# Applying the science of learning to medical education

Richard E Mayer

**OBJECTIVE** The goal of this paper is to examine how to apply the science of learning to medical education.

**SCIENCE OF LEARNING** The science of learning is the scientific study of how people learn. Multimedia learning – learning from words and pictures – is particularly relevant to medical education. The cognitive theory of multimedia learning is an information-processing explanation of how people learn from words and pictures. It is based on the idea that people have separate channels for processing words and pictures, that the capacity to process information in working memory is limited, and that meaningful learning requires appropriate cognitive processing during learning.

**SCIENCE OF INSTRUCTION** The science of instruction is the scientific study of how to help people learn. Three important instructional goals are: to reduce extraneous processing (cognitive processing that does not serve an instructional objective) during learning; to manage essential processing (cognitive processing aimed at representing the essential material in working memory) during learning, and to foster generative processing (cognitive processing aimed at making sense of the material) during learning. Nine evidence-based principles for accomplishing these goals are presented.

**CONCLUSIONS** Applying the science of learning to medical education can be a fruitful venture that improves medical instruction and cognitive theory.

*Medical Education 2010: **44**: 543–549*
doi:10.1111/j.1365-2923.2010.03624.x

Department of Psychology, University of California, Santa Barbara, California, USA

*Correspondence:* Richard E Mayer, Department of Psychology, University of California, Santa Barbara, California 93106, USA. Tel: 00 1 805 893 2472; Fax: 00 1 805 893 4303; E-mail: mayer@psych.ucsb.edu

## INTRODUCTION

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 design effective instruction (i.e. the science of instruction). Firstly, as an example of applying the science of learning to medical education, this article focuses on a research-based account of how people learn from words and pictures, namely, the cognitive theory of multimedia learning.[1,2] Secondly, as an example of applying the science of instruction to medical education, this article focuses on evidence-based principles for how to design multimedia instruction, including computer-based instruction.[3] Finally, in the conclusion, this article calls for future research that examines the conditions under which cognitive principles of multimedia instruction apply to medical education.

## SCIENCE OF LEARNING: THE COGNITIVE THEORY OF MULTIMEDIA LEARNING

### An introduction to the science of learning

An important goal of medical education is to foster learning in medical professionals. The science of learning is the scientific study of how people learn.[4] When the goal is to foster learning, it might be useful to understand how learning works.[4,5] In this article, one primary goal is to examine what it means to apply the science of learning to medical education.

Learning is a change in the learner's knowledge attributable to experience.[3–5] Changes in the learner's knowledge must be inferred by examining changes in the learner's performance. Knowledge includes facts and concepts (sometimes called knowledge in the narrow sense), procedures and strategies (sometimes called skills), and beliefs (sometimes called attitudes). Thus, whenever medical educators talk about learning, it is useful to pinpoint the knowledge that is to be changed in the learner.

Medical education often involves *multimedia learning*, which I define as learning from words and pictures.[1,3] In short, medical education often requires a combination of verbal and pictorial learning. *Verbal learning* involves learning with printed words (such as bullet points in a slide presentation or words printed in a textbook or on-screen text in a computer-based lesson) or spoken words (such as the speaker's voice in a slide presentation or the narrator's voice in a computer-based lesson). *Pictorial learning* involves learning with static graphics (such as illustrations, diagrams, photographs, drawings or charts) or dynamic graphics (such as animation or video).

### A research-based theory of multimedia learning

Understanding how people learn from words and pictures has a special relevance for medical education. One of the most developed research-based theories of how people learn from words and pictures is the cognitive theory of multimedia learning.[1,3] This theory is based on three research-supported principles in cognitive science:

- the *dual channels principle*, which proposes that learners have separate channels for processing verbal and pictorial material;[6]
- the *limited capacity principle*, which proposes that learners can process only a few elements in each channel at any one time,[7,8] and
- the *active processing principle*, which proposes that meaningful learning occurs when learners engage in appropriate cognitive processing during learning, including attending to relevant material, mentally organising it into a coherent cognitive representation, and integrating it with prior knowledge activated from long-term memory.[5,9]

In short, human information processing has two channels, is limited in capacity and supports cognitive processing of incoming material.

