited negative transfer. She used surface structure (hypotension) to incorrectly transfer the solution used on a hypotensive hypovolemic patient (volume infusion) to treat a hypotensive normovolemic patient who had an isoflurane overdose. The educator now has an opportunity to use elements of constructivism by asking the student to compare and contrast different causes for hypotension in these different cases (hypovolemia and vasodilation). It is likely that the student will reveal his/her misunderstandings during the discussion, and the educator can then help correct them.

FOR LEARNERS

Goal Orientation: Learning Versus Performance Orientation

Goal orientation scenario: *While on call one night you give a resident the choice to take over a laparoscopic cholecystectomy on* *a healthy patient or to start an emergent repair of a ruptured aortic aneurysm. The resident opts to take care of the patient having the cholecystectomy. You recognize that this resident routinely avoids challenging yet highly educational cases in favor of cases he can easily manage. Why is this? Are there strategies that can be used to help individuals choose more challenging cases that will enhance their clinical skills?*

Achievement goal orientation, or simply goal orientation, refers to the implicit goals that individuals have for themselves when they are placed in an achievement situations (i.e., they have the opportunity to succeed or fail). These goals illustrate a person's dominant beliefs regarding self-improvement. They also predict how an individual will respond to challenges and failure. There are 2 predominant goal orientations: "performance orientation" and "learning orientation." Individuals with a performance orientation have a primary goal of validating their abilities, mainly by demonstrating their abilities to others. Because their primary goal is to validate their abilities, they also try to avoid revealing that they do not understand something or are not able to perform a task correctly. In contrast, individuals with a learning orientation have the primary goal of increasing their competency or mastery of a topic. Their actual mastery matters much more to them than how their mastery is perceived by others. A frequent misconception arises because of the terminology used in labeling goal orientations. "Performance orientation" and "learning orientation" do not mean that individuals focus on performing and learning, respectively. Instead, they refer to how an individual construes challenges, setbacks, or failures. In particular, when performance-oriented individuals encounter a setback, they will conclude that they are not able to do the task because they view a setback as diagnostic of their inherent (in)ability. They see abilities as fixed. In contrast, when learning-oriented individuals encounter a setback, they will conclude that they need to increase their effort or change their strategy to improve their competency because they construe a setback as diagnostic of a need to improve. Learning-oriented individuals view their abilities as malleable.

These 2 different goal orientations have been shown to directly influence how resident physicians view feedback regarding their performance.[40] Residents who have a strong learning orientation perceive feedback as beneficial. They do not see negative costs associated with receiving feedback. Consistent with their goal of mastery, a learning-oriented resident will use the feedback to help improve their performance. In contrast, residents who have a strong performance orientation perceive feedback as costly. They do not recognize the benefits associated with feedback. Performance-oriented residents view feedback as a mechanism to point out the areas of weakness that interferes with their goal of validating their skills and abilities. The relationship of performance orientation to the goal of validating one's ability and attempting to impress others was recapitulated with medical students.[41] The overall measure of performance orientation increased significantly in the third-year medical students during their clinical rotations. This may have occurred as they increased the goal of validating themselves, especially in front of faculty members and residents. Importantly, these orientations are independent constructs, and thus, a single individual can have a low, medium, or high learning orientation and either a low, medium, or high performance orientation.[42] For the purposes of performance improvement, a high learning orientation seems to be the key and needed attribute.

How an individual approaches a challenge or a setback can differ depending on their dominant goal orientation. Performance-oriented individuals will tend to avoid challenging situations for fear of appearing inept. Similarly, if the task requires a great deal of effort, or does not come easily, a performance-oriented individual is likely to simply conclude that they are "not good" at the task. Furthermore, if a task is attempted and failure results, these individuals will be very concerned with the resulting negative judgments made by others about their abilities. They will work to sidestep being placed in a similar situation in the future. Conversely, learning-oriented individuals view challenges as opportunities for growth. They see failures as useful for improving and they strive to learn and grow from their mistakes.[43] Learning-oriented individuals see effort and strategy as normal factors to be used for improving performance.

