MEDICAL AND DENTAL EDUCATION

Designing Multimedia Instruction in Anatomy: An Evidence-Based Approach

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This paper summarizes 10 research-based principles for how to design effective multimedia instruction in medical education involving anatomy. Clin. Anat. 33:2–11, 2020.

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INTRODUCTION

Medical education sometimes involves multimedia instructional lessons such as classroom slideshow lectures, online presentations, and even computer-based simulations. This article explores how the design of multimedia lessons in medical education can benefit from applying the science of learning–that is, research and theory on how people learn (Mayer, 2009a, 2010, 2018). The goal of this article is to describe 10 evidence-based principles for the design of multimedia instruction that are relevant to medical education in anatomy, based on decades of research in our laboratory at the University of California, Santa Barbara (UCSB) and from researchers around the world (Clark and Mayer, 2017; Mayer, 2009b, 2014a).

Multimedia messages consist of words (in spoken or printed form) and graphics (in static form such as photos or diagrams or dynamic form such as video or animation); multimedia instructional messages are multimedia messages that are intended to cause learning (Clark and Mayer, 2017; Mayer, 2009b, in press). Figure 1 is an example of a multimedia instructional message because it contains printed words and graphics and is intended to foster learning. Multimedia instructional messages that are relevant to medical education include textbooks (with printed words and static graphics), face-to-face slideshow lectures (with spoken words, printed words, and static or dynamic graphics), and online presentations (with spoken or printed words and static or dynamic graphics).

Our laboratory at UCSB has a long-standing commitment to basic research on how to design effective instructional messages about the human body, including instruction about teeth (Stull et al., 2009, 2010), the blood stream (Mayer et al., 2008; Mayer and Estrella, 2014; Parong & Mayer, 2018), neural transmission (Wang et al., 2018; Xie et al., in press), the human heart and circulatory system (Leopold & Mayer, 2015; Leopold et al., in press), the human ear (Fiorella & Mayer, 2013), the human digestive system (Mayer et al., 2008), and the human lungs and respiratory system (Mayer et al., 2004; Mayer and Sims, 1994). This work contributes to the larger research base on how to design multimedia instruction (Clark and Mayer, 2017; Mayer, 2009b, in press).

Instructional technology has a long and somewhat disappointing history, ranging from instructional movies in the 1920s to instructional radio in the 1930s to educational television in the 1950s to programmed instruction in the 1960s, in which strong claims are made for the power of the latest cutting-edge instructional technology, major investments are made, and subsequent research fails to demonstrate much benefit (Cuban, 1986, 2001; Saettler, 2004). Today, we have new computer-based technologies that allow for the creation of dazzling multimedia lessons – including slideshows, animation, and video – but these technologies alone do not produce learning. The history of instructional technology teaches us that instructional technology does not cause learning, but instead instructional methods cause learning (Clark, 2001). Instead of taking a technology-centered approach that focuses on the capabilities of the latest technology, it makes sense to take a learner-centered approach that focuses on how to adapt technology to

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the requirements of how the human information processing system works (Mayer, 2009b).

Thus, the present article takes an evidence-based approach in which we seek to determine which instructional techniques have been shown to improve learning from multimedia messages in line with cognitive theories of learning. Four major steps in creating effective multimedia instruction suitable for medical education are: (1) Start with a clear instructional goal for the instructional message. (2) Help learners focus on the instructional message by reducing extraneous processing. (3) Help learners encode the instructional message by managing essential processing. (4) Help learners engage with the instructional message by fostering generative processing. These steps are explored in the remainder of this article.

START WITH A CLEAR INSTRUCTIONAL GOAL FOR THE INSTRUCTIONAL MESSAGE

The first step in effective instructional design is to clearly state your instructional objective (Anderson et al., 2001; Mayer, 2011; Pellegrino et al., 2001). As noted in Mayer (2011), an instructional objective is a description of the intended change in the learner's knowledge. An instructional objective includes a description of what is to be learned and how it will be tested. In short, you should be able to describe the knowledge that you want the learner to glean from the instructional message.

For example, consider the slide shown in Figure 1, showing some basic anatomic information about the human brain. Your instructional objective might be that the learner knows the names and locations of each of several key brain areas, and this can be tested by pointing to each area and asking the learner to say the name of the brain area. When you have a clear statement of your instructional objective, this can guide the creation of an effective instructional message - which is a slide in this case.

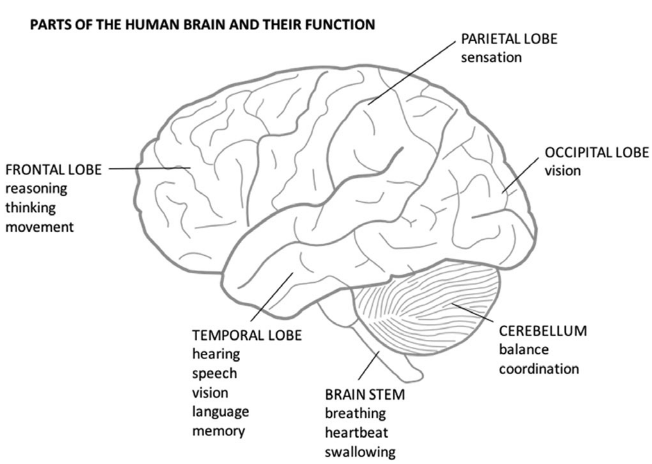

Fig. 1. A slide showing six brain regions.