Figure 1 shows the architecture of the human information-processing system as proposed by the cognitive theory of multimedia learning. There are three main boxes in Fig. 1:

- *sensory memory* holds an exact sensory copy of what was presented for a very brief time (i.e. < 0.25 second);
- *working memory* holds a more processed version of the input material for a short period (i.e. < 30 seconds) and can process only a few pieces of material at any one time, and
- *long-term memory* holds the learner's entire storehouse of knowledge for long periods of time.

Although sensory memory and long-term memory have unlimited capacity for holding information, working memory has limited capacity for processing information, which makes it act as a sort of bottleneck in the system. In working memory,

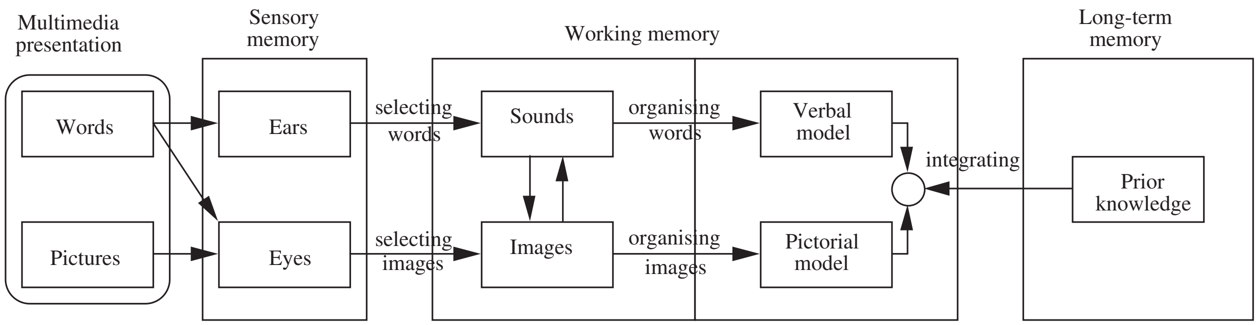


**Figure 1** A cognitive theory of multimedia learning

material must be condensed and organised into meaningful chunks in order for the learner to work within the constraints of limited processing capacity. In short, people must be active learners who seek meaningful learning because they do not have the processing capacity to attend to every piece of information that is available to them.

Five main types of cognitive process are depicted in Fig. 1:

- *selecting words* refers to attending to important incoming spoken words for further processing in working memory;
- *selecting images* refers to attending to important incoming printed words and pictures for further processing in working memory;
- *organising words* refers to mentally rearranging the words into a coherent cognitive representation (i.e. a verbal model) in working memory;
- *organising images* refers to mentally rearranging the images into a coherent cognitive representation (i.e. a pictorial model) in working memory, and
- *integrating* refers to mentally connecting the verbal and pictorial models with one another and with relevant prior knowledge activated from long-term memory.

Meaningful learning from words and pictures occurs when the learner engages in these five cognitive processes during learning.

As indicated on the far left of the figure in the *instructional presentation* column, instructional material is presented that may contain spoken words, printed words and pictures. As indicated in the *sensory memory* column, the spoken words impinge on the ears and an auditory copy is briefly held in auditory memory, whereas the printed words and pictures impinge on the eyes and a visual image is briefly held in visual sensory memory. If the learner attends to some of the fleeting auditory representation in sensory memory, it moves to working memory, as indicated by the *selecting words* arrow. If the learner attends to some of the fleeting visual image in sensory memory, it moves to working memory, as indicated by the *selecting images* arrow. As indicated on the left of the *working memory* box, incoming spoken words are held as sounds, whereas incoming printed words and pictures are held as images; however, the arrow from Images to Sounds indicates that the printed words are converted to sounds for processing in the verbal channel. Next, as shown on the right of the *working memory* box, the learner mentally organises the words into a verbal model, indicated by the *organising words* arrow, and mentally organises the images into a pictorial model, indicated by the *organising images* arrow. Finally, relevant knowledge is activated from *long-term memory* and transferred to *working memory*; the learner connects the verbal and pictorial models with one another and with relevant knowledge activated from long-term memory, as indicated by the *integrating* arrow. As you can see, meaningful learning involves active cognitive processing (i.e. selecting, organising and integrating) within two information-processing channels (i.e. the auditory-verbal channel and the visual-pictorial channel) with limited capacity (i.e. working memory is limited in processing capacity).