In an educational environment, particularly one beset with frequent challenges, it is ideal that the learner possesses a strong learning orientation. Although an individual may default toward either a performance orientation or a learning orientation, situational cues and a learner's educational environment can modify these tendencies.[42] This means that performance-oriented learners can be influenced toward a learning orientation through discussion and education. Such interventions have been shown to produce a significant change in an individual's goal orientation.[44] On a societal level, different cultures can affect the learning orientation of entire populations of people.[45,46] Thus, an educator can positively influence a learner's reaction to failure by creating an environment that emphasizes a learning orientation. This is especially beneficial for those learners who are naturally more performance oriented.[47] College students who received a low score on a test and who had an acute intervention that increased learning orientation were more interested in taking a remedial class to improve their scores than were the students who had an intervention that increased their performance orientation ($d = 1.1$).[48] In another study, college students who performed poorly on a test and were randomly assigned to an acute intervention that increased learning orientation were found to be more open to remediation and were less defensive ($d = 1.6$).[49] Educators who praise effort and strategy, encourage creativity and discovery, deemphasize the importance of natural ability, and reduce praise for static traits such as intelligence are promoting a learning orientation.

In our initial scenario, the resident appeared to hold a strong performance orientation because he consistently chose cases that he could successfully do so that he would validate his abilities to others. This will ensure that he "looks good," but it will not help the resident improve. The educator can help the resident choose the more challenging and educational cases (the ruptured abdominal aneurysm) by indicating to the resident that taking on challenges is the most effective path to improving performance. The educator must also ensure that when failures occur, no indications are made that would imply that these failures are because of some inherent limitation in the abilities of the resident. Instead, when challenges occur, the educator can provide concrete suggestions that will help improve the skills of the resident. Addressing setbacks with strategic actions and focused effort is consistent with a learning orientation. Praising a resident for effective actions they took or for useful efforts they made will also support a learning orientation. Because residency is characterized by frequent challenges, it behooves both the educator and the learner to adopt a learning orientation. In contrast, praising or complaining to a resident in a manner that implies that traits are static encourages a performance orientation. Telling a resident that they are "smart" (even though it is praise) focuses on innate ability over effort, self-improvement, and persistence, and will encourage a performance orientation.

Metacognition

Metacognition scenario: *You are assigned to provide anesthesia for a patient requiring tracheal resection and reconstruction. The night before the surgery, you read a chapter on the intricacies of the surgical procedure as well as a journal article on appropriate anesthetic management. After your review, you go to bed feeling well prepared for the case. However, the next day you are not able to easily remember some of the key concepts you thought you had mastered the night before. How did this happen? What can you do to prevent a similar episode in the future?*

Self-directed learning is a dynamic process in which learners choose objectives, monitor progress, and adjust study patterns accordingly.[50] A learner's ability to accurately monitor what he or she truly understands plays a critical role in effective learning. Metacognition is the act of thinking about one's own thinking and includes recognizing when one does or does not actually understand something. For example, if you were discussing a drug's mechanism of action with a colleague and you realized that you did not know how the drug worked on a deeper level, then you would have used metacognition to recognize the limits of your understanding. Metacognition also pertains to motor skills.[51] This means that some people can have poor motor skills and be unaware of it because of their poor metacognition. A related topic is metacomprehension, which is the term used to describe the awareness or understanding an individual has regarding his or her own level of comprehension about a topic. Accurate metacomprehension correlates with improved study patterns and better performance during testing.[52] More efficient learning occurs from learners with high metacomprehension, because they allocate the appropriate amount of time to subjects that are less well understood and spend little time reviewing items that have already been mastered. Unfortunately, human metacognition is generally poor.[53,54]

Learners should develop study habits that focus on improving metacognition. Deliberately creating a plan of how to approach a study topic can result in increased metacognition. For example, if a learner desires to know more about regional anesthesia, he or she should map the study guide dictating a systematic review of the subcategories of the topic (e.g., first reviewing upper extremity anatomy, then lower extremity anatomy, followed by the study of the characteristics of local anesthetics, and finishing with

