Improving learning

Cognitive science has taught us a lot about how humans learn. Now computer-based learning programs are putting those principles into action and improving student gains.

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Overview

CE credits: 1

Exam items: 10

Learning objectives: After reading this article, participants will be able to:

1. Identify some principles of learning that are grounded in cognitive science.
2. Describe some contemporary computerized learning environments.

This is one of those moments in history when people want to better understand how we learn. We worry about how well our children are learning, whether our schools are meeting educational standards and whether we are keeping up in competition with other countries. The signals are obvious. Parents want to believe that their children are above average and destined to receive the highest degrees in science, law, medicine, engineering and other areas that draw high salaries. The school systems are on a survival course to meet the idealistic, and sometimes naïve, visions of politicians who announce the new missions of *No Child Left Behind* and *Race to the Top*. Citizens wonder how American students compare with students in other countries and are horrified to learn our students rank below them. Meanwhile, the Institute of Education Sciences, National Science Foundation, Department of Defense and various foundations are investing serious money in learning.

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But it could be argued that researchers in cognitive science and education already know quite a lot about learning. There have been hundreds of scholarly reviews in journals and books and dozens of reports prepared by government-funded research panels. As an example, I have had the opportunity to work on a practice guide for teachers on "Organizing Instruction and Study to Improve Student Learning" (Pashler, Bain, Bottge, Graesser, Koedinger, McDaniel, and Metcalfe, 2007, http://ies.ed.gov/ncee/wwc/pdf/practiceguides/20072004.pdf), an initiative of the Institute of Education Sciences (IES) in the U.S. Department of Education. Another effort examined the cognitive principles of learning in an initiative called "Lifelong Learning at Work and at Home" (Graesser, Halpern, & Hakel, 2007, www.psyc.memphis.edu/learning/whatweknow/index.shtml) that was launched by APA and the Association of Psychological Sciences. NSF has invested heavily in Learning Science centers throughout the country. "How People Learn" (Bransford, Brown & Cocking, 2000) is an influential National Academy of Sciences report that reviews the foundations of the learning sciences and educational practice. There have also been scientific guidelines for the development of educational technologies, such as distance learning (O'Neil, 2005) and multimedia (Mayer, 2009).

These efforts have had a strong foundation in cognitive science, which is a departure from consensus opinions of experts with no grounding in science or of politicians who are grandstanding with a political agenda.

In this article, I hope to accomplish two goals. The first goal is to identify some principles of learning that are grounded in cognitive science. The second is to describe some advanced learning environments that attempt to weave in these principles and thereby improve education.

The ideal learner

The ideal vision of learning is that it be broad, deep, fast, precise and practically relevant. However, these virtues set a high bar that is rarely reached in current educational settings, particularly in a world of commercial informal media that are replete with distractions.

Many Americans worry that our learning is narrow, shallow, slow (or nonexistent) and vague, with a focus on frivolous content. Imagine a teenager spending 30 hours a week playing games, with no interest in formal academic content. That teenager, however, might be gaining important skills of managing limited resources, multitasking and communication with peers that scale up to the real world (Gee, 2004; Shaffer, 2007). Students can also benefit from serious games that smuggle in important academic content (Ritterfeld, Cody, & Vorderer, 2009). However, there are limits to the quality of the knowledge, skills and strategies that most games can teach us. In work settings, too, managers have limited resources for employee training, particularly at times of extreme economic recession. These challenges do not present a pretty picture for the ideal vision of learning.

The ideal vision of learning encourages self-regulated learning (Pintrich, 2000; Schunk & Zimmerman, 2008). Such learners formulate their own learning goals, track their progress on achieving these goals, identify their knowledge deficits, detect contradictions, ask good questions, search relevant information sources for answers, make inferences when answers are not directly available and build knowledge at deep levels of mastery. Unfortunately, the vast majority of adolescents and adults don't acquire these sophisticated cognitive skills. In order for self-regulated learning to succeed, a person has to have sufficient "meta" knowledge about cognition, emotions, communication and social interaction (Hacker, Dunlosky, & Graesser, 2009). Meta-comprehension is the knowledge we have about our comprehension processes. Examples include the need to slow down our pace of reading when the material is difficult and to scrutinize whether a text has contradictory claims. Meta-emotion is the knowledge a person has about the nature and regulation of their emotions, such as being patient and trying harder when material is confusing. Meta-communication is knowledge about the communication process, such as the insight that there can be discrepancies between the author's intended meaning and the meaning that a reader constructs. Meta-social knowledge is knowledge about social interactions, politeness norms, status, deception and so on.

