Applying the Science of Learning to Undergraduate Science Education

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Paper commissioned for the Committee on the Status, Contributions, and Future Directions of Discipline Based Education Research of the National Academies Board of Science Education

January 16, 2011

Introduction

Goal

The science of learning is the scientific study of how people learn. For more than 100 years, researchers have been taking a scientific approach to understanding how learning works--with early examples being Ebbinghaus's (1964) classic studies in 1885 of how people learned and remembered lists of nonsense syllables or Thorndike's (1911) classic studies in 1899 of how hungry cats and dogs learned to escape from a puzzle box. Within the past 50 years, cognitive approaches based on research with humans have come to dominate the study of learning, and within the past 30 years, research on learning increasingly has been carried out with educationally relevant materials and within educationally relevant contexts. The goal of this report is to explore whether the science of learning has produced a core set of general cognitive principles that are relevant to undergraduate science education. In short, the goal is to apply the science of learning to undergraduate science education.

History

The relation between psychology and education has been a rocky road over the past 100 years consisting of three main segments: (a) a one-way street, in the early 1900s, in which basic researchers sought to create a science of learning and educators were supposed to apply it; (b) a dead-end street, in the mid-1900s, in which basic researchers created a science of learning based on contrived learning situations that had little relevance for educational practice and educators created instructional practices that were unrelated to learning theory; and (c) a two-way street, in the later 1900s and beyond, in which researchers test learning principles in authentic learning situations and educators use evidence-based instructional principles that are grounded in learning theory (Mayer, 2010). The two-way street has been the most productive relationship between psychology and education, because education challenges psychologists to build learning theories that apply to real learning situations and psychology challenges educators to use instructional methods that are consistent with how people learn.

Rationale

What is the proper relation between the science of learning, which seeks to understand the basic theoretical question of how learning works, and the science of instruction, which seeks to address the applied practical question of how to design instruction that works? A common view is to see theoretical (or basic) research and practical (or applied) research as two opposite ends of a continuum, but the continuum metaphor is somewhat unproductive because it leads to a one-way street or dead-end street approach. Figure 1 (adapted from Stokes, 1997) presents a more productive conception of the relation between practical and theoretical research goals, in which a researcher can have one of four combinations of goals: (a) no practical goal and no theoretical goal, which can be called poor research; (b) a theoretical goal but no practical goal, which can be called pure basic research; (c) a practical goal but no theoretical goal, which can be called pure applied research; and (d) a theoretical goal and a practical goal, which can be called “use-inspired basic research” (Stokes, 1997) or “basic research on applied problems” (Mayer, 2010). This report focuses on this fourth quadrant in which researchers have overlapping goals of contributing to both the science of learning and the science of instruction, as this has proven to be a productive approach for both learning theory and educational practice.

FIGURE 1

What Does Learning Science Have to Offer?

What does cognitive science have to offer anyone who is interested in improving undergraduate science education? Three main contributions of cognitive science that are relevant to education are a focus on:

cognitive representations--Knowledge is at the heart of learning and instruction because the goal of instruction is to cause a change in the learner’s knowledge. Cognitive science offers ways of describing and measuring the learner’s knowledge (or cognitive representations).

cognitive processes--Cognitive processing is the key to learning and includes attending to relevant incoming material, mentally organizing it into a coherent structure, and integrating it with relevant prior knowledge. Cognitive science offers ways of describing and measuring cognitive processes during learning.

the human information processing system--Knowledge construction and cognitive processing take place within the learner’s information processing system. Cognitive science offers a description of the architecture of the human information processing system.

Overall, advances in cognitive science are highly relevant to the task of applying the science of learning to education.

Several related contributions of cognitive science that are relevant to science education are a focus on:

the role of domain specific knowledge--Building on research in expertise, a consistent theme in cognitive science is that some knowledge and skills are domain specific, so that knowledge and skills that support performance in one school subject may not be relevant to another. This contribution leads to a focus on psychologies of subject matter, that is, understanding how people learn in different subject areas such as reading, writing, mathematics, science, and history (Mayer, 2004a, 2008).

the role of cognitive strategies--Another theme is that successful performance on complex tasks requires cognitive strategies, including strategies for devising a plan. This contribution leads to focus on cognitive strategy instruction (Pressley & Woloshyn, 1995).

metacognition and motivation--Another highly relevant theme is that effective learning depends on learners’ awareness and control over their learning processes (i.e., metacognition) and learners’ effort to learn (i.e., motivation). This contribution leads to a focus on metacognition (Hacker, Dunlosky, & Graesser, 2009) and motivation (Wentzel & Wigfield, 2009) in learning.

multimedia--A final theme is that people have separate information processing systems for words and pictures. This contribution leads to a focus on multimedia learning that adds visualizations to verbal material (Mayer, 2009).

Overall, cognitive science contributes to core issues in undergraduate science education including the role of prior knowledge in learning (including the learner's preconceptions), the nature of constructing mental models during learning (including conceptual change), and teaching skills for scientific reasoning and scientific argumentation.

What Are Obstacles to Applying the Science of Learning to Science Education?

The current state of the field of research on science education is somewhat contentious, fragmented, and in some cases, lacking in methodological rigor. These disagreements can subject the field to the threat of becoming driven by ideology rather than evidence.

First, there are curricular disagreements about what counts as science education, such as whether students should acquire scientific information, conceptual understanding of key models and concepts, or how to engage in scientific reasoning and argumentation. A reasonable solution is to propose that proficient performance on most scientific tasks requires a collection of competencies including basic knowledge, conceptual knowledge, procedural knowledge, strategic knowledge, and productive beliefs.