## SCIENCE OF INSTRUCTION: RESEARCH-BASED PRINCIPLES FOR MULTIMEDIA INSTRUCTION

### An introduction to the science of instruction

Learners may need support and guidance in carrying out the cognitive processing described by the cognitive theory of multimedia learning in the previous section. Understanding how learning works is an important first step in medical education because instructional methods should be consistent with what we know about the human information-processing system. However, designing effective medical instruction also depends on understanding how instruction works, which is the focus of this section.

The science of instruction is the scientific study of how to help people learn.[4] Instruction is the teacher's manipulation of the learner's experiences in a manner intended to foster learning.[4] In short, instruction involves constructing situations for learners to experience that lead to an intended change in their knowledge.

The first step in designing effective instruction is to clearly specify the intended knowledge change in the learner.[10] An *instructional objective* is a clear statement of what knowledge is to be learned, the intended level of mastery, and how the learning will be assessed. For example, an instructional objective might be for the learner to be able to state the definition of 'instructional objective', which is an example of knowing a fact. Five kinds of knowledge are:

- *facts*: factual knowledge refers to knowledge about the characteristics of elements in the world, such as knowing that the right ventricle is a part of the heart;
- *concepts*: conceptual knowledge describes knowledge of models, principles, categories and schemas, such as knowing the cause-and-effect mechanism for how the human heart works;
- *procedures*: procedural knowledge consists of knowledge of step-by-step processes for how to carry out an action, such as knowing how to carry out long division computations;
- *strategies*: strategic knowledge consists of knowing general methods for approaching problems, such as by breaking a problem into parts, and
- *beliefs*: attitudinal knowledge refers to knowledge about how one's learning works or about one's competence as a learner, such as thinking: 'I am good at this.'

All of these types of knowledge are generally needed to be proficient in most cognitive tasks, such as arriving at a diagnosis.

Learning outcomes can be measured with retention tests and transfer tests. Retention tests measure how well the learner remembers the presented material, such as whether he or she is able to recall what was presented (e.g. 'Define retention test') or recognise what was presented (e.g. 'Remembering what was presented is an example of: [a] a retention test, [b] a transfer test'). Transfer tests measure how well the learner can apply what was learned to new situations (e.g. 'Generate a transfer test item for this section'). The learner's pattern of performance on retention and transfer tests indicates the quality of his or her learning outcome: *no learning* is indicated by poor performance on both types of test; *rote learning* is indicated by good performance on retention and poor performance on transfer, and *meaningful learning* is indicated by good performance on both types of test. My focus in this review is on meaningful learning.

In any learning situation there are three types of demands on the learner's cognitive system: extraneous processing; essential processing, and generative processing.[3,8] *Extraneous processing* is cognitive processing that does not support the learning objective and is caused by poor instructional design. For example, extraneous processing may be caused when text describing how the heart works is on one page of a book and the corresponding illustrations are on another page, so the learner has to waste precious cognitive processing resources by scanning back and forth between the words and the illustrations. An important instructional challenge is to reduce extraneous cognitive processing during learning, thereby freeing up cognitive capacity.

*Essential cognitive processing* describes the cognitive processing required to mentally represent the essential material from a lesson in working memory (mainly through the cognitive processes of selecting and minimal amounts of organising). It is caused by the inherent complexity of the essential material for the learner, so it is not appropriate to try to reduce essential processing. Instead, an important instructional goal is to manage essential processing so that it can be accomplished in ways that do not overload the learner's cognitive capacity.

*Generative cognitive processing* is cognitive processing aimed at making sense of the presented material (i.e. mainly the cognitive processes of integrating and organising) and is caused by the learner's motivation to understand the material. Even when learners have cognitive capacity available, they may not engage in deep learning because they are not motivated to do so. Thus, an important instructional goal is to foster generative processing.

In designing instruction, it is important to make sure that the learner's cognitive processing during learning does not exceed the learner's cognitive capacity. When there is too much extraneous processing because the instruction is poorly designed (which I call *extraneous overload*), the learner may not have enough remaining capacity to engage in needed generative processing and therefore does not achieve a meaningful learning outcome. An example of something that causes extraneous overload is a website on how to cope with cancer that presents an entire screen full of windows with flashing coloured frames, background photographs that are irrelevant, background sounds, animated words that fly across the screen and ongoing videos.