Unfortunately, most adults don't acquire meta-knowledge so they need direct training to fill this void. For example, deep comprehension of technical text involves understanding underlying mental models of complex systems, causal relationships between events and explanations of why events occur. Strategies of comprehending material at deeper levels are underdeveloped in most children and adults, particularly for technical text, so they need deep comprehension strategy training (McNamara, 2007).

Computerized learning environments have grown in sophistication, particularly during the last decade. They are available to all web users, but they are not used by most K–12 students, the work force or households — a deficit in access that is expected to change in the short-term.

There is a modest ($r = .27$) correlation between college students' impressions of how well they comprehend technical text and their actual test scores on the text (Maki, 1998). Students have serious limitations in their knowledge or judgments of memory, comprehension, learning, planning, problem-solving and decision processes (Hacker et al., 2009). As a consequence, they are not good at planning, selecting, monitoring and evaluating their strategies of self-regulated learning (Azevedo & Cromley, 2004; Winne, 2001), of question-based inquiry learning (White & Frederiksen, 2005; Wiley et al., 2009), and of learning through active discovery (Kirschner, Sweller, & Clark, 2006; Klahr, 2002).

Students, whether children or adults, need to have explicit training, modeling and guided practice before they can acquire adequate strategies of deep comprehension, critical thinking, self-regulated learning, inquiry learning, discovery learning and other sophisticated active forms of learning.

Principles of learning

As previously mentioned, researchers from various scientific communities have identified some principles of learning that are supported by empirical evidence and learning theories. There were seven cognitive principles identified in the IES report by Pashler et al. (2007):

1. *Space learning over time.* Spaced schedules of studying and testing produce better long-term retention than a single study session or test.

2. *Interleave worked example solutions with problem solving exercises.* Presenting the students step-by-step solutions to problems should be intermixed with having the students solve the problems by themselves.

3. *Combine graphics with verbal descriptions.* Materials presented in verbal, visual and multimedia form richer representations than a single modality or medium.

4. *Connect and integrate abstract and concrete representations of concepts.* An understanding of an abstract concept improves with multiple and varied concrete examples.

5. *Use quizzing to promote learning.* Testing enhances learning, particularly when the tests are aligned with important content.

6. *Help students allocate study time effectively.* Students need to allocate more time on difficult material and to have repeated practice for some concepts and skills. Outlining, integrating and synthesizing information produces better learning than re-reading materials or other more passive strategies.

7. *Ask deep explanatory questions.* Students benefit more from asking and answering deep questions that elicit explanations (e.g., why, why not, how, what if) than shallow questions (e.g., who, what, when, where).

The 25 cognitive principles of learning in "Lifelong Learning at Work and at Home" (Graesser, Halpern, & Hakel, 2007) included these principles, plus many others. It is beyond the scope of this article to cover all of them, but the spotlight will shine on 10 more:

1. *Contiguity.* Ideas that need to be associated should be presented contiguously in space and time.

2. *Perceptual-motor grounding.* Student learn better when teachers link concepts to concrete perceptual motor experiences, particularly at early stages of learning.

3. *Generation effect.* Learning is better when learners actively produce answers, rather than merely recognize answers as in multiple choice questions.

4. *Stories and example cases.* Learners tend to remember stories and example cases better than didactic facts and abstract principles.

5. *Feedback.* Students benefit from feedback on their performance in a learning task, with the timing depending on the task. Learning incorrect information can be reduced when students are given immediate feedback.

6. *Manageable cognitive load.* Learning materials should not overload working memory.

7. *Cognitive disequilibrium.* Deep reasoning and learning is stimulated by problems that create cognitive disequilibrium, such as obstacles to goals, contradictions, conflict and anomalies.

8. *Cognitive flexibility.* Students' cognitive flexibility improves when they are presented with multiple viewpoints that link facts, skills, procedures and deep conceptual principles.

9. *Goldilocks principle.* Assignments should not be too hard or too easy, but at the right level of difficulty for each student's skill and prior knowledge.

