

# What Neurosurgeons Should Discover About the Science of Learning

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Medical education, particularly in neurosurgery, represents the epitome of multimedia learning because instruction often involves both words (e.g., printed or spoken text) and pictures (e.g., illustrations, photographs, animation, video). For example, multimedia instruction occurs when a medical professional narrates what is happening in a video of a surgical procedure, when a textbook shows a photograph of the brain along with printed labels for various parts, or when a conference speaker presents PowerPoint slides consisting of medical graphics and text. The premise of this chapter is that the design of medical education should be informed by a research-based theory of how people learn (i.e., the science of learning) and evidence-based principles for how to help people learn (i.e., the science of instruction). In this chapter, I provide an introduction to the science learning and the science of instruction and examine research-based principles for how to design multimedia instruction.

## THE SCIENCE OF LEARNING

### What Is Learning?

The science of learning is the scientific study of how people learn.<sup>2,7</sup> Learning is a change in knowledge attributable to experience. Multimedia learning involves learning from words (such as printed or spoken text) and pictures (such as animation, video, illustrations, or photographs).

### How Does Learning Work?

During its 100-year history, the science of learning has produced three metaphors of learning: learning as response strengthening, learning as information acquisition, and learning as knowledge construction.<sup>8</sup> According to the response strengthening view, learning involves the strengthening or weakening of an association. The instructor's role is to dispense rewards and punishments, and the learner's role is to passively receive rewards and punishments. According to the information acquisition view, learning involves adding information to memory. The instructor's role is to dispense information and the learner's role is to passively receive information. According

to the knowledge acquisition view, learning occurs when the learner builds cognitive representations. The instructor's role is to help guide the learner's cognitive processing during learning, and the learner's role is to engage in cognitive processing that helps make sense of the incoming information. All three views are supported by substantial research evidence, and all three have an impact on current instructional practice. However, I focus mainly on the knowledge construction view because it is most relevant to helping people learn deeply.

### What Is Active Learning?

Learners can be behaviorally active (e.g., engaging in a hands-on science activity) or behaviorally passive during learning (e.g., sitting passively in a lecture). Similarly, learners can be cognitively active (e.g., engaging in appropriate cognitive processing during learning) or cognitively passive (e.g., not engaging in deep cognitive processing during learning). According to the knowledge construction view, active learning depends on cognitive activity during learning rather than behavioral activity during learning. For example, learners can sit passively in a lecture or as they read a book, but they are active learners if they engage in appropriate cognitive activity during learning. In short, active learning occurs when learners engage in appropriate cognitive processing during learning.

### How Learning Works

#### Three Principles From the Science of Learning

In considering how people learn, three important principles discovered by learning scientists are *dual channels*, people have separate channels for processing verbal and visual material; *limited capacity*, people can process only small amounts of material in each channel at any one time; and *active processing*, meaningful learning occurs when learners engage in appropriate cognitive processing during learning (such as attending to relevant material, organizing it into a coherent representation, and integrating it with relevant previous knowledge).

## A Cognitive Theory of Multimedia Learning

Figure 11.1 summarizes a cognitive theory of multimedia learning.<sup>6,8</sup> It consists of two channels: a verbal channel (top) and a visual channel (bottom). It consists of three memory stores: *sensory memory*, which briefly can hold sounds impinging in the ears and images impinging on the eyes; *working memory*, which temporarily can hold only a limited amount of material for active processing; and *long-term memory*, which can hold a large amount of knowledge over long time periods. Finally, it consists of three major cognitive processes: *selecting* (indicated by the “selecting words” and “selecting images,” arrows), *organizing* (indicated by the “organizing words” and “organizing images,” arrows), and *integrating* (indicated by the arrow from previous knowledge in long-term memory and between verbal model and pictorial model in working memory).

The first step occurs when the learner receives a multimedia presentation consisting of words and pictures, such as a computer-based lesson, a book-based lesson, or a live presentation. Spoken words impinge on the ears and are held briefly as sounds in verbal sensory memory; printed words and pictures impinge on the eyes and are held briefly as images in visual sensory memory. If the learner attends to the fleeting sensory representations, some of the sounds are transferred to working memory (indicated by the “selecting words,” arrow) and some of the images are transferred to working memory (indicated by the “selecting images,” arrow). In working memory, the learner may mentally organize the incoming words to form a verbal model (indicated by the “organizing words,” arrow) and the learner may mentally organize the incoming images to form a pictorial model (indicated by the “organizing image,” arrow). Finally, learners may integrate the verbal and pictorial models with each other and with relevant prior knowledge from long-term memory (indicated by “integrating,” arrows). The learning outcome constructed in working memory is stored in long-term memory for future reference.