Table 2. Concepts for the Learner

Description	Relationship to learning
Goal orientation: Goal orientation refers to the implicit goals that individuals have when in achievement situations. An individual whose main goal is to increase competence and strive toward mastery is said to have a learning orientation. These individuals tend to believe that their skills and abilities can be increased through effort and strategy. An individual whose main goal is to validate their inherent ability by demonstrating to others that they are competent is said to have a performance orientation. These individuals tend to believe that their skills and abilities are fixed.	Learning-orientated individuals readily accept feedback on how to improve and are willing to ask questions when they do not understand something. Performance-oriented individuals are unlikely to try difficult problem because they may fail. Both goal orientations are equally effective when there are no challenges.
Metacognition: Metacognition is thinking about one's own thinking. It is the cognitive process of reflecting on what one knows and understands. When an individual realizes that they do not understand the solution to a problem they are using metacognition to come to that realization.	Better metacognition is associated with better learning. This occurs because metacognition allows the learner to indentify and focus their studies on areas that are more poorly understood.
Retrieval: Retrieval is the active recall of information or a concept. The very act of recalling information enhances the memory of that information and makes it more available for future use. This is in contrast to restudy, which is the passive encoding of information or a concept (e.g., by reading or lecture) and does little to increase the future availability of information.	Retrieval strongly enhances the ability to again retrieve information in the future. Repeated retrieval enhances the durability of what was initially learned (encoded), so that it will be available for use at a later time
Spaced learning: Spaced learning refers to the insertion of distinct temporal gaps between learning episodes. This is in contrast to massed learning, which refers to learning with little or no time between learning sessions.	For a given total study time, spaced learning is more effective than massed learning for long-term retention. Longer interstudy intervals are more effective than shorter intervals. Spaced learning works for both learning new information and learning new motor skills.
Deliberate practice: Deliberate practice is designed to improve a specific area of one's performance. It requires working at the edge of competency, is effortful, usually difficult, requires feedback, and focuses on areas of weakness or areas that can be improved. As soon as the learner attains an element of comfort and fluency with their current level of performance, they are then in a good position to reapply deliberate practice to attain the next level of performance.	Deliberate practice can be applied to any aspect of performance. It is effective for both cognitive skills and motor skills. It is fair to say that expertise will not be attained without the regular use of deliberate practice to one's domain of performance.

strategies for ultrasound optimization). Once planning is completed and study has commenced, it is then important to periodically evaluate understanding to ensure that mastery of the previously reviewed concepts has been retained. Evaluation can be accomplished by self-testing through practice questions or flash cards, or even simply through deliberate mental review. The key is that by focusing on the process of learning and by regular self-evaluation, students can increase their awareness of what is known and what needs additional review (i.e., their metacognition) and thus improve learning.

Study Techniques That Improve Metacognition

Certain specific study techniques can naturally improve metacognition. For example, reading a passage more than once increases a learner's understanding of the material and also improves the learner's metacognition (i.e., it enhances the learner's awareness of which parts of the passage are well understood and which require more review).[55] Taking practice tests is another method that can aid in improving metacognition.[56]

Summarizing study material after a study session is another learning technique that has been examined extensively. Generating written summaries of the material reviewed has been shown to improve comprehension.[57] The act of summarizing better enables learners to determine which concepts are fundamental. They can then focus attention on these central elements. In addition, creating a summary acts as a form of self-testing, a practice which is known to improve metacognition. Some investigators argue that the enhanced comprehension that comes with summarization is primarily a result of improved metacognition.[57]

Of note, when summarization is used, metacognition is improved to a greater degree when material is summarized after a time delay.[52,58] Summarizing immediately after reviewing material allows a learner to easily recount concepts that are stored only in short-term memory. Much of this material will never transition to long-term memory. Thus, immediate and effortless recall after study can fool learners into believing that they have mastered the material when, in fact, that material may not shift into long-term memory. By summarizing after a delay, a learner will more accurately assess what concepts have actually been learned. Thus, delayed summarization alerts learners to material that has not been learned in a durable fashion and that deserves additional attention. By incorporating delayed summarization into their study, learners can improve overall comprehension and develop greater metacognition.[57] This can directly translate into better learning as reflected by better test performance.[52]

In our tracheal resection scenario, it is likely that the clinician was misled into believing that he or she fully understood the case because of a solid grasp of the steps and anesthetic considerations immediately after having read the material. Unfortunately, only a fraction of the recently read material made it into long-term memory, and thus, much of the material was lost and not available the following day when it was needed. This situation could be improved by simply taking a short (15–30 minutes) break after finishing the material and then trying to recount the salient features of the material. Any failure to recall key steps would then be detected, and these gaps could be repaired by reviewing the unlearned material.