10. *Anchored learning.* Learning is deeper and students are more motivated when the materials and skills are anchored in real-world problems that matter to the learner.

These principles emphasize the cognitive foundations of learning, but it is important also to consider the important psychological factors of motivation, emotion, social interaction, personality, development and neuroscience.

Computer technologies that help people learn

Unfortunately, most "experts" in pedagogy have not received adequate training to implement these principles of learning, so most of the pedagogical techniques are absent when we examine videotapes of tutoring and classroom teaching (Graesser, D'Mello, & Cade, in press; Graesser, Person, & Magliano, 1995). As a result, some researchers in cognitive science have turned to computers to implement the sophisticated strategies.

Computerized learning environments have grown in sophistication, particularly during the last decade. The major categories of these environments are: traditional computerassessed instruction, multimedia, interactive simulation, hypertext and hypermedia, intelligent tutoring systems, inquiry-based information retrieval, animated pedagogical agents, virtual environments, serious games and computer supported collaborative learning.

All of these are available to Web users, but they are not used by the majority of students in K–12, the work force and households — a deficit in access that is expected to change in the short-term.

Most of the public is familiar with traditional computer-assisted instruction. These systems adapt to individual learners at a course-grain level that incorporates the learning principles of organization, feedback and the Goldilocks principle. That is, the learner studies material presented in a lesson, gets tested on it, gets feedback on the test performance, re-studies the material if the performance is below threshold and progresses to a new topic if performance exceeds threshold. The order of topics presented and tested typically follows a predetermined order, such as moving from simple to complex. The materials presented include text with figures, tables and diagrams (essentially books on the web), multimedia, problems to solve, example problems with solutions worked out and other classes of learning objects. Traditional computer-assisted instruction is a mature technology that improves learning over and above traditional classroom teaching (Dodds & Fletcher, 2004).

Intelligent learning environments go a giant step further by enhancing the adaptability, grain-size and power of computer-based training. Unlike traditional computer-assisted instruction, every intelligent learning environment offers unique tutorial interaction and possible interactions are infinite. For example, intelligent tutoring systems attempt to fill in very specific learning deficits, to correct very specific misconceptions and to sequence material dynamically. Several intelligent learning environments incorporate cognitive principles of learning. All of these systems have been tested on thousands of students and improve learning by approximately a letter grade compared with standard classroom environments, according to some evaluations (Dodds & Fletcher, 2004; Graesser, Conley, & Olney, in press).

One prominent example is the Cognitive Tutors, developed by the Pittsburgh Science of Learning Center and Carnegie Learning (Ritter, Koedinger, Anderson, & Corbett, 2007). The Cognitive Tutors help students learn algebra, geometry and programming languages by applying learning principles inspired by the ACT-R cognitive model (Anderson, 1990). There is a textbook and curriculum to provide the content and the context of learning, but the salient contribution of the Cognitive Tutors is to help students solve problems. The Cognitive Tutors are now used in over 2000 school systems nationwide. According to Ritter et al. (2007), standardized tests show that the use of the program improves student learning over suitable control conditions and is particularly effective for difficult subcomponents of problem-solving and for the use of multiple representations. Other successful intelligent tutoring systems environments have been developed for quantitatively well-formed topics, including mathematics (*ALEKS*: Doignon & Falmagne, 1999), physics (*Andes, Atlas,* and *Why/Atlas*: VanLehn et al., 2007) and electronics (*SHERLOCK*: Lesgold, Lajoie, Bunzo, & Eggan, 1992).

Intelligent learning environments also handle subject matters and skills that have a stronger verbal foundation, rather than mathematics and precise analytical reasoning. The *Intelligent Essay Assessor* (Landauer, Laham, & Foltz, 2003) and *e-Rater* (Attali & Burstein, 2006) grade essays on science, history and other topics as reliably as experts of English composition (Shermis, Burstein, Higgins, & Zechner, 2010). *AutoTutor* (Graesser et al., 2004; VanLehn et al., 2007) helps college students learn about computer literacy, physics and critical thinking skills by holding conversations in natural language. These systems automatically analyze language and discourse by incorporating recent advances in computational linguistics, information retrieval, and statistical analyses of world knowledge (Landauer, McNamara, Dennis, & Kintsch, 2007).