As you can see, there are three main cognitive processes required for meaningful learning: *selecting*, which involves paying attention to relevant words and pictures in

the presentation and is indicated by the transfer of material from sensory memory to working memory; *organizing*, which involves mentally arranging selected words and images into coherent mental representations and is indicated by manipulation of material in working memory; and *integrating*, which involves connecting verbal and pictorial representations with each other and with relevant prior knowledge from long-term memory.

## THE SCIENCE OF INSTRUCTION

### What Is Instruction?

The science of instruction is the scientific study of how to help people learn.<sup>3,7</sup> Instruction is the instructor’s manipulation of the learner’s environment to foster learning. Multimedia instruction is instruction that uses words (such as printed and spoken text) and pictures (such as illustrations, photographs, animation, and video).

### Two Approaches to the Role of Technology in Multimedia Instruction

In a *technology-centered approach* to multimedia instruction, the starting point is the capability of a cutting-edge technology, the goal is provide access to that technology, and the instructional challenge is to figure out how to redesign instruction so that it makes use of the technology. The technology-centered approach has led to a disappointing chain of failures throughout the 20th century, including motion pictures in the 1920s, educational radio in the 1930s and 1940s, educational television in the 1950s, and programmed instruction in the 1960s.<sup>5</sup> The shortcoming of this approach is that it focuses on technology rather than on learners, so I favor a *learner-centered approach* to educational technology. In a learner-centered approach, the starting point is an appreciation of how the human mind works, the goal is to use technology as an aid to human learning, and the instructional challenge is to figure out how to adapt technology to fit into effective instructional programs.

### What Is an Instructional Objective?

An instructional objective is a description of the intended change in the learner’s knowledge. It includes a

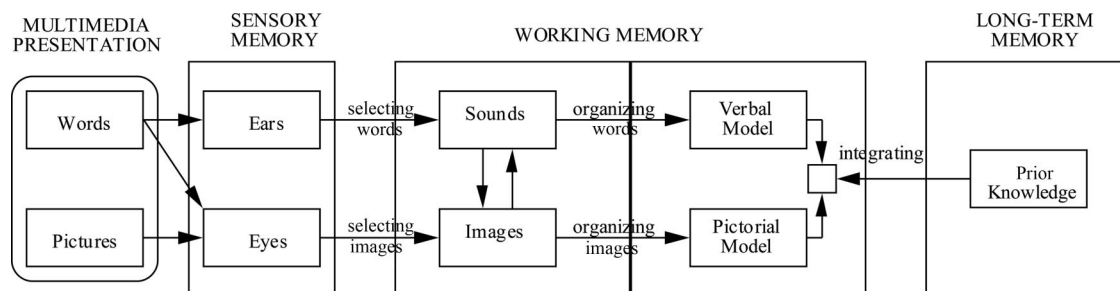


FIGURE 11.1. Cognitive theory of multimedia learning. (Copyright 1998 American Psychological Association. Reprinted with permission.)

description of what is learned, how it is used, and how to interpret the learner's performance.<sup>1,9</sup>

### Five Kinds of Knowledge

Five kinds of knowledge involved in instructional objectives are *facts*, factual knowledge about the world such as "Boston is in Massachusetts"; *concepts*, categories, schemas, models, or principles such as "In the number 65, the six refers to the number of tens"; *procedures*, step-by-step processes, such as how to multiply 252 by 12; *strategies*, general methods such as breaking a problem into parts; and *beliefs*, thoughts about learning such as "I am not good at statistics." Proficiency on an authentic task may involve all five kinds of knowledge.<sup>1,7,9</sup>

### Two Ways to Measure Learning Outcomes

Two common ways to measure the outcome of learning are retention tests and transfer tests. Retention tests are intended to assess how well the learner remembers the lesson; they require the learner to recall or recognize the presented material. For example, a retention test item for a lesson on how the human respiratory works could be "Write down all you can remember from the lesson about how the human respiratory system works." Transfer tests are intended to assess how well the learner understands the lesson; they require the learner to use the material in a new situation. For example, a transfer test item could be "Tom is breathing in air, but oxygen is not reaching his bloodstream. What could be wrong?" My focus is on transfer because I am most interested in instructional methods that enable learners to use what they have learned in new situations.

### Three Kinds of Learning Outcomes

Retention and transfer tests can reveal three kinds of learning outcomes: *no learning*, in which the learner performs poorly on retention and transfer tests; *rote learning*, in which the learner performs well on retention but poorly on transfer; and *meaningful learning*, in which the learner performs well on both retention and transfer tests. As you can see, transfer tests are essential in distinguishing rote and meaningful learning. When the instructional goal is to promote meaningful learning, transfer tests should be used in the assessment of learning outcomes.