In this example, the instructional goal is for the learner to know the spatial layout of the brain - which is a focus on structural knowledge (e.g., Where is the X?). In contrast, the instructional goal could be to understand how the brain works – which is a focus on process knowledge (e.g., What happens in the brain when someone tries to remember their phone number?). Alternatively, the instructional goal could be to know about the characteristics of each part of the brain – which is a focus on factual knowledge (e.g., What does X do?). Thus, the way you create the instruction message depends on the type of knowledge you want the learner to acquire.

Once you have a draft of the instructional message that conveys the target information, you have not completed your job as an instructor. In addition to presenting the target information, your job as an instructor is to guide the learner's cognitive processing of the material. This can be done by following evidence-based principles for the design of multimedia instructional messages (Clark and Mayer, 2017; Mayer, 2009b, 2014a, in press). I break this task of guiding the learner's cognitive processing into three sub-tasks: helping the learner focus on the target information, helping the learner mentally represent the target information, and encouraging the learner to make sense of the target information.

In the next three sections, I provide some evidence-based techniques for accomplishing these sub-tasks. The supporting evidence consists of studies that compare the learning outcome scores on posttest of groups of students who learn from a standard lesson versus the same lesson with one feature added, such as a lesson on the human respiratory system with words spoken in formal language or conversational language. In intervention studies such as these, differences between the groups is often expressed as effect size (d), which is the number of standard deviations better (or worse) that the enhanced group did on the post-test as compared to the control group (Cohen, 1988). Effect size provides a common metric to aggregate across studies, with effect sizes greater than d = 0.4 considered to be educationally significant (Hattie, 2009).

HELP LEARNERS FOCUS ON THE INSTRUCTIONAL MESSAGE BY REDUCING EXTRANEOUS PROCESSING

In terms of guiding cognitive processing, we want instructional techniques that guide the learner toward processing of the target information in the instructional message. Learners have a limited working memory capacity, which means they can only process a few pieces of information at any one time (Mayer, 2009b, 2011). If they use their limited capacity on *extraneous processing* – cognitive processing that does not support the instructional goal – they are less likely to focus on the target information. Thus, a primary goal in designing effective multimedia messages is to reduce extraneous processing. In this section, we explore five techniques for reducing extraneous processing: the coherence, signaling, spatial contiguity, temporal contiguity, and redundancy principles.