Second, there are instructional disagreements over whether students should be taught using direct instruction, guided exploration, or pure discovery and open discussion. A reasonable solution is to base instructional decisions on research evidence and a cognitive theory of theory of how people learn, in which case pure discovery would not be recommended as an effective instructional method for novices.

Third, there are philosophy of science disagreements concerning what counts as research in science education, with some sides focusing on ideological approaches, and others disagreeing over the role of qualitative versus quantitative measures and observational versus experimental methodology. Critics claim that some educational research is of low scientific quality and that some educational researchers lack adequate training in educational research methodology (Phye, Robinson, & Levin, 2005). A reasonable solution is to select rigorous scientific research methods that suit the research question rather that to base research approaches on ideology. When the goal is to determine the effect of an instructional method on student learning, experimental methods are called for (Shavelson & Towne, 2002). What is needed is high-quality research that addresses important theoretical and practical issues.

Introduction to Applying the Science of Learning to Science Education

Is there a core set of general learning principles that are relevant to undergraduate science education? This section explores how to apply to the science of learning to science education (as described in Mayer, 2010), and is broken down into three complementary topics: how learning works (i.e., the science of learning), how instruction works (i.e., the science of instruction), and how assessment works (i.e., the science of assessment).

Science of Learning

The science of learning is the scientific study of how people learn. The goal of the science of learning is a research-based model of how learning works.

Learning is a change in the learner's knowledge attributable to the learner's experience. A change in the learner's knowledge can be inferred from a change in the learner's behavior.

During the past 100-plus years, the science of learning has produced three distinct models of how learning works--*learning as response strengthening, learning as information acquisition*, and *learning as knowledge construction* (Mayer, 2010). In the response-strengthening model, which developed in the early 1900s, learning involves strengthening and weakening of associations so the teacher's role is to dispense rewards and punishments, the learner's role is to receive rewards and punishments, and a typical instruction method is drill and practice. In the information-acquisition model, which developed in the mid-1900s, learning involves adding information to memory, so the teacher is a dispenser of information, the student is a recipient of information, and a typical instructional method is lecturing. In the knowledge-construction model, which developed in the late 1900s, learning involves building mental representations, so the teacher is a cognitive guide, the learner is a sense maker, and a typical instructional method is guided discovery. A possible fourth model of learning is social knowledge construction, which posits that knowledge construction is facilitated by (or depends on) social interaction so a typical instructional method is group discussion and activity. Although all models have an influence on current educational practices, my focus in this report is on knowledge construction because it is today's dominant view in educational psychology.

Figure 2 shows a model of how learning works that is based on three basic principles from cognitive science: (a) *dual channels principle*--people have separate channels for processing verbal (i.e., printed or spoken words) and visual material (indicated by the two rows in Figure 2); (b) *limited capacity principle*--people can process only small amounts of material in each channel at one time (indicated by the "working memory" box); (c) *active learning principle*--meaningful learning occurs when learners engage in appropriate cognitive processing during learning such as attending to relevant incoming material, mentally organizing incoming information into a coherent representation, and integrating it with relevant prior knowledge (indicated by the selecting, organizing, and integrating arrows, respectively).

FIGURE 2

As can be seen, instructional experiences (shown on the left side) enter sensory memory through learner's eyes and/or ears. If the learner attends to the fleeting sensory input some of the words and pictures are transferred to working memory for further processing as indicated by the "selecting" arrows. In working memory, the learner can mentally organize the incoming verbal material into a verbal model and organize the incoming visual material into a pictorial model as indicated by the "organizing" arrows. Finally, the learner can integrate the verbal and pictorial models with each other and with knowledge activated from long-term memory, as indicated by the "integrating" arrows.

In addition, motivation and metacognition play essential roles in learning (Hacker, Dunlosky, & Graesser, 2009; Wentzel & Wigfield, 2009). Motivation is an internal state of the learner that initiates and maintains goal directed behavior, such as effort to learn (Mayer, 2010). Five conceptions of how motivation works are: (a) *interest*--people work harder to learn material that has personal value to them; (b) *beliefs*--people work harder to learn when they believe their efforts will be effective; (c) *attributions*--people work harder to learn when they attribute their successes and failures to effort rather than ability; (d) *goals*--people try harder to learn when their goal is to master the material; and (e) *partnership*--people try harder to learn when they view their instructor as a someone who cares about them. In short, learners must be motivated to engage in the cognitive processes shown in Figure 2.

Metacognition is the learner's awareness and control of cognitive processing during learning. For example, comprehension monitoring is a learner's awareness of how well he or she understands a lesson. In Figure 2, metacognitive skill is needed to coordinate the cognitive processing required for meaningful learning.

Science of Instruction

The science of instruction is the scientific study of how to help people learn. The goal of the science of instruction is a set of evidence-based principles for how to design effective instructional methods.

Instruction is the instructor's manipulation of the learner's environment in order to foster learning. Instruction affects the learner's experience, which in turn affects the knowledge that is learned, which can be evaluated by observing the learner's performance.

Sound instructional design begins with a clear statement of the instructional objective. An instructional objective is a description of the intended change in the learner, and includes a description of (a) what is learned, (b) how it is used, and (c) how to evaluate the learner's performance.

Knowledge is at the heart of learning of instruction, because the goal of instruction is to promote a change in the learner's knowledge. Research in cognitive science has identified five kinds of knowledge: *facts*--factual knowledge about the world; *concepts*--categories, schemas, models, or principles; *procedures*--step-by-step processes; *strategies*--general approaches; and *beliefs*--thoughts about learning (Anderson et al., 2001; Mayer, 2010).