### How Instruction Works: Three Demands on Cognitive Capacity During Learning

Given the limited processing capacity of working memory, a major challenge of instructional designers is to create instructional experiences that do not overload the learner's cognitive system. Three demands on the learner's cognitive capacity during learning are extraneous processing, essential processing, and generative processing.<sup>6,8</sup> Extraneous processing is cognitive processing that does not support the objective of the lesson and is caused by poor instructional design. A

corresponding design goal is to reduce extraneous processing. Essential processing is cognitive processing required to mentally represent the material and is caused by the inherent complexity of the material for the learner. A corresponding design goal is to manage essential processing. Generative processing is cognitive processing required to make sense of the presented material and is caused by the learner's motivation to make an effort to learn. A corresponding design goal is to foster generative processing. In summary, three top-level goals for the design of instruction are reduce extraneous processing, manage essential processing, and foster generative processing.

### What Is Evidence-Based Instruction?

Evidence-based instruction refers to determining which instructional methods are effective for teaching which kinds of material to which kinds of learners. The goal of evidence-based instruction is to base instructional decisions on research evidence concerning the effectiveness of instructional methods.

### What Is Research on Instructional Methods?

Research on instructional methods is concerned with what works, when it works, and how it works.<sup>10</sup> When the goal is to determine what works, i.e., which instructional manipulations cause learning, experimental comparisons are preferred. In an experimental comparison, one group of learners (i.e., control group) learns with the standard method and one group (i.e., treatment group) learns with the instructional manipulated added to the standard method. Both groups take subsequent retention and transfer tests. Three requirements of an experimental comparison are *experimental control*, the control and treatment conditions are identical except for the factor that is being varied; *random assignment*, learners are randomly assigned to the control and treatment groups; and *appropriate assessment*, learning outcomes are assessed using valid and reliable measures.

When the goal is to determine when an instructional manipulation works, such as for whom or for what kind of instructional objective, a factorial design is preferred. In a factorial design, the experimental and control groups may be broken into subgroups based on learner characteristics (such as high versus low prior knowledge) or instructional content (such as lessons on procedures versus lessons on conceptual knowledge). In short, it is worthwhile to establish the boundary conditions under which instructional methods work best.

When the goal is to determine how an instructional method works, an observational method may be appropriate in which we observe what the learner does during learning or we survey or interview the learner concerning what he or she was thinking during learning. It is worthwhile to understand the mechanisms underlying the effectiveness of an instructional method.