Retrieval

Retrieval scenario: *You have always preferred teaching using the Socratic method where educators repeatedly ask learners questions to facilitate instruction. One day a resident tells you he strongly dislikes this method of education and believes it is less effective. The resident feels that when he is put on the spot he is unable to focus on learning. He states he prefers when the attending physicians simply tell him what they are thinking rather than "quizzing" him. Are the resident's concerns valid? Should you change your teaching style? Are there benefits to teaching by the Socratic method that might outweigh the discomfort felt by some learners when asked questions directly?*

Traditionally, students have learned new material by *encoding*, a process of taking in information by repeatedly reviewing the information until it is learned. Examples of encoding in formal education are reading textbooks and listening to lectures. Research has shown that this approach is not optimal for long-term retention.[59] Instead, study methods that require a student to *retrieve* (or pull out) information from memory will result in much better long-term retention of the information compared with simply rereading the material. One analysis demonstrated that, under certain conditions, study that incorporated retrieval resulted in correct answers on final testing 80% of the time, whereas a control group who used restudy without retrieval only answered 33% to 36% of final testing questions correctly.[60]

In 1978, Slamecka and Graf[61] investigated whether students who simply read a passage repeatedly would learn as much as students who attempted to recall details from memory after reading a passage. Slamecka and Graf found that the cohort who learned by retrieving answers from memory retained knowledge much better over the long term. Numerous subsequent studies have confirmed that learning using active retrieval (i.e., practice tests where the answers are not provided until after the test is completed) results in superior long-term memory when compared with learning that focuses on repeated encoding (i.e., rereading textbooks, relistening to lectures).[62,63] One study demonstrated that the learner's long-term retention (1 week) was improved by 4 SDs (Cohen $d = 4$) when using retrieval strategies compared with using the normal strategy of simply rereading the material.[60] This reinforces the concept that repeated retrieval is one of the most effective strategies to ensure that new material is learned in a durable fashion. More recently retrieval-based learning was directly compared with concept mapping, which is a strategy used to enhance understanding of conceptual material like that found in biological systems. Retrieval-based learning outperformed the well-known concept mapping technique with an effect size of 1.5.[64] Thus, retrieval-based learning augments conceptual learning in addition to its well-known effects on simple information retention. Retrieval exercises such as self-testing are also an effective way of improving metacognition.[59] Self-testing reveals gaps in knowledge and allows for more efficient and focused learning.[55]

Conventional wisdom says that after information is learned to the point where it can be recalled once, there is no benefit from additional study.[60] Research indicates otherwise and points to the usefulness of repeated recall. Continued study by repeated retrieval, even after the target study material can be successfully recalled once, results in significant positive effects on long-term retention. In contrast, additional study by encoding seems to provide little long-term benefit.[60]

Learners are generally unaware of the benefits of retrieval-based learning,[60] and thus educators should encourage learners to incorporate these methods into their study processes. Textbooks, journal articles, and didactic lectures are well suited for the initial exposure to new material. However, if the material is deemed important to know for long-term purposes, then further study of that material should incorporate active recall instead of simple review. Flashcards, when used appropriately, function well to promote retrieval. Similarly, actively recalling fundamental algorithms (i.e., advanced cardiac life support, malignant hyperthermia, difficult airway) will benefit a learner to a greater extent than repeated readings of the algorithm. Both educator and learner would profit from embracing greater use of the Socratic method in education,[65] because it is based on the principle of retrieval (and constructivism). By choosing retrieval-based exercises over simple encoding, learners can increase metacognition and enhance long-term information retention.

In our scenario, the learner prefers to be told information instead of being made to answer questions. However, the evidence favors having students retrieve the information after it has been presented. Thus, it is reasonable to tell the resident what he needs to know but then the educator needs to follow up to ensure that the learner can self-produce (retrieve) the information. The very act of retrieval is an act of learning and will help the resident to know the material in a much more durable fashion. Self-testing will also accomplish this goal and may be a useful approach for the motivated learner.