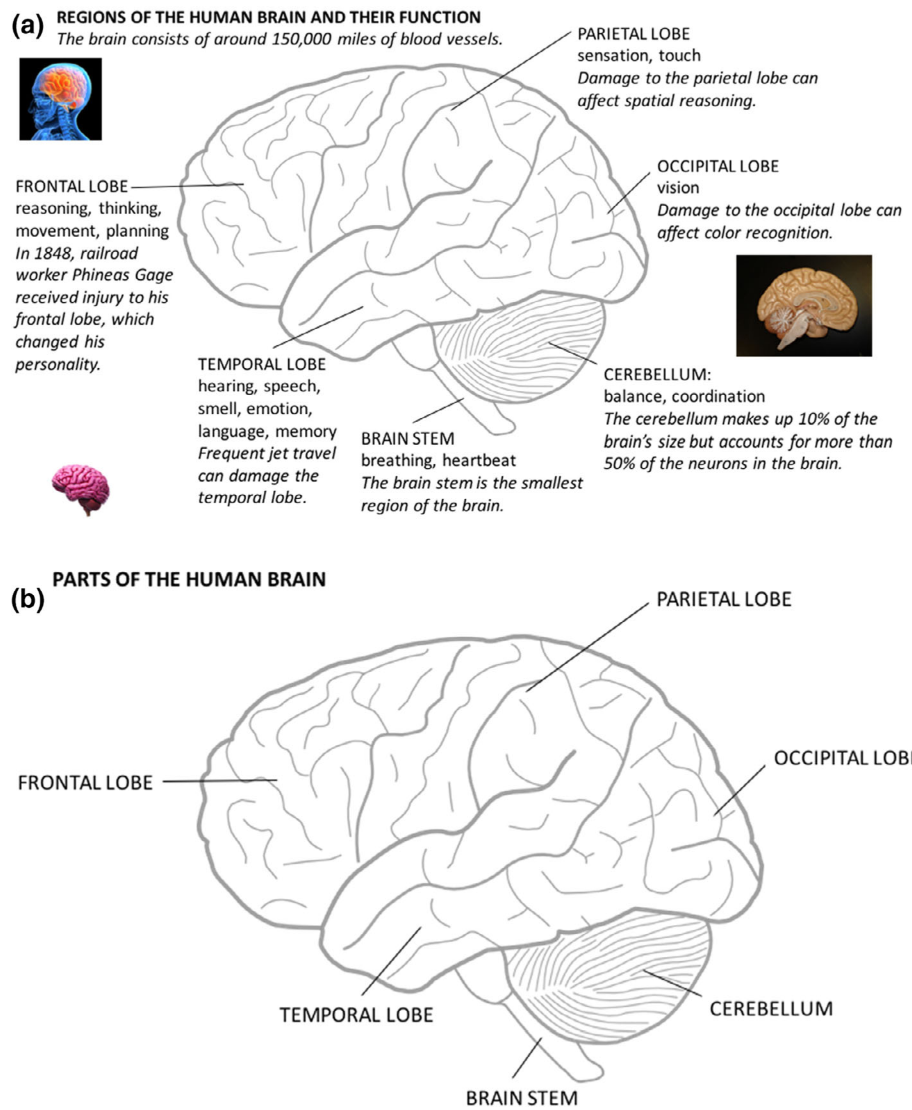

Fig. 2. **(a)** Slide with extraneous material. **(b)** Slide without extraneous material. [Color figure can be viewed at wileyonlinelibrary.com]

Coherence Principle

For example, consider a situation in which the screen is of full of interesting but irrelevant graphics and factoids, such as shown in Figure 2a. If the learner spends time focusing on these aspects of the slide, there is less cognitive capacity available to focus on the names and locations of the major brain areas. In contrast, Figure 2b shows a revised version of the slide in which the irrelevant material has been weeded out. In a recent review, in 23 out of 23 experimental comparisons, students performed better on learning outcome tests with multimedia lessons that eliminated extraneous material, yielding a median effect size of 0.86, which is considered a large effect (Mayer and Fiorella, 2014). This effect is strongest for learners with smaller working memory capacity, when the extraneous material is highly distracting, and when the pace of the lesson is controlled by the instructor rather than the learner (Mayer and Fiorella, 2014; Rey, 2012). In summary, the coherence principle is that people learn better from a multimedia instructional message when extraneous material is eliminated.

Signaling Principle

If you cannot completely eliminate the extraneous material, the next best strategy is to highlight the essential material. For example, if there is a lot of nonessential printed text on the screen, you can highlight the essential material, such as putting it in bold font, underlining it, giving it a different color, or repeating it in the margin. If there is a lot of nonessential spoken text in the narration, you can highlight the essential material by speaking it with higher volume or more stress. If there are many nonessential graphical elements on the screen in an animation or video or even in a static graphic, you can highlight the essential material through spotlighting in which you gray out all the other areas except for the area being described in the narration or by cueing the relevant area on screen with an arrow or with distinctive coloring. Figure 3a shows an example of a slide on regions of the human brain, in which a narration describes each region in turn. In Figure 3b, the region being described by the narration is circled, as a form of cueing. In a recent review, in 24 out of 28 experimental comparisons, students performed better on learning outcome tests with multimedia lessons that signaled essential material, yielding a median effect size of 0.41, which is in the small-to-medium range (Mayer and Fiorella, 2014). The signaling effect was also found in a more recent meta-analysis involving 103 studies (Schneider et al., 2018). This effect may be strongest for students who lack prior knowledge, when the display is complicated, and when signaling is used sparingly. In summary, the signaling principle is that people learn better from a multimedia instructional message when essential material is highlighted.

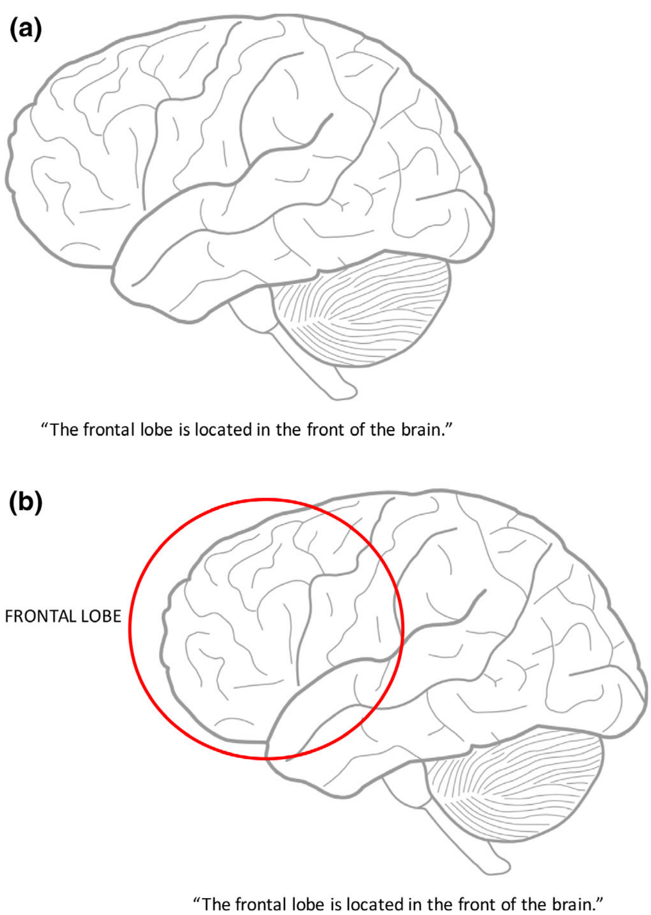

Fig. 3. **(a)** Slide without cueing. **(b)** Slide with cueing. [Color figure can be viewed at wileyonlinelibrary.com]