## What Is Effect Size?

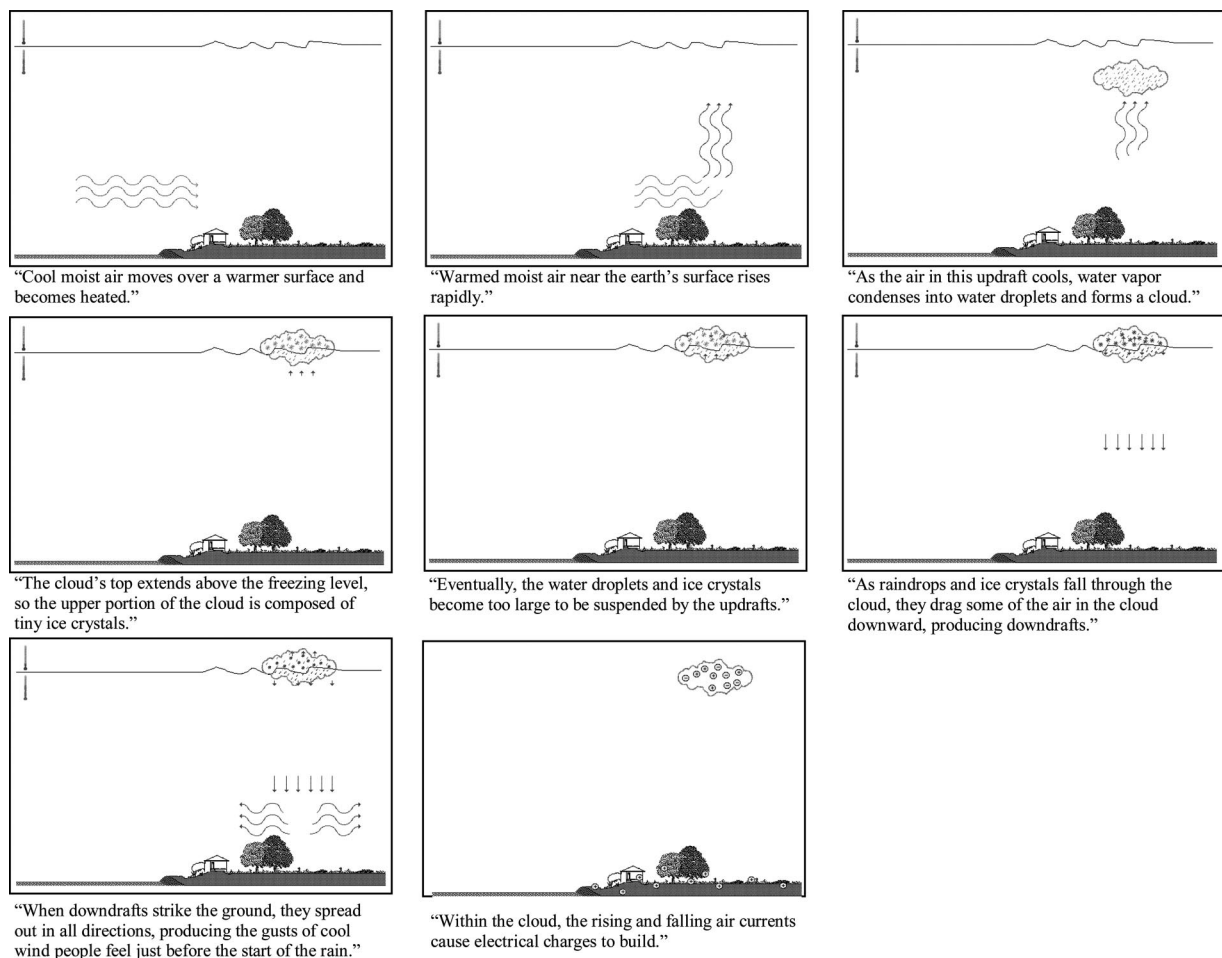
Effect size is common metric for expressing instructional effectiveness. A commonly used measure of effect size ( $d$ ) is computed by subtracting the mean score of the control group from the mean score of the treatment group and dividing by the pooled standard deviation. According to Cohen,<sup>4</sup> an effect size of 0.8 is large, 0.5 is medium, and 0.2 is small. Thus, I am most interested in instruction methods that produce a large or medium effect because these have the most practical significance for improving student learning. In short, I am looking for instructional methods that can improve learning by at least one half standard deviation and I am particularly interested in improving learning by at least 0.8 standard deviation.

## EVIDENCE-BASED PRINCIPLES OF MULTIMEDIA INSTRUCTION

For the past 20 years, my colleagues and I at the University of California, Santa Barbara have been conducting

research aimed at identifying research-based principles for the design of multimedia lessons.<sup>3,6,8</sup> We have conducted more than 100 experimental comparisons involving lessons on how mechanical systems work, how biological systems work, and how physical systems work, as well as how people learn with online games, simulations, pedagogical agents, and virtual reality. In each experimental comparison, the control group learns with a standard lesson and the treatment group learns with the same lesson except the instructional feature is added. Then, all learners take tests, including a transfer test, which is my focus in this report.

For example, *Figure 11.2* shows slides from a narrated animation on how lightning storms develop. The narrated animation runs about 2.5 minutes and describes 16 major cause-and-effect steps in lightning formation. A retention question is “Please write down all you can remember about how lightning works.” Some transfer questions are “Suppose you see clouds in the sky but no lightning. Why not?” and “What could you do to reduce the intensity of a lightning



**FIGURE 11.2.** Frames from a narrated animation on lightning formation. (Copyright 1998 American Psychological Association. Reprinted with permission.)