Based on the model of learning presented in Figure 2, instructional designers should be sensitive to three kinds of demands on the learner's limited cognitive capacity during learning: *extraneous processing*--cognitive processing during learning that does not support the instructional object and may be caused by poor instructional design or poor learner strategies; *essential processing*--basic cognitive processing during learning aimed at mentally representing the presented material (i.e., selecting in Figure 2) and that depends on the complexity of the essential material in the lesson; *generative processing*--deep cognitive processing during learning (i.e, organizing and integrating in Figure 2) that are caused by the learner's motivation to make an effort to learn (Mayer, 2009, 2010). This model is derived and adapted from Sweller's (1999) cognitive load theory.

Figure 3 summarizes three instructional scenarios concerning the three demands on cognitive capacity. In the *extraneous overload situation*, the learner uses so much cognitive capacity during learning that there is not enough cognitive capacity left over for the essential and generative processing that is required for the learner. The solution is to design instruction in ways that reduce extraneous processing, thereby freeing up cognitive capacity that can be used for essential and generative processing. In the *essential overload situation*, although extraneous processing has been minimized, the amount of essential processing required for learning exceeds the learner's cognitive capacity. The solution is to design instruction in ways that manage essential processing. In the *generative underutilization situation*, the learner has cognitive capacity available but opts not to use it for generative processing. The solution is to design instruction in ways that foster generative processing. In the upcoming section on research-based instructional principles, the principles are organized by whether they are intended to reduce extraneous processing, manage essential processing, or foster generative processing.

FIGURE 3

Science of Assessment

The science of assessment is the scientific study of how to determine what people know (Pellegrino, Chudowsky, & Glaser, 2001). The goal of the science of assessment is to develop valid and reliable instruments for assessing learning outcomes (as well as learning processing and learning capabilities).

Assessment may take place: (a) before instruction (i.e., pre-assessment) to determine the characteristics of the learner in order to plan appropriate instruction; (b) during instruction (i.e., formative assessment) to determine what the learner is learning in order to adjust ongoing instruction; and (c) after instruction (i.e., summative assessment) to document student learning in order to support program revision and accountability (Mayer, 2010).

Research on instructional effectiveness can focus on three kinds of issues: (a) determining whether an instructional method causes learning (i.e., what works?) using experimental comparison; (b) determining whether an instructional method works better for certain kinds of learners, instructional objectives, or learning environments (i.e., when does it work?) using factorial experimental comparison; and (c) determining the mechanisms underlying the effectiveness of the method (i.e., how does it work?) using observational analysis, interview, or questionnaire techniques. There is consensus among educational researchers that experimental methods are best suited for determining casual effects of instruction (Pellegrino, Chudowsky, & Glaser, 2001; Shavelson & Towne, 2002). The most common metric for evaluating instructional effectiveness in experimental comparisons is effect size, such as Cohen's *d* (Cohen, 1988), which is computed by subtracting the mean test score of the control group from the mean test score of the treatment group and dividing by the pooled standard deviation. Hattie (2009) proposed that an effect size greater than *d* = .4 is educationally important, and Cohen (1988) classified anything above *d* = .8 as a large effect, *d* = .5 as a medium effect, and *d* = .2 as a small effect.

Two major types of tests are retention tests, which evaluate the learner's recall or recognition of the material (i.e., remembering), and transfer tests, which evaluate the learner's use of the material in a new situation (i.e., understanding). Figure 4 summarizes three kinds of learning outcomes that can be detected using retention and transfer tests: (a) *no learning*, in which students perform poorly on retention and transfer tests; (b) *rote learning*, in which students perform well on retention tests and poorly on transfer tests; and (c) *meaningful learning*, in which students perform well on retention and transfer tests. When the goal of instruction is to promote meaningful learning, learning outcome measures should include measures of transfer.

FIGURE 4

Instructional Techniques that Improve Learning

Is there a core set of instructional principles relevant to undergraduate science education? This section briefly summarizes evidence-based instructional techniques and study techniques that have been shown to improve learning and that are relevant to the design of science instruction. The techniques are drawn from several recent summaries of successful instructional principles: a report commissioned by the Association of Psychological Science entitled, *25 Principles of Learning* (Halpern, Graesser, & Hakel, 2007); a report commissioned by the Institute of Education Sciences entitled, *Organizing Instruction and Study to Improve Student Learning* (Pashler, et al., 2007); and two books summarizing instructional design principles for multimedia learning entitled, *Multimedia Learning* (Mayer, 2009) and *The Cambridge Handbook of Multimedia Learning* (Mayer, 2005).

Design Techniques for Reducing Extraneous Processing

The rationale for the first set of principles is that students have limited capacity for cognitive processing during learning. Consider a situation where poor instructional design causes the learner to use precious processing capacity to engage in extraneous processing during learning. When large amounts of the learner's limited capacity are used for extraneous processing--cognitive processing that does not serve the instructional goal--there may not be sufficient remaining capacity for essential and generative processing--cognitive processing needed to mentally represent, organize, and integrate the relevant material. It follows that an important instructional goal is to reduce extraneous processing. Three techniques for reducing extraneous processing are the coherence principle, the signaling principle, and the contiguity principle.