Animated conversational agents — automated talking heads — have played a prominent role in some of the more recent intelligent learning environments. These agents act like human tutors and peers. They help students learn by modelling good learning practices or by holding conversations with them. Single agents model individuals with different knowledge, personalities, physical features and styles. Groups of agents model social interaction. The agents may take on different roles: mentors, tutors, peers, players in multiparty games or avatars in the virtual worlds. The students communicate with the agents through speech or keyboard, whereas the agents express themselves with speech, facial expression, gesture, posture and other embodied actions. AutoTutor (Graesser et al., 2004) is one example of an animated agent that tutors the student through conversation. AutoTutor's dialogues are organized around difficult questions and problems that put the student in cognitive disequilibrium and that require lengthy explanation-based reasoning in the answers. Students often become confused and frustrated with these challenges, so a version was developed to be responsive to the students' emotional states in addition to their cognitive states (D'Mello & Graesser, 2010).

A number of other systems with conversational agents also incorporate cognitive principles of learning. They, too, have been tested on thousands of students, who have shown solid learning gains compared with control conditions. For example, *Interactive Strategy Trainer for Active Reading and Thinking, iSTART* (McNamara, O'Reilly, Rowe, Boonthum, & Levinstein, 2007) helps students understand science content during reading by generating explanations of the text while they read. A system called *iDRIVE (Instruction with Deep-level Reasoning questions In Vicarious Environments)* has dyads of animated agents train students to learn science content by modeling deep reasoning questions in question-answer dialogues (Gholson & Craig, 2006). *Tactical Language and Culture System* (Johnson & Valente, 2008) helps students learn the language and cultural norms of other nations by immersing them in a virtual world with agents. These intelligent learning environments are very different from the page-turning systems with fill-in-the-blank questions or multiple-choice questions that many associate with computer-based learning.

Some intelligent learning environments under development are designed to train people about meta-knowledge and self-regulated learning. MetaTutor (Azevedo et al., 2009) trains students on 13 strategies that are theoretically important for self-regulated learning, a process that involves constructing a plan, monitoring meta-cognitive activities, implementing learning strategies, and reflecting on progress and achievements (Pintrich, 2000; Winne, 2001). There is a main agent (Gavin) that coordinates the overall learning environment and three satellite agents that handle three phases of self-regulated learning, namely planning, monitoring and applying learning strategies. These phases are broken down into the 13 SRL strategies. Planning involves constructing goals and methods to achieve the goals. Metacognitive monitoring includes judgments of learning, feeling of knowing, content evaluation, monitoring the adequacy of a strategy, and monitoring progress towards goals. Examples of learning strategies include searching for relevant information in a goal-directed fashion, taking notes, drawing tables or diagrams, re-reading, elaborating the material, making inferences, and coordinating information sources (text and diagrams). Each of these metacognitive and self-regulated learning skills is tracked during the course of the student's interacting with MetaTutor and the profile of skill mastery guides MetaTutor's activities.

Serious games are being developed to make these learning environments more motivating. This is particularly important when the content is difficult and the students experience cognitive disequilibrium. Students are prone to become confused, frustrated and eventually bored to the point of disengaging from the learning activities (D'Mello & Graesser, 2010). Recent intelligent learning environments have been embedding the serious content and skills in game environments in order to offset the threats to motivation and persistence (Ritterfeld, Cody, & Vorderer, 2009). Games have the potential to turn serious learning into an engaging state of flow (Csikszentmihalyi, 1990), when concentration is so extreme that time and fatigue disappear. Imagine the hard work of learning difficult material being converted into play (Lepper & Henderlong, 2000).

One recent system under development called *Operation ARIES! (Acquiring Research Investigative and Evaluative Skills)* helps students acquire scientific critical thinking skills in a game environment that is integrated with an eBook and several animated pedagogical agents that interact with the student in natural language (Millis, Cai, Graesser, Halpern, & Wallace, 2009). The design of ARIES is directly aligned with cognitive principles of learning, self-regulated learning and also the motivational components of games (e.g., narrative, fantasy, feedback, interactivity, challenge, and control). Coordinating these three sets of constraints is a daunting challenge that may end up being impractical or impossible. But perhaps we will see the day when serious games are ubiquitous in schools, home and the work force.

If or when that happens, deep learning will be fun, rather than painful. ■

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