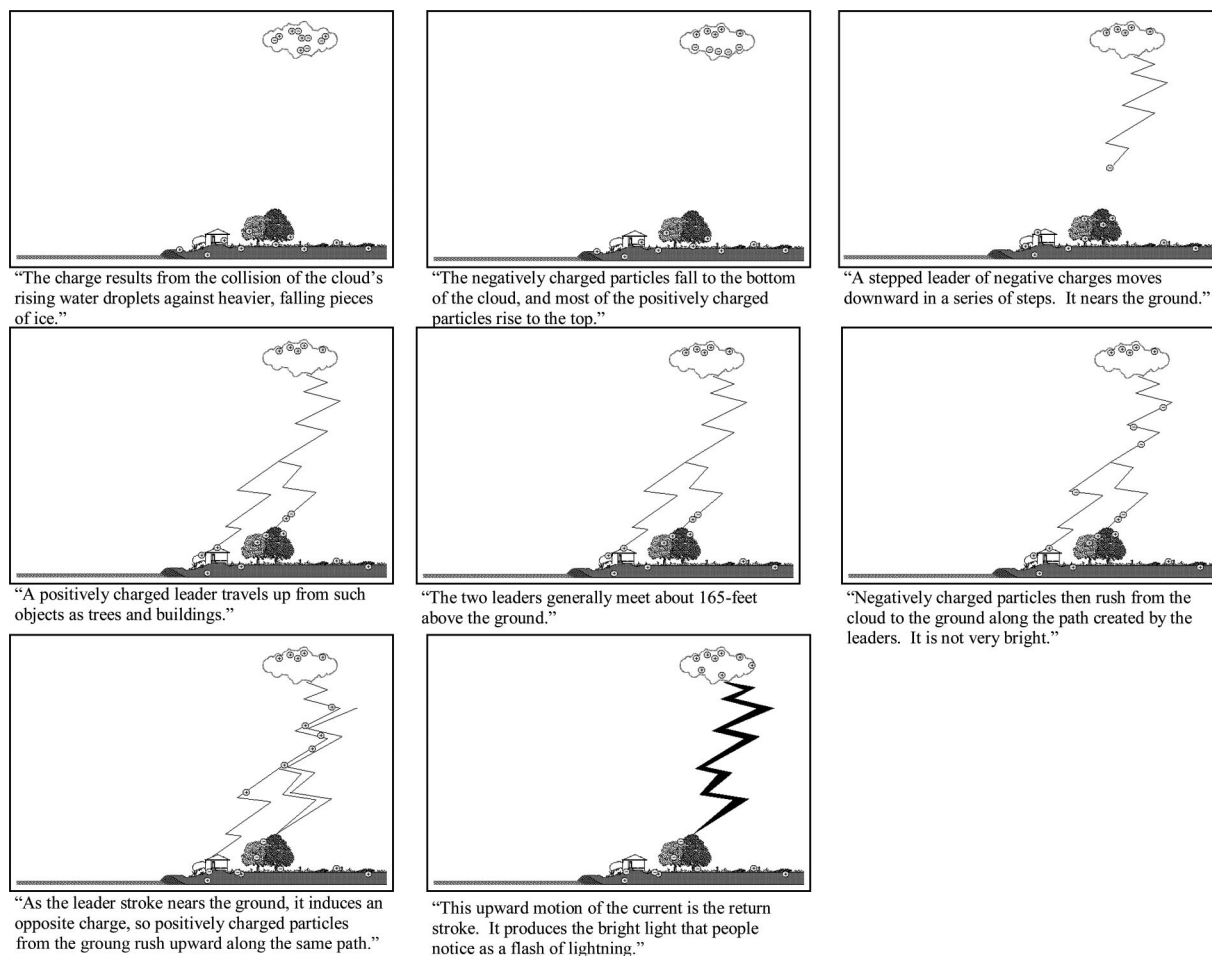


FIGURE 11.2. (Continued).

TABLE 11.1. Five Evidence-Based and Theoretically Grounded Principles for Reducing Extraneous Processing

Principle	Definition	Effect Size	Number of Tests
Coherence	Reduce extraneous material	0.97	13 of 14
Signaling	Highlight essential material	0.52	6 of 6
Redundancy	Do not add on-screen text to narrated animation	0.72	5 of 5
Spatial contiguity	Place printed words next to corresponding graphics	1.12	5 of 5
Temporal contiguity	Present corresponding narration and animation at the same time	1.31	8 of 8

storm?” In this section, I focus only on experimental comparisons based on transfer test scores because I am most interested in helping people to understand the material.

### Five Principles for Reducing Extraneous Processing

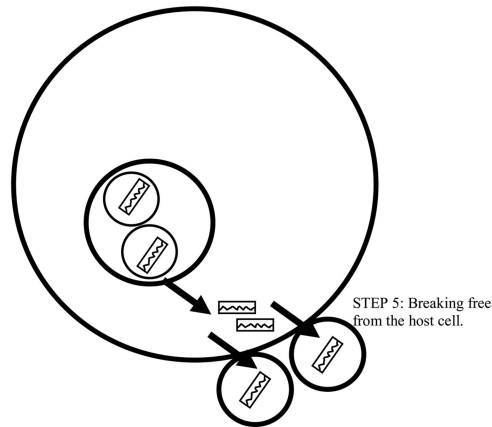
Table 11.1 summarizes our research on five techniques aimed at reducing extraneous processing: coherence principle, signaling principle, redundancy principle, spatial contiguity principle, and temporal contiguity principles.