Spatial Contiguity Principle

Consider the slide shown in Figure 4a, which involves the common practice of using a legend that is keyed to parts of a graphic. Similarly, it is common to have a caption at the bottom of a graphic. What is wrong with these situations in which the words are separated from the graphics they describe? The problem is that legends and captions can create extraneous processing, in which the learner must scan back and forth between the printed words and the corresponding part of the graphic. This wastes precious processing capacity that could have been used for trying to encode and make sense of the material. To alleviate this design flaw, we can move the printed words next to the corresponding part of the graphic, as shown in Figure 4b. This makes it easier for the learner to build connections between corresponding words and graphics, as has been shown in eye-tracking studies (Johnson and Mayer, 2012). In a recent review, in 22 out of 22 experimental comparisons, students learned better when corresponding printed words and graphics were near each other on the screen, yielding a median effect size of 1.10, which is a large effect (Mayer and Fiorella, 2014). A more recent meta-analysis of 58 studies also found strong evidence for the spatial contiguity effect (Schroeder and Cenkci, in press). The effect may be strongest for students who lack prior knowledge and when the material is complicated. In summary, the spatial contiguity principle is that people learn better from a multimedia instructional message when corresponding printed words and graphics are placed near each other on the screen.

Temporal Contiguity Principle

Consider an instructional episode in which an instructor first explains what the students are about to see in a brief animation on how one neuron communicates with another, and then the instructor shows the animation. In terms of multimedia learning theory, this is a problematic approach because the learner's working memory is too limited to be able to hold the entire verbal explanation so it is available when the animation is presented. By separating corresponding words and graphics in time, the instructor is reducing the chances that the learner will be able to make connections between them in working memory. The solution is to present corresponding graphics and spoken words simultaneously. In nine out of nine experimental comparisons, students who received multimedia lessons with simultaneous words and graphics scored higher on learning outcome posttests than students who received