Coherence principle. The coherence principle is that people learn better when extraneous material is excluded from a lesson rather than included. Across 14 experimental comparisons carried out in our lab, students performed better on transfer tests after learning from concise versions of science lessons rather than from identical versions that added interesting but irrelevant words, pictures, background music, or video clips, or unneeded words or symbols, with a median effect size of $d = 0.97$ (Mayer, 2009). The rationale for the coherence principle is that if learners use their cognitive capacity to process extraneous material in the lesson, they may not have sufficient remaining capacity to engage in essential and generative processing of the essential material in the lesson.

For example, consider Figure 5, which attempts to explain the process of photosynthesis. It contains so many technical terms, lines, arrows, and boxes that a novice learner would easily become overwhelmed. Similarly, Figure 6's depiction of the water cycle contains realistic color drawings of ocean, land, and mountains along with many different kinds of arrows and terms, but the novice learner may be distracted by the irrelevant details in the graphics. When the goal is to help a novice learner understand the main steps in a scientific system, the solution is to present a graphic that contains only the names of key steps in the to-be-learned process, uses the same simple kinds of arrows throughout, and presents key elements as uncomplicated line drawings.

FIGURE 5
FIGURE 6

The coherence principle also calls for redesigning textbooks and online lessons by reducing the number of interesting but irrelevant graphics such as photos and cartoons; interesting but irrelevant text, such as anecdotes; eliminating gratuitous use of many different colors, font styles, and font sizes; and cutting unnecessary mathematical notation. According to the coherence principle, only material that is directly needed for achieving the instructional goal should be included.

In a broader context, college textbooks and courses can be encyclopedic in their coverage, with many different concepts presented briefly without enough depth to foster deep understanding. It is not uncommon for a textbook to run 800 or 1000 pages or more. The goal appears to be to cover material rather than to help students master the basic conceptual models of the science. According to the coherence principle, a more productive strategy would be to limit the number of instructional objectives somewhat, with a focus on a few central conceptual models that are covered in some depth.

Signaling principle. The signaling principle is that people learn better when cues that highlight the organization of the essential material are added to a lesson. Signaling includes adding an outline, headings keyed to the outline, and pointer words to highlight the lesson's organization, as well as using italics, color, or spacing to highlight essential material in the lesson. Across six experimental comparisons carried out in our lab, students performed better on a transfer test after learning from a signaled version of a science lesson rather than a nonsignaled version, with a median effect size of *d* = 0.52 (Mayer, 2009). The rationale for the signaling principle is that appropriate cues can direct the learner's attention away from extraneous material and thereby reduce extraneous processing during learning.

For example, consider a lesson on reproductive barriers, such as partially shown in the text on the left side of Figure 7. The text contains a lot of information so the novice learner may not know what to attend to. By adding the graphic organizer in the upper right side of the page, no new information is presented but the essential material is highlighted and spatially organized for the learner. Other ways to signal the essential material in a lesson are to begin the lesson with a statement of the instructional objective of the lesson or a test question that can be answered by studying the lesson (Mayer, 2008). Most undergraduate science textbooks use signaling devices, but their use could be improved by (a) keeping outlines short and simple, (b) using parallel constructions for elements at the same level of the outline, and (c) presenting appropriate and clear pre-questions or instructional objective statements.

FIGURE 7

Contiguity principle. The contiguity principle is that people learn better from a lesson when corresponding printed words and graphics are presented near each other on the page or screen. Across five experimental comparisons carried out in our lab, students performed better on a transfer test after learning from a lesson in which printed text was placed next to the corresponding part of the graphic rather than as a caption or in the body of the text, with a median effect size of *d* = 1.12 (Mayer, 2009). In a more comprehensive review involving 37 experimental comparisons, Ginns (2006) found an average effect size of *d* = 0.72 favoring integrated presentation rather than separated presentation. The rationale for the contiguity principle (also called the spatial contiguity principle) is that separated presentation causes the learner to have to scan back and forth between the words in the caption (or words in body of the text) and the corresponding part of the graphic, thereby creating extraneous processing. When printed text is placed next to the corresponding part the graphic, the need for visual searching is reduced and learners can spend more cognitive resources mentally integrating corresponding words and pictures--an important cognitive process in meaningful learning.

For example, in Figure 8, the graphic depicting the digestive system is physically separated from the caption describing the digestive process in words. A solution is to place each clause next to the appropriate part of the graphic (perhaps linked by a light line). The contiguity principle applies to books, online presentations, and face-to-face presentations with slides.

FIGURE 8

Design Techniques for Managing Essential Processing

The rationale for the second set of principles is that students' limited capacity for processing information during learning may be overloaded when the to-be-learned material is too complex for them. Consider a situation in which the lesson is well designed so that extraneous processing is minimized, but the to-be-learned material is so complex for the learner that the amount of required essential and generative processing exceeds the learner's cognitive processing capacity. In this situation, it is not appropriate to cut material from the lesson, because the lesson consists of only essential material. Instead, the situation calls for techniques to manage essential processing--that is, techniques that help learners process the complex material within their limited-capacity processing system. Three techniques for managing essential processing are the segmenting principle, the pretraining principle, and the modality principle.

Segmenting principle. The segmenting principle is that people learn better when a complex continuous lesson is broken into separate segments. Examples include breaking a complex figure into two or more smaller figures dealing with different parts of the original one; presenting one graphic at a time rather than putting multiple graphics in the same figure (or having multiple windows on the screen); or breaking a continuous presentation into short chunks that can be paced by the learner. In three experimental comparisons carried out in our lab, students performed better on a transfer test after receiving a segmented lesson rather than a continuous one, with a median effect size of $d = 0.98$ (Mayer, 2009). The rationale for the segmenting principle is that the learner's working memory is less likely to be overloaded with essential processing when the essential material is presented in bite-size chunks rather than as a whole continuous lesson.