#### Coherence Principle

The coherence principle is that people learn more deeply when extraneous material is excluded from a lesson. For example, in the lightning lesson, we could spice up the lesson by including interesting facts (e.g., “Each year 150 Americans are killed by lightning.”), including interesting graphics (e.g., video clips of lightning strikes), or including interesting sounds (e.g., background music). Figure 11.3 shows an example of extraneous material, called a seductive detail, in a multimedia lesson on how a virus causes a cold. In 13 out of 14 experimental comparisons, people performed better on transfer tests if these kinds of extra-

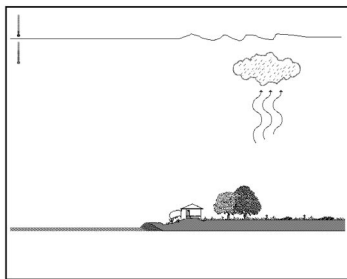
**Step 5: Breaking Free from the Host Cell**

The new parts are packaged into new virus within the host cell. The new viruses break free from the host cell. In some cases, they break the host cell open, destroying the host cell in the process, which is called lysis. In other cases, they punch out of the cell membrane surrounding them, which is called budding. A study conducted by researchers at Wilkes University in Wilkes-Barre, Pennsylvania, reveals that people who make love once or twice a week are more immune to colds than folks who abstain from sex. Researchers believe that the bedroom activity somehow stimulates an immune-boosting antibody called IgA.



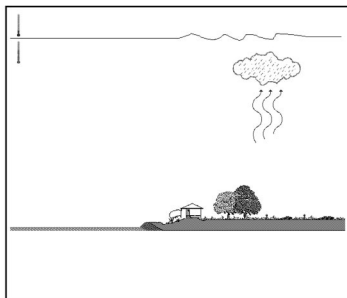
**FIGURE 11.3.** Example of the coherence principle in a lesson on how a virus causes a cold. Last two sentences of the text constitute a seductive detail. (Copyright 2008 American Psychological Association. Reprinted with permission.)

### Animation and Narration



“As the air in this updraft cools, water vapor condenses into water droplets and forms a cloud.”

### Animation, Narration, and On-Screen



As the air in this updraft cools, water vapor condenses into water droplets and forms a cloud.

**FIGURE 11.4.** Example of the redundancy principle in a lesson on lightning formation. Second frame shows a redundant presentation. (Copyright 2002 American Psychological Association. Reprinted with permission.)

neous materials were excluded rather than included, yielding a median effect size of  $d = 0.97$ , which is in the large range.

### Signaling Principle

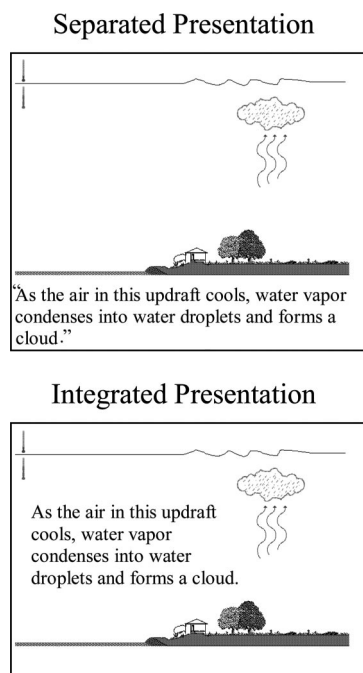
The signaling principle is that people learn more deeply when essential material is highlighted. For example, in a narrated animation on how airplanes achieve lift, the signaled version included an outline sentence, headings keyed to the outline, and spoken emphasis on the key concepts. In six out of six experimental comparisons, people performed better on a transfer test if they received signaled rather than nonsignaled versions of a multimedia lesson, yielding a median effect size of  $d = 0.52$ , which is in the medium range.

### Redundancy Principle

The redundancy principle is that people learn more deeply from animation and narration than from animation, narration, and on-screen text. For example, as shown in *Figure 11.4*, in the narrated animation for lightning, we could add concurrent captions at the bottom of the screen containing the same sentences that the narrator is speaking. In five out of five experimental comparisons, people performed better when the redundant captions were excluded, yielding a median effect size of  $d = 0.72$ .

### Spatial Contiguity Principle

The spatial contiguity principle is that people learn more deeply when printed words are placed next to the corresponding part of the graphic rather than far away. For example, as shown in *Figure 11.5*, in the lightning lesson



**FIGURE 11.5.** Example of the spatial contiguity principle in a lesson on lightning formation. First frame shows a separated presentation. (Copyright 1995 American Psychological Association. Reprinted with permission.)