Spaced Learning

Spaced learning scenario: *Your board examination is coming up in 6 months and you are planning your study schedule. In college, you performed quite well by cramming for final examinations at the end of each semester. In medical school, you continued to get good grades; however, your method of preparing for examinations changed such that you spread your studying over a longer period of time. Which strategy should you use to prepare for your board examination? Is one superior to the other?*

Spaced learning is the practice of learning information by studying the material with distinct time intervals between each study period. In contrast, *massed learning* is learning information without significant interruption. Cramming for an examination is an example of *massed learning*. The results of >100 years of study[66,67] strongly support spaced learning over massed learning to achieve long-term retention of studied material. This benefit is known as the *spacing effect*, and it applies both to studying for knowledge acquisition and to practicing for motor skill development.[68] Spaced education has been used to increase practicing clinicians' medical knowledge of inappropriately ordered medical tests (d = 1.1).[69] This translated into 40% fewer inappropriate tests being ordered on actual patients.[69]

Hundreds of studies analyzing spaced learning have emerged, and the precise details of the spacing itself can appear quite different. Interstudy intervals can range from a few seconds to a few days, spacing schedules can be fixed or variable,[70] studied retention times can vary significantly, and the general domain of the material can differ dramatically from study to study. However, meta-analyses identify at least 3 consistent themes with regards to spaced learning.[67] First, regardless of the interstudy interval, spaced learning is always superior to massed learning. For example, a total study time of 2 hours is more effective when used as 4 30-minute sessions (with space between each session) compared with a single 2-hour session regardless of the time between sessions. Second, longer interstudy intervals are generally associated with better long-term retention (provided the interstudy interval is not increased to the point that the learner completely forgets the previous learning episode). Finally, spaced learning works equally well with verbal tasks and motor tasks, with the most substantial gains observed in tasks of lower complexity. Paradoxically, learners usually prefer massed learning and believe that it is more effective than spaced learning. This occurs despite their own test performance demonstrating the opposite results.[54] This means that learners can be fooled by the illusion that massed learning is more effective than spacing when in fact the opposite is true. This is an example of failure in the domain of metacognition. Interestingly, the spacing effect is not as readily apparent with computational or mathematical tasks.[71]

In the practice of medicine, the concept of spaced learning can be applied broadly. New residents striving to learn standard dosages of rarely used medications should focus on brief daily reviews of these values as opposed to studying them in longer, less frequent study sessions. Similarly, seasoned physicians hoping to improve their transesophageal echocardiography image acquisition abilities might opt for more regular practice with departmental simulators instead of attending an intensive 3-day crash course. Even at the curriculum level, educators may decide that 2 separate 1-month rotations in cardiac anesthesia are preferable to a single 2-month rotation. Given the evidence in favor of spaced learning, it is surprising that its application is not more ubiquitous.

In our scenario concerning how best to study for an upcoming examination, the evidence strongly supports spacing the study sessions over time instead of consolidating the study into a short high-intensity episode. For an equivalent total study duration, spaced learning will result in better long-term retention of the material. Both spaced learning and retrieval are examples of knowledge acquisition and retention strategies. Although they are distinct strategies, both of these approaches act as evidence that traditional methods of learning by lecture or simple review can be improved on.

Deliberate Practice

Deliberate practice scenario: *You hear about a colleague who recently canceled an elective case scheduled for general anesthesia because she recognized a small spontaneous pneumothorax on the patient's preoperative chest radiograph. You wonder if you* *would have caught such a subtle finding and recognize the need to improve your proficiency at reading chest radiographs. What is the best method to approach such a goal?*

To become expert in a given domain, it is essential to have experience. However, experience alone is insufficient to achieve mastery. By examining the practice methods of expert performers, Ericsson et al.[72] found that elite performers engaged in much more deliberate practice than lower level performers. Deliberate practice is a specific type of practice with the singular goal of improving performance. It is highly structured, focuses on overcoming weaknesses, and requires significant effort. Performance is monitored, and feedback is provided with the goal of enhancing performance. Deliberate practice focuses on well-defined tasks that are manageable in size and scope. The topic for practice should appropriately challenge the learner (i.e., the learner may not initially be successful at the task). The learner should also be afforded abundant opportunities for repetition to allow for correction of errors.[72]