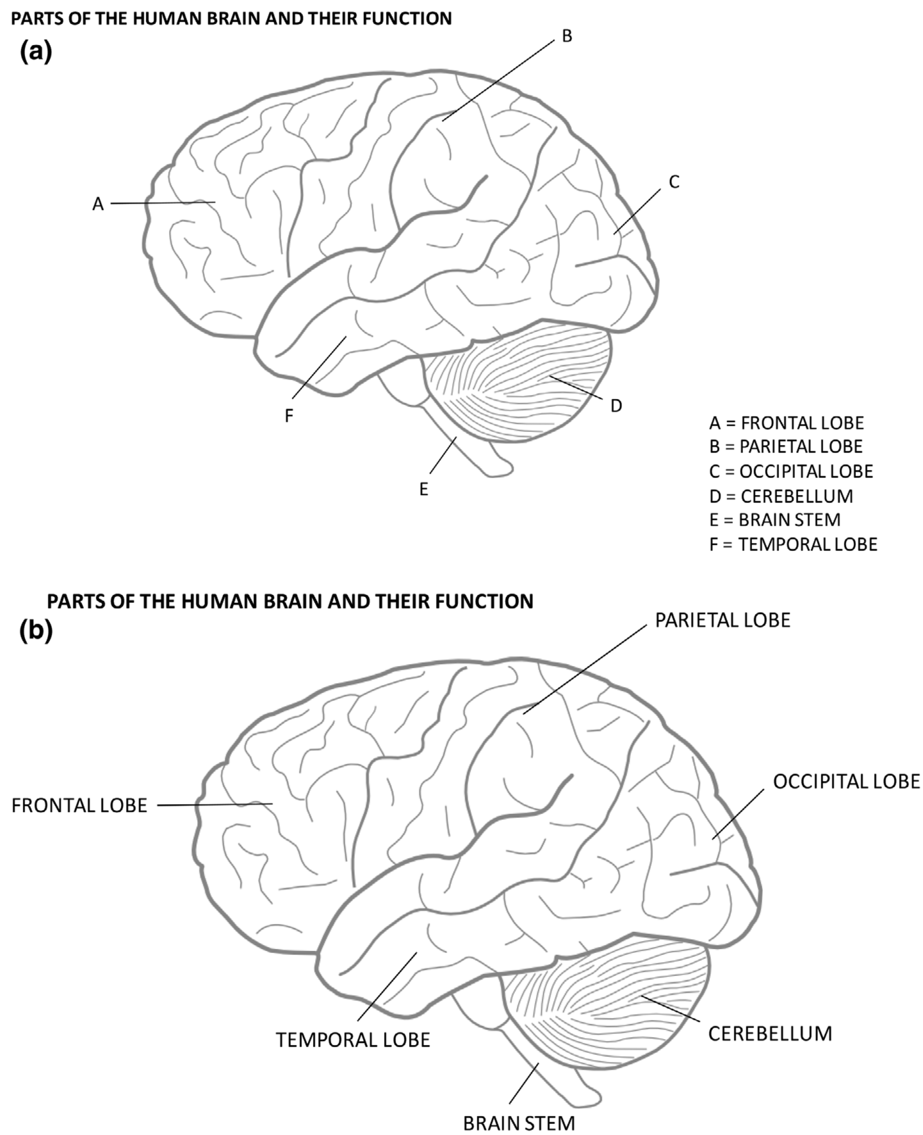

Fig. 4. (a) Slide with legend. **(b)** Slide with text integrated into graphic.

lessons with corresponding words and graphics separated in time, yielding a median effect size of 1.22, which is a large effect (Mayer and Fiorella, 2014). The effect is strongest when the segments are large and the pacing is not controlled by the learner. Analogous to the spatial contiguity principle, the temporal contiguity principle is that people learn better from multimedia instructional messages when corresponding graphics and narration are presented simultaneously.

Redundancy Principle

Suppose you have a narrated animation on how the human respiratory and circulatory systems work. You might suppose that it would be useful to add concurrent printed text at the bottom of the screen that is identical to the spoken text, so that learners could have the option of reading or listening. However, in terms of multimedia learning theory, having redundant spoken and printed text can create extraneous processing because learners may try to reconcile the spoken and printed streams of words or they may have to scan back and forth between the captions and the animation (Mayer, 2009b; Mayer and Fiorella, 2014). In 16 out of 16 experimental comparisons, students learned better from graphics and narration than from graphics, narration, and on-screen text, with a median effect size of 0.86, which is a large effect. Some important exceptions are that it can be helpful to add just one or two basic printed words to a narrated animation (Mayer and Johnson,

2008) or to restate the printed sentence in a different way than the spoken one (Yue et al., 2013); also, printed text is useful when the words are technical or unfamiliar or not in the learner's first language (Mayer and Fiorella, 2014). In summary, the redundancy principle is that people learn better from multimedia instructional messages containing graphics and narration rather than graphics, narration, and on-screen text.

HELP LEARNERS ENCODE THE INSTRUCTIONAL MESSAGE BY MANAGING ESSENTIAL PROCESSING

Suppose you have designed your instructional materials so they achieve the goal of reducing extraneous processing by using some of the techniques described in the previous section. The next important step in guiding cognitive processing is to encourage learners to mentally represent the essential material from the lesson in their working memory, a process that is called *essential processing* (Mayer, 2009b, 2011). In some cases, when the essential material is complex for the learner, the amount of essential material required for learning may threaten to overwhelm the learner's limited working memory capacity. Thus, a primary goal in designing effective multimedia messages is to manage essential processing. In this section, we explore three techniques for managing essential processing: the segmenting, pretraining, and modality principles.

Segmenting Principle

Suppose you have a long multimedia lesson, explaining the regions of the brain. We could present a single, complete graphic showing the entire system and describe it with a complete continuous verbal narration, as shown in Figure 5a. The problem with this approach to instructional design is that presenting all the information at once in a fast-paced narrated animation may overwhelm the learner's processing capacity. A solution is to break the lesson into basic segments, each covering one main idea; the lesson could stop after each segment and continue when the student presses a CONTINUE key, as shown in Figure 5b. In this way, the student can completely digest one portion of the lesson before moving on to the next one. In a recent review, in 10 out of 10 experimental comparisons, students learned better when a multimedia message was presented in learner-paced segments rather than as a continuous presentation, yielding a median effect size of 0.79, which approaches a large effect (Mayer and Pilegard, 2014). The effect is stronger for students with low prior knowledge or low working memory capacity, and when the segments are small. In summary, the segmenting principle is that people learn better when a multimedia instructional message is broken into learner-paced segments.

Pretraining Principle

Instead of breaking a complicated lesson into parts that are presented under learner control, another way to manage essential processing is to provide pretraining in the names and characteristics of the key components. For example, before viewing a narrated animation on the process of neural transmission, students could be shown a diagram of the entire system with each component labeled. When the student clicks on a component, that component is spotlighted and a brief animation shows what that component does, while words describe the component's behavior. In a review of studies involving pretraining, adding pretraining before a multimedia presentation improved learning outcome test scores in 13 out of 16 experimental comparisons, yielding a median effect size of 0.75, which approaches a large effect (Mayer and Pilegard, 2014). The effect may apply mainly to students who lack prior knowledge. In summary, the pretraining principle is that people learn better from multimedia instructional messages when they know the names and characteristics of the key components.