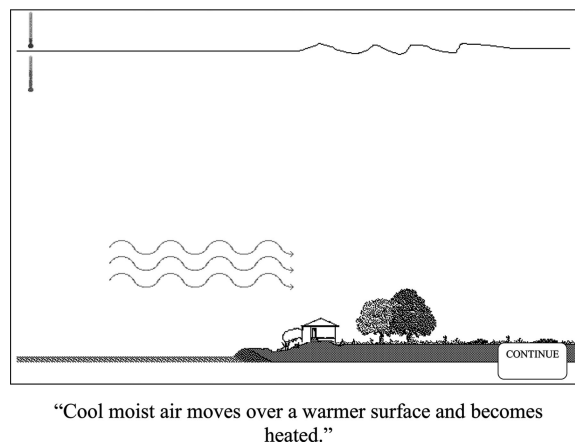
**TABLE 11.2.** Three Evidence-Based and Theoretically Grounded Principles for Managing Essential Processing

Principle	Definition	Effect size	Number of Tests
Segmenting	Present animation in learner-paced segments	0.98	3 of 3
Pretraining	Provide pretraining in the name, location, and characteristics of key components	0.85	5 of 5
Modality	Present words as spoken text rather than printed text	1.02	17 of 17

involving animation and printed text, a separated version has the words at the bottom of the screen as a caption, whereas an integrated version has the words within the graphic next to the element that is the subject of the sentence. In five out of five experimental comparisons, people performed better on a transfer test when the printed words were placed next to the corresponding graphic, yielding a median effect size of  $d = 1.12$ .

**Temporal Contiguity Principle**

The temporal contiguity principle is that people learn more deeply when corresponding animation and narration are presented simultaneously rather than successively. For example, in a narrated animation on lightning, we could create a successive version by playing the entire narration either



**FIGURE 11.6.** Example of the segmenting principle in a lesson on lightning formation. Learners click on the CONTINUE button to see the next animation segment. (Copyright 2001 American Psychological Association. Reprinted with permission.)

before or after the animation. In eight out of eight experimental comparisons, people performed better on a transfer test for simultaneous rather successive presentation of animation and narration, yielding an effect size of  $d = 1.31$ .

**Three Principles for Managing Essential Processing**

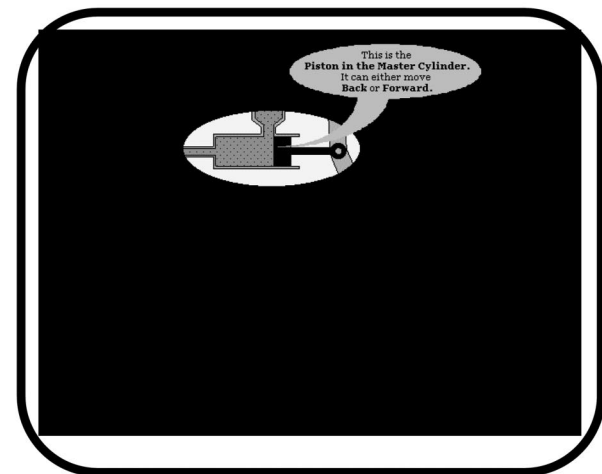
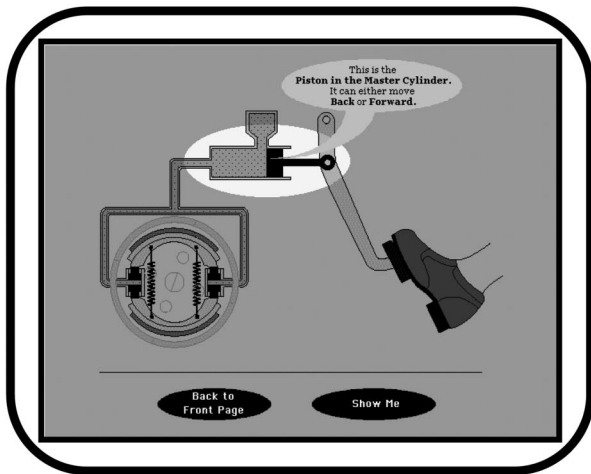
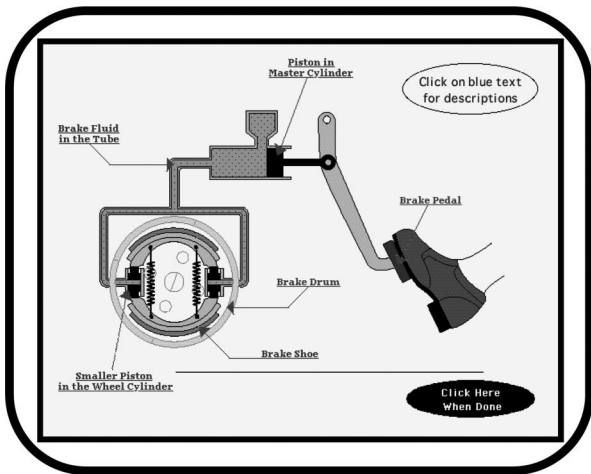
Table 11.2 summarizes our research on three techniques aimed at managing essential processing: segmenting principle, pretraining principle, and modality principle.