For example, in a lesson on gas laws in physics, a graphic might show a single graph demonstrating both Charles' Law and Boyles' Law--with two different lines and two different y-axes. According to the segmenting principle, essential cognitive processing could be better managed by presenting graphs for each law successively rather than all in one frame. Similarly, in a lesson on the Hjulstrom curve (as shown in Figure 9), novice learners are better able to understand the graphic if each of the three processes (erosion, transportation, and disposition) are presented successively. As another example, in a lesson showing the four steps in how a neuron fires, it might be better to show four frames--one for each step within the neuron--than to try to give an explanation using just a single frame showing the neuron. In a broader context, the segmenting principle calls for breaking a large lesson into a series of smaller manageable parts and making sure the learner masters one part before moving on to the next.

FIGURE 9

Pretraining principle. The pretraining principle is that people learn better when a complex continuous lesson is preceded by training in the names and characteristics of the main concepts. In five experimental comparisons conducted in our lab, students who received pretraining performed better on transfer tests than did students who received the same lesson without pretraining, yielding a median effect size of *d* = 0.85 (Mayer, 2009). The rationale is that when students are given a complicated lesson that explains how a complex system works, for example, they may concentrate on learning the names and characteristics of the key elements in the system (i.e., building a "component models"). This form of essential processing may use up so much processing capacity than there is not enough remaining capacity to allow the learner to see the relations among the elements (i.e., building a "causal model") which is the main goal of the lesson.

For example, in a narrated animation showing how a car's braking system works, students must learn how a change in one part (e.g., a piston moves forward in the master cylinder) causes a change in another part (e.g., an increase in fluid pressure in the brake tube). However, if a learner has to focus attention on trying to understand what a piston is, then less cognitive capacity is available for building an overall causal model of the braking system. If the learner receives a pre-lesson that shows the location of each key part in the braking system and shows the behavior of each part, such as in Figure 10, then during the main lesson the learner can focus more on the causal links necessary for understanding how a braking system works. The pretraining contains exactly the same information as in the main lesson, but allows the learner to digest some of the basic material--about names and characteristics of main parts--before seeing the main lesson. Similarly, in a lesson that shows the four steps in how a neuron fires, students would understand the lesson better if they were already familiar with the key elements such as dendrite, cell body, myelin sheath, and axon terminals.

FIGURE 10

Modality principle. The modality principle is that people learn better from a lesson containing words and graphics when the words are spoken rather than printed. Across 17 experimental comparisons carried out in our lab, students performed better on a transfer test when they received animation or a fast-paced set of graphic slides accompanied by narration rather than on-screen printed text, with a median effect size of *d* = 1.02 (Mayer, 2009). In a large-scale meta-analysis involving 39 experimental comparisons, Ginns (2005) reported an average effect size of *d* = 0.72 favoring the modality principle. Important boundary conditions are that the modality principle may not apply strongly when the material is not complex or is not fast-paced; additionally, onscreen text may be helpful when the words are technical, unfamiliar, or not in the learner's first language (Mayer, 2009).

The rationale for the modality principle is that when a lesson consists of onscreen text and graphics learners must split their visual attention between the words and the graphics. When they are looking at the words they may be missing part of graphic, and when they are looking at the graphic they may be missing part of the verbal message.

The solution is to offload the verbal information onto the auditory channel by using spoken text instead of printed text, effectively increasing the learner's processing capacity.

For example, in a lesson on how lightning storms develop, such as partially shown in Figure 11, students view an animation that contains printed captions at the bottom of the screen. However, if the lesson is fast paced and complex, the learner may not be able to process all of the essential words and pictures in the visual channel. To help manage essential processing, the captions can be removed and replaced with simultaneous narration in which the same words are spoken rather than printed.

FIGURE 11

Design Techniques for Fostering Generative Processing

So far, we have explored techniques that reduce extraneous processing and manage essential processing. These techniques allow us to create a learning situation in which a lesson is well designed so that it successfully reduces extraneous processing and manages essential processing for a learner. In this case the learner has sufficient remaining cognitive capacity to engage in generative processing, but may choose not to expend the effort to do so. The appropriate instructional goal for this situation is to foster generative processing. Some techniques for fostering generative processing include the personalization principle and the multimedia principle.

Personalization principle. The personalization principle is that people learn better when the words in a lesson are presented in conversational style rather than formal style. At a minimum, personalization involves using first and second person constructions (e.g., using "I" and "you") and may include adding brief self-revealing comments intended to build rapport. In 11 experimental comparisons carried out in our lab, students learned better from lessons in which the words were in conversational style rather than formal style, yielding a median effect size of $d = 1.11$ (Mayer, 2009).

The rationale is based on social agency theory (Mayer, 2009) and media equation theory (Nass & Brave, 2005; Reeves & Nass, 1996), which posit that people try harder to make sense of a lesson when they feel they are in a social partnership with the instructor. Using conversational style is intended to prime a social stance in the learner and thereby create the sense that the learner and instructor are in a conversation. Accordingly, people exert effort to process the message more deeply--i.e., engage in generative processing--when they feel they are in a conversation.

For example, in a lesson on how the human respiratory system works such as shown in Figure 12, learners may view an animation or a series of slides while listening to the following description: "There are three phases in respiration: inhaling, exchanging, and exhaling. During inhaling, the diaphragm moves down, creating more space for the lungs; air enters through the nose or mouth, moves down through the throat and bronchial tubes to tiny air sacs in the lungs..." In order to personalize the lesson, we can simply change “the” to “your” throughout the lesson so the narrator says “your lungs” rather than “the lungs,” for example.