Modality Principle

Consider what can happen when students view a fast-paced multimedia lesson containing graphics and printed words, such as exemplified in Figure 6a. This situation can create split attention in which students cannot be viewing the graphic when they are reading the caption and cannot be reading the caption when they are viewing the graphic. In short, the visual channel may become overloaded. As exemplified in Figure 6b, a solution to this problem is to off-load the verbal material from the learner's visual channel to the learner's auditory channel, by presenting the words as spoken text (i.e., narration) rather than printed text (i.e., captions). Humans have separate information processing channels for processing images (through the eyes) and sounds (through the ears), so presenting words as spoken text frees up capacity in the visual channel and makes more effective use of the auditory channel (Mayer, 2009b; Mayer and Pilegard, 2014). In a review, students scored higher on learning outcome tests when the words in a multimedia lesson where changed from printed to spoken text in 53 out of 61 experimental comparisons, yielding a median effect size of 0.76, which approaches a large effect (Mayer and Pilegard, 2014). There are cases in which the modality effect does not occur, but these are consistent with multimedia learning theory: when the material is simple for the learner, when the pacing of the material is under learner control, when the words are highly familiar for the learner, and when the learner has high prior knowledge (Mayer and Pilegard, 2014). In summary, the modality principle is that people learn better from a multimedia instructional message when the words are spoken rather printed.

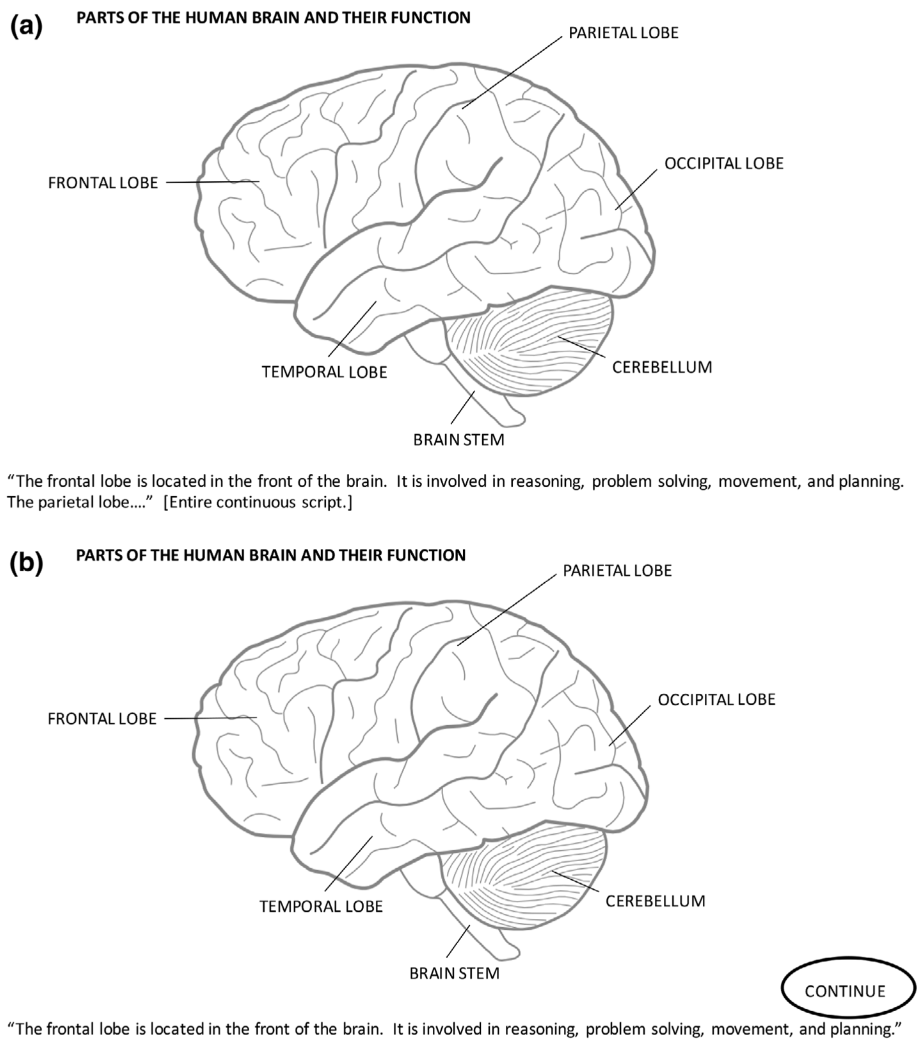

Fig. 5. (a) Slide from continuous presentation. **(b)** Slide from segmented presentation.

HELP LEARNERS ENGAGE WITH THE INSTRUCTIONAL MESSAGE BY FOSTERING GENERATIVE PROCESSING

Even if students are able to encode the essential material from a multimedia lesson and even if they have cognitive capacity available because they have not engaged in extraneous processing, they may not exert the effort to understand the lesson. Thus, the third instructional design goal is to motivate learners to try to make sense of the essential material – a process that can be called *generative processing* (Mayer, 2009b, 2011; Fiorella and Mayer, 2015). Generative processing involves mentally organizing the material into a coherent structure and integrating it with relevant prior knowledge. Two instructional design techniques intended to foster generative processing are personalization and embodiment.