**Segmenting Principle**

The segmenting principle is that people learn more deeply when a multimedia lesson is broken into learner-paced segments. For example, a narrated animation on lightning formation could be broken into 16 segments, each expressing on main step and taking about 10 seconds of animation, with a CONTINUE button appearing in the lower right corner (Fig. 11.6). When the learner clicks on the CONTINUE button, the next segment is presented. In three out of three experimental comparisons, people performed better on a transfer test when they received segmented rather than continuous presentations, yielding an effect size of  $d = 0.98$ .

**Pretraining Principle**

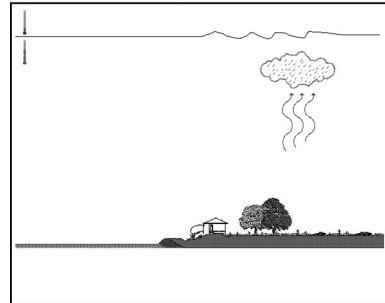
The pretraining principle is that people learn more deeply when they receive pretraining in the names and characteristics of key components. For example, as shown in Figure 11.7, in a narrated animation on how a car’s braking system works, pretraining involves describing the characteristics and location for each of six components such as the brake pedal, the piston in the master cylinder, brake fluid, smaller pistons in the wheel cylinders, the brake shoe, and the brake drum. In five out of five experimental comparisons, people who received pretraining performed better on a trans-



**FIGURE 11.7.** Example of the pretraining principle in a lesson on a braking system. Learners can click on any part to see how it operates. (Copyright 2002 American Psychological Association. Reprinted with permission.)

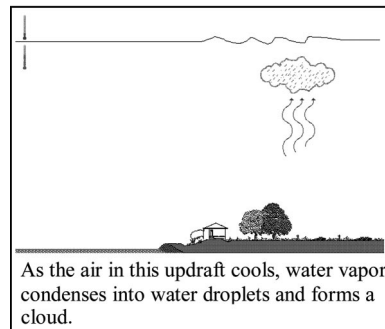
fer test than people who did not receive pretraining, yielding a median effect size of  $d = 0.85$ .

**Words as Narration**



“As the air in this updraft cools, water vapor condenses into water droplets and forms a cloud.”

**Words as On-Screen Text**



**FIGURE 11.8.** Example of the modality principle in a lesson on lightning formation. Second frame shows a graphic with on-screen text. (Copyright 1999 American Psychological Association. Reprinted with permission.)

**Modality Principle**

The modality principle is that people learn more deeply from animation and narration than from animation and on-screen text. For example, as shown in *Figure 11.8*, the narrated animation on lightning could be converted to animation and on-screen text by replacing the narration with captions that appear at the bottom of the screen containing the same sentences and appearing at the same time as the narration would have been spoken. In 17 out of 17 experimental comparisons, people performed better on a transfer test if they had learned from animation and narration rather than if they had learned from animation and on-screen text, yielding a median effect size of  $d = 1.02$ .

**Two Principles for Fostering Generative Processing**

*Table 11.3* summarizes our research on two techniques aimed at fostering generative processing: multimedia and personalization.

**Multimedia Principle**

The multimedia principle is that people learn more deeply from words and pictures than from words alone. The



**TABLE 11.3.** Two Evidence-Based and Theoretically Grounded Principles for Fostering Generative Processing

Principle	Definition Size	Effect of	
		Tests	Number
Multimedia	Present words and pictures rather than words alone	1.39	11 of 11
Personalization	Present words in conversational style rather than formal style	1.11	11 of 11

narrated animation summarized in *Figure 11.2* is an example of learning from words and pictures, whereas the narration is an example of learning from words alone. In 11 out of 11 experimental comparisons, people performed better on a transfer test if they had learned with words and pictures rather than words alone, with a median effect size of  $d = 1.39$ . This finding points to the potential of graphics to improve learner understanding.

#### Personalization Principle

The personalization principle is that people learn better from a multimedia lesson when the words are in conversational style rather than formal style. For example, in a lesson on how the human respiratory system works, formal style is “the diaphragm moves down, creating more room for the lungs” and conversational style is “your diagram moves down, creating more room for your lungs.” In 11 out of 11 experimental comparisons, people performed better on a transfer test when they had learned with words in conversational style rather than formal style, yielding a median effect size of  $d = 1.11$ .

## CONCLUSION

The design of medical instruction should be based on research evidence (i.e., the science of instruction) and grounded in a research-based theory of how people learn (i.e., the science of learning). An example is provided by 10 evidence-based principles for how to design multimedia instruction.

## Disclosure

The author has no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.

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