When extraneous processing is reduced but there is too much essential processing because the material is complex (which I call *essential overload*), the learner may not have enough remaining capacity to engage in meaningful learning. An example of something causing essential overload is a PowerPoint presentation on principles of genetics that goes at a fast pace for 20 minutes without pausing to allow the learner to digest the information delivered.

When extraneous processing is reduced and essential processing is managed, the learner may have processing capacity but not be motivated to use it to engage in meaningful learning (which I call *generative underutilisation*). Asking someone to take a computer-based course on how to use a new computer system when the person will never have to actually use the system and therefore has no interest in learning about it is an example of generative underutilisation. In short, these three types of instructional challenge suggest three major instructional goals, respectively: to reduce extraneous processing (in extraneous overload situations); to manage essential processing (in essential overload situations), and to foster generative processing (in generative underutilisation situations).

**Research on instructional design of multimedia lessons**

During the past 20 years, my colleagues and I at the University of California, Santa Barbara have been investigating evidence-based principles for how to accomplish these three instructional goals. We have conducted dozens of experimental comparisons in which we compare the retention and transfer test performance of people who learn from a lesson that is consistent with one of our principles versus from an otherwise identical lesson that is not consistent with the principle. The lessons are generally about how some biological, physical, or mechanical system works (such as how lungs work, how lightning storms develop, or how a tyre pump works) and are presented either on a computer screen (such as in a short narrated animation or a short PowerPoint presentation) or as a booklet (such as in eight pages of text and illustrations). The retention tests ask the learners to write down all they can remember in a limited amount of time (e.g. 'Please explain how the human respiratory system works'). We then tally the number of important idea units in the answer. The transfer tests ask the learner to write answers to troubleshooting questions (e.g. 'Suppose someone is having trouble breathing. What could have gone wrong?'), re-design questions (e.g. 'What could be done to improve on the human respiratory system?') or conceptual questions (e.g. 'Why does air enter the lungs?') in a limited amount of time. We then tally the number of acceptable solutions across all the transfer questions for each learner.

For each comparison, we compute the effect size – the difference between the mean test scores of the two groups divided by the pooled standard deviation – in order to create a common metric for expressing the strength of the effects. We are most interested in effect sizes $\geq 0.5$ as these have practical significance for improving student learning. We include only experimental comparisons conducted in our laboratory and published in peer-reviewed original research journals.

Table 1 summarises evidence-based techniques for reducing extraneous processing, managing essential processing, and fostering generative processing. Each line presents the name, description, average effect size (ES) and number of comparisons (Tests) for an instructional design principle based on transfer test performance. The ES column contains the average of effect sizes across all the comparisons conducted for a particular principle. The Tests column indicates the number of positive effects out of the total number of comparisons made for each principle. For details about each experimental test and the specific instructional interventions, please see *Multimedia Learning*.[3]

The first section in Table 1 summarises three principles for reducing extraneous processing: the *coherence*, *signalling*, and *contiguity* principles. The coherence principle is that people learn better from multimedia lessons that exclude rather than include extraneous material. For example, people can learn better from black-and-white line drawings than from colour photographs, when interesting but irrelevant stories are deleted, or when stunning but irrelevant video is deleted. The signalling principle is that people learn better from multimedia lessons that highlight the essential material by using an outline, headings and

*Table 1 Research-based principles for instructional design of multimedia lessons*

| Principle | ES | Tests |
|---|---|---|
| Principles for reducing extraneous processing | | |
| Coherence principle: eliminate extraneous material | 0.97 | 14 of 14 |
| Signalling principle: highlight essential material | 0.52 | 5 of 6 |
| Contiguity principle: place printed words near corresponding graphics | 1.19 | 5 of 5 |
| Principles for managing essential processing | | |
| Pre-training principle: provide pre-training in names and characteristics of key concepts | 0.98 | 3 of 3 |
| Segmenting principle: break lessons into learner-controlled segments | 0.85 | 5 of 5 |
| Modality principle: present words in spoken form | 1.02 | 17 of 17 |
| Principles for fostering generative processing | | |
| Multimedia principle: present words and pictures rather than words alone | 1.39 | 11 of 11 |
| Personalisation principle: present words in conversational or polite style | 1.11 | 11 of 11 |
| Voice principle: use a human voice rather than a machine voice | 0.78 | 3 of 3 |

ES = effect size

pointer words such as 'first,... second,... third'. For example, people will learn better from a lesson on how the heart works when it contains headings that correspond to each of the main steps in a process. The contiguity principle is that people learn better when printed words are placed near rather than far from corresponding portions of the graphic on the page or screen. For example, in a figure depicting the human heart, text describing each chamber should be placed next to the corresponding chamber.