It is also important to understand which activities do not represent deliberate practice. In a retrospective examination of the study habits of musical performers in an elite institution, the total amount of time spent in general musical activities did not vary between elite and average students.[73] Examples of general musical activities include time spent performing for an audience and playing for fun or practicing a piece from beginning to end without breaking it down and focusing more heavily on challenging sections. These general activities do not reflect deliberate practice and do not appear to promote mastery. When the various musical activities were further broken down and analyzed by type, it became clear that top students focused on a significantly larger portion of their time engaged in deliberate practice than did middle or bottom performers.[73] In an analysis of elite chess players, this theme emerged again.[74] Players who dedicated more time to studying chess positions and comparing their moves with those of a grandmaster subsequently attained higher rankings than did players who focused on playing games in tournaments or for fun. Across multiple other disciplines (sports,[75] memory,[76] spelling,[77] and typing[78]), the evidence supports the conclusion that elite performance can be linked to the amount of time spent in deliberate practice with effect sizes ranging from 0.4 to 1.2.[79]

Deliberate practice has been successfully applied to improving performance in a variety of medical skills. For example, deliberate practice has been used to significantly improve the performance of advanced cardiac life support,[80] central line placement,[81,82] lumbar puncture,[83] and thoracentesis[84] with effect sizes ranging from 1.9 to 3.9.

Additional factors also play a role in the development of elite performance. In addition to training and practice, Howe et al.'s[85] review of the literature identified early experiences in a field, individual preferences, opportunities, and an individual's habits, as determinants of excellence. Notably, there appears to be only modest evidence supporting the notion that innate talents or abilities are required to develop expertise in most fields.[85] Even if natural aptitude does confer a performance benefit, large additional gains can still be obtained through the consistent engagement in deliberate practice.[86] The concept that years of experience alone result in domain expertise has also been called into question.[87] In the field of medicine, physicians who have been in practice longer have been shown to be at risk of providing lower quality care.[88] This is likely because of a lack of continued focused training. A recent study explored how physicians learn in the workplace and found that physicians in practice did not engage in meaningful deliberate practice.[89] Conversely, high performers can maintain their abilities even into older ages if they persist in regular deliberate practice.[90,91]

There are abundant opportunities for learners in the medical field to incorporate deliberate practice into their education. For example, medical learners desiring to improve their ability to read electrocardiograms might gather and review a large number of tracings, interpret them on their own, and then check their conclusions with an expert such as a cardiologist who specializes in electrophysiology. Ideally, a learner would receive feedback from the cardiologist when an error was made. As learners become more adept, increasingly difficult electrocardiograms should be introduced to keep them practicing at the edge of their skills. This concept is broadly applicable and could easily be applied to interpreting arterial blood gas results, reading head computed tomograms, or diagnosing valvular lesions by transesophageal echocardiography.

Deliberate practice can also serve a particularly important role in developing abilities related to scenarios that are both difficult and uncommon. Studies have indicated that the reliable superiority of true experts is principally evident in more challenging cases.[92,93] Mastery of these more complex problems should be the goal of every learner aspiring for expert performance. The growth of medical simulation offers opportunities for deliberate practice in rare or challenging situations. Even in everyday practice, a motivated learner can create ways to rehearse vital but infrequently used skills. For example, practicing fiberoptic intubation on a patient who could be intubated via direct laryngoscopy is a method of increasing proficiency in a skill that is only necessary in infrequent but challenging situations.

The literature highlights that domain mastery can be achieved by those willing to engage in appropriate practice patterns, but it takes an enormous amounts of work to attain such expertise. Ericsson[87] and Ericsson et al.[94] estimate that it may require thousands of hours of deliberate practice to achieve elite performance. In the pursuit of excellence, there are no shortcuts. As Sloboda[95] aptly stated, "There is absolutely no evidence of 'fast-track' for high achievers."

Our initial scenario demonstrates that sophisticated or advanced levels of medical care are achievable when individuals engage in deliberate practice deigned to increase performance in targeted areas. There is every reason to believe that any clinician who is willing to engage in deliberate practice could ultimately reach this level of performance.