Personalization Principle

Consider the portion of a script for a narrated animation on the brain listed in the top of Table 1. As you can see, the wording is in formal style, as indicated, for example, by the use of third person constructions (e.g. "the frontal lobe is located in the front of the brain"). Learners can interpret formal wording as meaning that the instructor does not care about them, and therefore, the learner may not feel much of a social partnership with the instructor. In contrast, as exemplified in the bottom of Table 1, suppose we change the wording into conversational style, as indicated by using first and second person constructions (e.g., "your frontal lobe is located in the front of your brain"). The use of conversational language (which can be called *personalization*) is a social cue that can prime a feeling of social partnership between the learner and instructor, which motivates the learner to

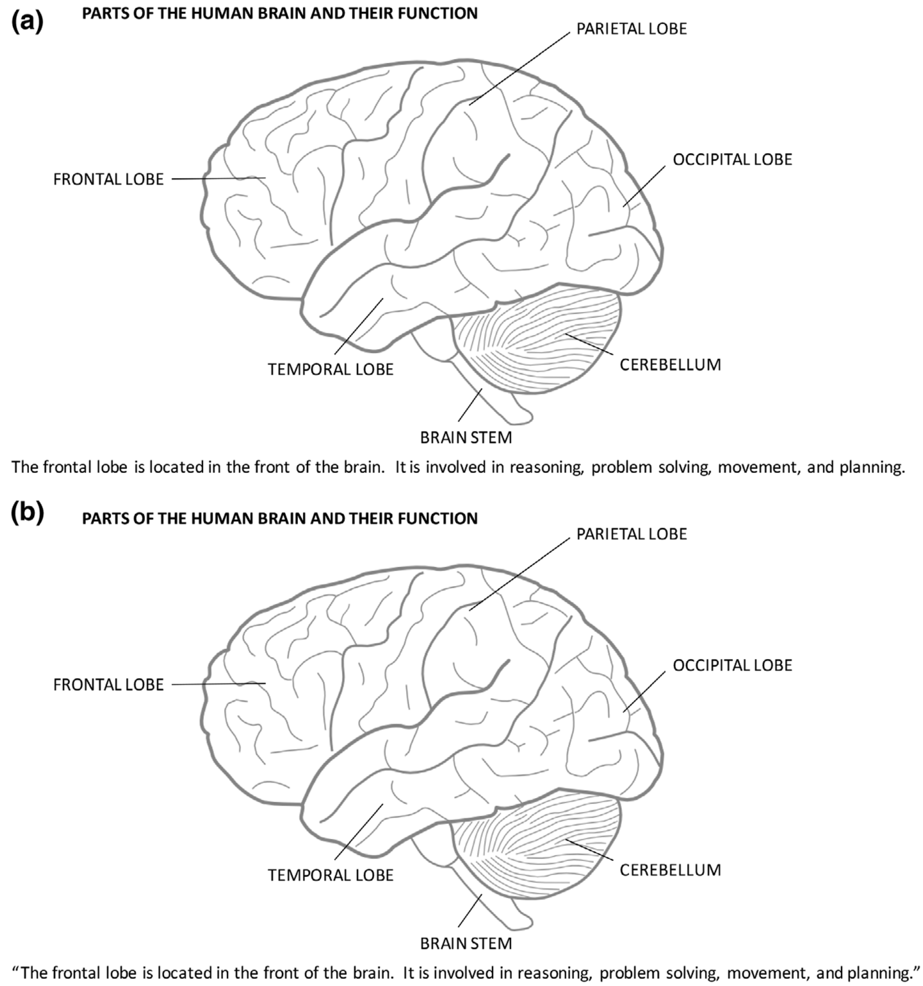

Fig. 6. **(a)** Slide with printed text. **(b)** Slide with spoken text.

try harder to make sense of what the instructor is communicating, and thereby improves the learning outcome (Mayer, 2014b). In a recent review, using conversational wording in multimedia lessons improved learning outcome test scores in 14 out of 17 experimental comparisons, yielding a median effect size of 0.79, which approaches a large effect. Ginns et al. (2013) reported a similar effect in their meta-analysis of personalization. The effect is strongest for students who have low prior knowledge or low achievement, and for short lessons. In summary, the personalization principle is that people learn better from a multimedia instructional message when the words are in conversational style.

Embodiment Principle

Suppose a student is watching a video of a classroom lecture in which an instructor narrates a slideshow, or an animation in which an onscreen animated character (i.e., animated pedagogical agent) narrates a slideshow. This can be a somewhat alienating

TABLE 1. Partial Script for Multimedia Lesson on the Brain

Formal Version
"The frontal lobe is located in the front of the brain. It is involved in reasoning, problem solving, movement, and planning."
Personalized Version
"Your frontal lobe is located in the front of your brain. You are using your frontal lobe when you reason, solve a problem, engage in movement, or make a plan."