FIGURE 12

A more intrusive form of personalization includes directly addressing the learner, such as saying “I will be guiding you by giving out some hints” rather than “Some hints are presented throughout the program.” Another way to personalize a lesson is to use polite wording of hints, such as “Should we press the ENTER key?” rather than “Press the ENTER key.”

Multimedia principle. The multimedia principle is that people learn better from words and graphics than from words alone. In 11 experimental comparisons carried out in our lab, students performed better on transfer tests when corresponding illustrations or animations were added to a verbal description of how a mechanical or biological system works, yielding a median effect size of $d = 1.39$ (Mayer, 2009). The rationale is that students given multimedia lessons process more deeply by trying to make connections between corresponding words and pictures. Multimedia lessons encourage and facilitate the cognitive process of integrating words and pictures, which is the essence of generative processing.

For example, consider the following words-only description of how a bicycle tire pump works: “As the rod is pulled out, air passes through the piston and fills the area between the piston and the outlet valve. As the rod is pushed in, the inlet valve closes and the piston forces air through the outlet valve.” In order, to create a multimedia lesson, we can add two frames depicting the state of the pump before and after pressing the handle, as shown in Figure 13. As you can see, we have followed the contiguity principle as well by placing the words next to the corresponding part of the pump. Adding pictures to words creates the strongest positive effects on deep understanding of any of the principles tested, but not all graphics are equally effective. Designing effective graphics is addressed in many of the other principles described in this report.

FIGURE 13

Additional principles. Some additional design principles that may be relevant to fostering generative processing during learning are principles based on social cues such as the voice, image, and gesturing principles, and principles based on analogy such as anchoring, concrete analogical model, and worked example principles.

The voice principle is that people learn better with onscreen agents in computer-based lessons when narration is presented in a human voice rather than a machine voice (Mayer, 2009). The gesturing principle is that people learn better from onscreen agents that display human-like gesturing and facial expression rather than no gesturing and no facial expression (Lester, Towns, Callaway, Voerman, and Fitzgerald, 2000). The image principle is that people do not necessarily learn better when the static image of an onscreen agent is presented onscreen (Mayer, 2009).

The anchoring principle is that people learn better when problems are presented in a realistic context (Bransford, Brown, & Cocking, 1999). The concrete analogical model principle is that people learn better when a concrete analogical model is included (Mayer, 1989). The worked example principle is that people learn better when practice on solving problems is supplemented by worked examples showing each step in a problem solution (Renkl, 2005).

Study Techniques for Fostering Generative Processing

In addition to redesigning instructional materials, learning can be improved by priming the learner to engage in productive study strategies during learning. Some evidence-based study strategies are the self-explanation principle, testing principle, and generation principle.

Self-explanation principle. The self-explanation principle is that people learn better from a lesson when they spontaneously explain or are prompted to explain the material during learning (Chi, Bassok, Lewis, & Reimann, 1989; Roy & Chi, 2005). Across three experimental comparisons carried out in our lab, students who were prompted to select an explanation from a menu for each decision in a science game performed better on a transfer test than did students who did not self-explain, yielding a median effect size of $d = 0.91$ (Johnson & Mayer, 2010; Mayer & Johnson, 2010). In a broader review, Roy and Chi (2005) found strong evidence that students who were asked to generate self-explanations as they read a lesson performed better on a transfer test than did students who did not self-explain. The rationale is that self-explanation activity encourages students to relate the incoming material with their relevant existing knowledge (which we call integrating), or encourages students to relate one piece of the incoming material to another (which we call organizing).

For example, in reading a science textbook, a student may be asked to explain the material to herself as she reads. As another example, a student may be prompted at various points to explain the material or to describe any inconsistencies or things that do not make sense.

Testing principle. The testing principle is that people learn better when they take a practice test on the material rather than restudy it. For example, after receiving a lesson on how lightning storms develop, students may be asked to write an explanation or to answer a transfer question (testing condition) or may simply receive the same lesson again (control condition). In a recent study carried out in our lab using a science lesson, students who received a lesson followed by a practice test performed better on a delayed transfer test than did students who received the lesson twice, with an effect size of $d = 0.56$ (Johnson & Mayer, 2009). In a review of research studies, Roediger and Karpicke (2006) found strong evidence for the testing principle when the test involved retention of the presented material. The rationale is that the cognitive activity of test taking helps students reorganize material in ways that make it easier to access later.

Generation principle. The generation principle is that people learn better when they are asked to elaborate on the presented material during learning. Generation activities include writing a summary, creating an outline, drawing a picture, or producing a question for a given lesson. For example, we found that transfer performance was improved when students are asked to produce summary notes on a lecture (Peper & Mayer, 1978, 1986) or to create a drawing corresponding to a lesson (Schwamborn, Mayer, Thillmann, Leopold, & Leutner, 2010). In a review, Mayer and Wittrock (2006) reported that generative activities such as these tended to improve student learning, including performance on transfer tests. The rationale is that requiring students to perform generative activities during learning encourages them to engage in the cognitive processes of organizing and integrating incoming information--that is, the component processes in generative processing.

Additional study principles. Two widely recognized study principles are the guided discovery principle and the collaboration principle. The guided discovery principle is that novices learn better when they are given guidance as they solve a problem rather than no guidance (de Jong, 2005; Mayer, 2004b). A cautionary point is that pure discovery methods in which novices are given minimal guidance have been shown to be ineffective across many domains (Kirshner, Sweller, & Clark, 2006; Tobias & Duffy, 2009).