The second section of Table 1 lists three principles for managing essential processing: the *pre-training*, *segmenting*, and *modality* principles. The pre-training principle is that people learn better from a multimedia lesson when they already know the names and characteristics of the key concepts. Thus, before receiving an explanation of the steps of how the human heart works, learners should receive pre-training in the names and characteristics of each major part. The segmenting principle is that people learn better when a continuous or large lesson is broken down into smaller, learner-paced segments. For example, in a computer-based, narrated animation on how the human heart works, the presentation can stop at major points and continue when the learner presses a CONTINUE button. The modality principle is that the words in a multimedia lesson should be spoken rather than printed, thereby offloading information from the visual-pictorial channel, which may be overloaded, onto the auditory-verbal channel, which is under-used.

The third section of Table 1 lists three principles for fostering generative processing: the *multimedia*, *personalisation* and *voice* principles. The multimedia principle is that people learn better from words and pictures than from words alone. For example, instead of explaining the steps in how the heart works solely in words, add a series of illustration frames showing each state of the heart. The personalisation principle is that people learn better when words are delivered in a conversational or polite form rather than in a formal or direct form. For example, people learn better when the narrator talks about 'your heart' rather than 'the heart'. The voice principle is that people learn better from computer-based multimedia lessons when the narrator speaks in a human voice rather than a machine voice. The rationale behind this is that people try harder to make sense of what a narrator is saying when they feel they are in a social partnership with the narrator.

## CONCLUSIONS

My main goal in this article is to provide an example of what it means to apply the science of learning to medical education. This article is motivated by the idea that advances in cognitive science may have useful implications for how to design effective instruction in medicine.[11] For example, as medical education increasingly uses computer-based simulations of the human body, it is useful to conduct research on how to help people learn in simulated medical environments.[12] Overall, cognitive research on medical education is an important venue for improving both medical instruction and cognitive theories of multimedia learning.

*Acknowledgements:* none.
*Funding:* the preparation of this paper was supported by grant N000140810018 from the Office of Naval Research, Washington, DC, USA.
*Conflicts of interest:* none.
*Ethical approval:* not applicable.

REFERENCES

1 Mayer RE ed. *The Cambridge Handbook of Multimedia Learning*. New York, NY: Cambridge University Press 2005.
2 Mayer RE, Moreno R. Nine ways to reduce cognitive load in multimedia learning. *Educ Psychol* 2003;**38**:43–52.
3 Mayer RE. *Multimedia Learning*, 2nd edn. New York, NY: Cambridge University Press 2009.
4 Mayer RE. *Applying the Science of Learning*. Boston, MA: Pearson 2011.
5 Mayer RE. *Learning and Instruction*, 2nd edn. Upper Saddle River, NJ: Merrill Prentice Hall Pearson 2008.
6 Paivio A. *Mental Representations: A Dual-Coding Approach*. Oxford: Oxford University Press 1986.
7 Baddeley AD. *Human Memory*. Boston, MA: Allyn & Bacon 1999.
8 Sweller J. *Instructional Design in Technical Areas*. Camberwell, Australia: ACER Press 1999.
9 Wittrock MC. Generative processes in comprehension. *Educ Psychol* 1989;**24**:345–76.
10 Anderson LW, Krathwohl DR, Airsian PW, Cruikshank KA, Mayer RE, Pintrich P, Raths J, Wittrock MC. *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*. New York, NY: Longman 2001.
11 Mayer RE. What neurosurgeons should discover about the science of learning. *Neurosurgery* 2009;**56**:57–65.
12 Stull A, Hegarty M, Mayer RE. Getting a handle on learning anatomy with interactive 3D graphics. *J Educ Psychol* 2009;**101**:803–16.

*Received 15 December 2009; editorial comments to author 17 December 2009; accepted for publication 30 December 2009*