CAVEATS AND LIMITATIONS

The concepts reviewed in this article (cognitive load theory, constructivism, analogical transfer, goal orientation,

Table 3. Examples of Effect Sizes of Key Concepts on Learning

Cognitive load theory	
	Reducing extraneous load results in better learning (d ~ 1,[96] d ~ 1.2[11])
	Managing intrinsic load by dividing complex concepts into smaller and more cognitively manageable segments results in better learning (d ~ 0.9[96])
	Optimization of germane cognitive load through the use of metaphor or worked examples enhances learning (d ~ 1.3[10])
Constructivism	
	Constructivism improved learning, especially with more difficult concepts (d ~ 1,[27] d ~ 0.5[25])
	Constructivism outperformed traditional lecture-based learning of physics (d ~ 2[26])
Analogical transfer	
	Analogical transfer is improved when learners receive explanatory feedback compared with corrective feedback (d = 0.9–1.6[38])
	Analogical transfer is promoted when problems are taught with abstract representations (as opposed using concrete examples), so that deep structure is learned (d ~ 1.7[36])
	Reflection on recently learned material enhances subsequent transfer and more accurate medical diagnoses made by medical students (d ~ 1.0[97])
Goal orientation	
	Interventions that acutely increase learning orientation increase willingness to take a remedial tutorial after poor test performances (d ~ 1.1[48]). Students are also less defensive and more interested in remediation after a poor test performance (d ~ 1.6[49])
Metacognition	
	Delayed summarization results in better metacognition and better learning (d ~ 1–1.3[54])
Retrieval	
	Repeated retrieval is more effective than simple restudy (d ~ 4[60])
	Learners who benefit from retrieval are entirely unaware of its effect on learning (d ~ 0[60])
Spaced learning	
	Spacing learning sessions out over time results in better retention compared with massed learning (d ~ 1.4[70])
	Longer interstudy intervals generally results in more durable learning (d ~ 1.4[70])
	Practicing clinicians used spaced learning to increase their knowledge of inappropriate medical testing (d ~ 1.1[69])
Deliberate practice	
	Deliberate practice has been used to improve learning in cognitive domains (Physics, d ~ 2[98])
	Deliberate practice has been used to improve clinical skills (Advanced Cardiac Life Support, d ~ 2.8[80]; central line placement, d ~ 1.9–2.0,[81] lumbar puncture, d ~ 3.8,[83] and thoracentesis, d ~ 3.9[84])
	Deliberate practice had a range of effect sizes when a broad variety of domains (games, sports, music, education, and professions) were assessed (d = 0.4–1.2[79])

Effect size is given by Cohen d where 0.3 is small, 0.5 is medium, and 0.7 is large.[99]

metacognition, retrieval, spaced learning, and deliberate practice) rest on empirical evidence to support them (Table 3). The primary limitation of these concepts arises when teachers and learners attempt to implement them to improve education. Cognitive load theory is a nice example of a concept that has significant empirical evidence to support it as consequential for teaching and learning[96] but that has not been widely adopted into educational practice. Integrating cognitive load theory into educational practice would require developing educational content and then designing the educational process to optimally use cognitive load theory for the most efficient learning. There is little information about how to do this, never mind doing it in an optimal fashion. Most medical educators focus on content (the subject matter that they want to teach) and very few then design the teaching of that material using cognitive load theory to maximize teaching. Fortunately, Issa et al.[11] have published an example showing how they effectively used cognitive load theory to redesign a series of lectures for medical students on circulatory shock, which resulted in significantly better learning of the material at 4 weeks (Cohen d = 1.17). Such examples are currently rare. The limitations are thus 2-fold: many educators still do not know these concepts and far fewer know how to implement these concepts as strategies for better education. This partly stems from the fact that many of these concepts have been studied in highly controlled experimental settings but have not then been extensively tested in common educational environments. Fortunately, all of these concepts are now well supported and are represented in widely available peer-reviewed journals. The next steps to improving medical education are broader appreciation of these and other essential educational concepts by educators, followed by effective application of these principles to common educational environments.

CONCLUSIONS

As discoveries continue to expand our understanding of medicine, effective learning and teaching remain essential to both the development and the maintenance of a physician's knowledge base. Although there is no replacement for the amount of time dedicated to study, a better understanding of established learning and teaching methods can dramatically improve the effectiveness of the time spent in these activities. During the early years of training, it is fundamental that medical schools and residency programs use educational practices based on evidence as they plan curricula for educating physicians. After the completion of formal training, specific learning methods designed to enhance education and performance will assist practicing physicians as they strive to both maintain and grow their knowledge over the course of their career.

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