The collaboration principle is that learning in groups is effective when students who learn in groups receive group reward based on individual learning rather than individual reward or group reward based on group product (Jonassen, Lee, Yang, and Leffey, 2005; Slavin, Hurley, & Chamberlain, 2003). A cautionary point is that learning in groups is not necessarily an effective instructional method and collaborative learning can easily be implemented in ineffective ways (Slavin, Hurley, & Chamberlain, 2003).

Boundary Conditions

Each of the principles described in this section should not be taken as an absolute law that applies in all situations but rather each principle should be implemented based on an understanding of how learning works, such as summarized in the cognitive theory of multimedia learning. Based on learning theory, there are some conditions under which the principles are more likely to apply and some conditions under which the principles are less likely to apply. Recent research is beginning to delineate the boundary conditions for the principles described in this section (Mayer, 2009). Overall, an important theoretical and empirical task is to examine when each principle is most effective--that is, for which kinds of learners, which kinds of instructional objectives, and which kinds of learning environments.

For example, an important boundary condition concerns individual differences among learners and the single most important individual differences dimension for instruction is the learner's prior knowledge. Several of the principles described in this section (i.e., multimedia principle and coherence principle) have been shown to be more effective for low-knowledge learners than for high-knowledge learners, so these principles should be directed mainly at beginners. Prior knowledge was assessed by asking learners to rate their knowledge of the topic on a scale from “very much” to “very little” and to check items on a checklist concerning the domain, such as “I have changed oil in a car” for a lesson on car brakes or “I can distinguish between cumulous and nimbus clouds” for a lesson lightning. Kalyuga (2005) has coined the term, *expertise reversal effect*, to refer to the idea that instructional methods that are effective for novices may be ineffective or even detrimental for experts. In the most of the studies summarized in this section, the learners were first or second year college students, and the material was suitable for high school students or other learners with little or no prior knowledge.

Not all individual difference dimensions are equally important for instructional design. Another individual differences dimension that has received much attention is *learning style*--the learner’s preferred mode of learning--and one of the most popular learning style dimensions is the verbalizer-visualizer dimension, in which verbalizers prefer words and visualizers prefer pictures (Pashler et al., 2008; Mayer & Massa, 2003). However, a recent review did not find convincing evidence that students learn better when instructional methods are adjusted to accommodate learning style (Pashler et al., 2008). For example, in a set of studies Massa and Mayer (2006) found no benefit of adjusting instruction so that verbalizers received a verbal-based instructional lesson and visualizers received a visually-based lesson. In short, learning style has not been shown to be crucial for instructional design decisions in spite of strong claims to the contrary.

Examples of other boundary conditions include that the modality effect is strongest when the lesson is fast-paced and the words are familiar to the learner and the spatial contiguity effect is strongest when the material is complex (Mayer, 2009). The evidence base and theoretical rationale for boundary conditions is expected to continue to grow as the field matures.

Conclusion

Overall, there is encouraging evidence that the science of learning and the science of instruction have important roles in improving undergraduate science education. For example, Figure 14 shows frames from a lesson on lightning formation that is consistent with the multimedia principle because words and pictures are presented, the coherence principle because the amount of detail is minimized, the modality principle because the words are spoken, and the personalization principle because the words are in conversational style. In any well-designed science lesson, some combination of research-based principles will be implemented. This paper focuses on a confined section of cognitive research relevant to teaching and learning STEM content.

FIGURE 14 HERE

The science of learning provides an educationally relevant model of how students learn and the science of instruction provides a set of evidence-based principles for how to help students learn. Although the goal of this report is to examine general learning principles, an important next step is to focus specifically on learning principles for undergraduate science education.

References

Anderson, L. W., Krathwohl, D. R., Airasian, P. W., Cruikshank, K. A., Mayer, R. E., Pintrich, P. R., Raths, J., & Wittrock, M. C. (2001). *A Taxonomy of Learning for Teaching: A Revision of Bloom's Taxonomy of Educational Objectives*. New York: Longman.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (1999). *How people learn.* Washington, DC: National Academy Press.

Chi, M. T. H., Bassok, M., Lewis, M., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science, 13,* 145-182.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed). Hillsdale, NJ: Erlbaum.

de Jong, T. (2005). The guided discovery principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 215-228). New York: Cambridge University Press.

Ebbinghaus, H. (1964). *Memory*. New York: Dover.

Ginns, P. (2005). Meta-analysis of the modality effect. *Learning and Instruction, 15,* 313-332.

Ginns, P. (2006). Integrating information: A meta-analysis of the spatial contiguity and temporal contiguity effects. *Learning and Instruction, 16,* 511-525.

Hackler, D. J., Dunlosky, J., & Graesser, A. C. (Eds.). (2009). *Handbook of metacognition in education.* New York: Routledge.

Halpern, D. F., Graesser, A., & Haklel, M. (2007). *25 learning principles to guide pedagogy and the design of learning environments.* Washing, DC: Association for Psychological Science Taskforce on Life Long Learning at Work and at Home.

Hattie, J. (2009). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement.* New York: Routledge.

Johnson, C. I., & Mayer, R. E. (2009). A testing effect with multimedia learning. *Journal of Educational Psychology, 101*, 621-629.

Johnson, C. I., & Mayer, R. E. (2010). Adding the self-explanation principle to multimedia learning in a computer-based game-like environment. *Computers in Human Behavior, 26*, 1246-1252.

Jonassen, D. H., Lee, C. B., Yang, C., & Laffey, J. (2005). The collaboration principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 247-270). New York: Cambridge University Press.

Kalyuga, S. (2005). Prior knowledge principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 325-338). New York: Cambridge University Press.

Kirschner, P. A., Sweller, J., & Clark, R. (2006). Why minimally guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41,* 75-86.

Lester, J., C., Towns, S. G., Callaway, C. B., Voerman, J. L., & FitzGerald, P. J. (2000). Deictic and emotive communication in animated pedagogical agents. In J. Cassell, J.

Sullivan, S. Prevost, & E. Churchill (Eds.), *Embodied conversational agents* (pp. 123-154). Cambridge. MA: MIT Press.

Massa, L. J., & Mayer, R. E. (2006). Testing the ATI hypothesis: Should multimedia instruction accommodate verbalizer-visualizer cognitive style? *Learning and Individual Differences, 16,* 321-336.

Mayer, R. E. (1989). Models for understanding. *Review of Educational Research, 59,* 43-64.

Mayer, R. E. (2004a). Teaching of subject matter. In S. T. Fiske (Ed.), *Annual Review of Psychology* (vol. 55, pp. 715-744). Palo Alto, CA: Annual Reviews.

Mayer, R. E.(2004b). Should there be a three strikes rule against pure discovery? The case for guided methods of instruction. *American Psychologist, 59(1),* 14-19.

Mayer, R. E. (Ed.). (2005). *The Cambridge handbook of multimedia learning.* New York: Cambridge University Press.

Mayer, R. E. (2008). *Learning and instruction* (2nd ed). Upper Saddle River, NJ: Pearson Merrill Prentice Hall.

Mayer, R. E. (2009). *Multimedia learning* (2nd ed). New York: Cambridge University Press.

Mayer, R. E. (2010). *Applying the science of learning.* Upper Saddle River, NJ: Pearson.

Mayer, R. E., & Johnson, C. I. (2010). Adding instructional features that promote learning in a game-like environment. *Journal of Educational Computing Research, 42,* 241-265.

Mayer, R. E., & Massa, L. J. (2003). Three facets of visual and verbal learners: Cognitive ability, cognitive style, and learning preference. *Journal of Educational Psychology, 95,* 833-846.

Mayer, R. E., & Wittrock, M. C. (2006). Problem solving. In P. Alexander, P. Winne, & G. Phye (Eds.), *Handbook of educational psychology* (pp. 287-303). Mahwah. NJ: Erlbaum.

Nass, C., & Brave, S. (2005). *Wired for speech: How voice activates and advances the human-computer relationship.* Cambridge, MA: MIT Press.

Pashler, H., Bain, P., Bottage, B., Graesser, A., Koedinger, K., McDaniel, M., & Metcalfe, J. (2007). *Organizing instruction and study to improve student learning* (NCER 2007-2004). Washington, DC: National Center for Educational Research, Institute of Educational Sciences, U.S. Department of Education.

Pashler, H., McDaniel, M., Rohrer, D., & Bjork, R. (2008). Learning styles: Concepts and evidence. *Psychological Science in the Public Interest, 9,* 105-119.

Pellegrino, J. W., Chudowsky, N., & Glaser, R. (Eds.). (2001). *Knowing what students know: The science and design of assessment.* Washington, DC: National Academy Press.

Peper, R. & Mayer, R. E. (l978). Note-taking as a generative activity. *Journal of Educational Psychology, 70,* 5l4-522.

Peper, R. J., & Mayer, R. E. (1986). Generative effects of note taking during science lectures. *Journal of Educational Psychology, 78,* 23-28.

Phye, G. D., Robinson, D. H., & Levin, J. (Eds.). (2005). *Empirical methods for evaluating educational interventions.* San Diego: Elsevier Academic Press.

Pressley, M., & Woloshyn, V. (1995). *Cognitive strategy instruction that really improves children's academic performance.* Cambridge, MA: Brookline Books.

Reeves, B., & Nass, C. (1996). *The media equation.* New York: Cambridge University Press.

Renkl, A. (2005). The worked-out examples principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 229-246). New York: Cambridge University Press.

Roediger, H. L., & Karpicke, J. D. (2006). The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science, 1,* 181-210.

Roy, M., & Chi, M. T. H. (2005). The self-explanation principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 271-286). New York: Cambridge University Press.

Schwamborn, A., Mayer, R. E., Thillmann, H., Leopold, C., & Leutner, D. (2010). Drawing as a generative activity and drawing as a prognostic activity *Journal of Educational Psychology, 102*, 000-000.

Shavelson, R. J., & Towne, L. (Eds.). (2002). *Scientific research in education.* Washington, DC: National Academy Press.

Slavin, R. E., Hurley, E. A., & Chamberlain, A. (2003). Cooperative learning and achievement: Theory and practice. In W. M. Reynolds & G. E. Miller (Eds.), *Handbook of psychology* (vol. 7; pp. 177-198). New York: Wiley.

Stokes, D. E. (1997). *Pasteur's quadrant: Basic science and technological innovation.* Washington, DC: Brookings Institution Press.

Sweller, J. (1999). *Instructional design in technical areas.* Camberwell, Australia: ACER Press.

Tobias, S., & Duffy, T. M. (Eds.). (2009). *Constructivist instruction: Success or failure?* New York: Rouledge.

Thorndike, E. L. (1911). *Animal learning*. New York: Macmillan.

Wentzel, K. R., & Wigfield, A. (Eds.). (2009). *Handbook of motivation at school.* New York: Routledge.