TABLE 2. Ten Evidence-Based Principles for Designing Multimedia Instruction

1. Coherence principle: Remove extraneous material.
2. Signaling principle: Highlight essential material.
3. Spatial contiguity principle: Place printed text next to the corresponding part of the graphic.
4. Temporal contiguity principle: Present corresponding narration and graphics at the same time.
5. Redundancy principle: Present graphics and narration rather than graphics, narration, and on-screen text.
6. Segmenting principle: Break a continuous presentation into learner-paced segments.
7. Pretraining principle: Describe the names and characteristics of key components before presenting a multimedia lesson.
8. Modality principle: Present words in spoken form rather than printed form.
9. Personalization principle: Use conversational language style.
10. Embodiment principle: Show an instructor who uses human-like gesture, eye-gaze, and movement.

experience that causes the learner to disengage from the lesson. What can we do to prime the learner to process the material more deeply, that is, to engage in generative processing? One technique involves putting the instructor (or agent) on the screen next to the slide and making sure he or she engages in human-like gesture, body movement, facial expression, and eye-contact. According to theories of multimedia learning, when the instructor displays high levels of embodiment (such as human-like gesture), the learner is more likely to form a social partnership with the instructor, and try harder to make sense of what the instructor is saying (Mayer, 2014b). In a review, Mayer (2014b) reported that in 11 out of 11 experimental comparisons, students learned better from a multimedia lesson when the onscreen instructor or agent displayed human-like gesture and movement, yielding a median effect size of 0.36, which is in the small-to-medium range. More recently, Wang et al. (2018) found that pointing gestures can be particularly helpful, suggesting that the signaling principle may also come into play. In summary, the embodiment principle is that people learn better from a multimedia instructional message when the onscreen instructor engages in human-like gesturing, movement, eye-contact, and facial expression. This applies both to human instructors as well as animated agents that appear on the screen.

APPLYING MULTIMEDIA DESIGN PRINCIPLES TO MEDICAL EDUCATION

Table 2 summarizes ten evidence-based principles for designing multimedia instruction. As you can see, research on multimedia message design has implications for medical education, including in anatomy, but is there any evidence from actual medical classrooms? For example, suppose we took a slideshow lecture from an actual class in medical school and redesigned the slideshow lecture based on the instructional design principles described in this article. In a series of experiments intended to address this question, medical students who learned from a redesigned slideshow lecture scored substantially higher on immediate and delayed post-tests than medical students who learned the same material in its original format, with effect sizes in the large range (Issa et al., 2013; Issa et al., 2011). This work encourages us to continue to explore the potential benefits of applying evidence-based design principles to the design of multimedia instructional lessons in medical education, including anatomy.

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REFERENCES

Anderson LW, Karthwohl DR, Airasian PW, Cruikshank KA, Mayer RE, Pintrich PR, Raths J, Wittrock MC. 2001. A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom’s Taxonomy of Educational Objectives. New York: Longman.

Clark RC, Mayer RE. 2017. E-Learning and the Science of Instruction. Hoboken, NJ: Wiley.

Clark RE. 2001. Learning from Media. Greenwich, CT: Information Age Publishing.

Cohen J. 1988. Statistical Power Analysis for the Behavioral. Sciences. 2nd Ed. Hillsdale, NJ: Erlbaum.

Cuban L. 1986. Teachers and Machines: The Classroom Use of Technology since 1920. New York: Teachers College Press.

Cuban L. 2001. Oversold & Underused: Computers in the Classroom. Cambridge, MA: Harvard University Press.

Fiorella L, Mayer RE. 2013. The relative benefits of learning by teaching and teaching expectancy. Contemp Educ Psychol 38: 281–288.

Fiorella L, Mayer RE. 2015. Learning as a Generative Activity. New York: Cambridge University Press.

Ginns P, Martin AJ, Marsh HM. 2013. Designing instructional text for conversational style: a meta-analysis. Educ Psychol Rev 25: 445–472.

Hattie J. 2009. Visible Learning. New York: Routledge.

Issa N, Schuller M, Santacaterina S, Shapiro M, Wang E, Mayer RE, DaRosa DA. 2011. Applying multimedia design principles enhances learning in medical education. Med Educ 45:818–826.

Issa N, Mayer RE, Schuller M, Wang E, Shapiro M, DaRosa DA. 2013. Teaching for understanding in medical classrooms using multimedia design principles. Med Educ 47:388–396.

Johnson C, Mayer RE. 2012. An eye movement analysis of the spatial contiguity effect in multimedia learning. J Exp Psychol-Appl 18: 178–191.

Leopold C, Mayer RE. 2015. An imagination effect in learning from scientific text. J Educ Psychol 107:47–63.

Leopold C, Mayer RE, Dutke S. in press. The power of imagination and perspective in learning from science text. J Educ Psychol 110:000–000.

Mayer RE. 2009a. What neurosurgeons should discover about the science of learning. Clin Neurosurg 56:57–65.

Mayer RE. 2009b. Multimedia Learning. 2nd. New York: Cambridge University Press.

Mayer RE. 2010. Applying the science of learning to medical education. Med Educ 44:543–549.

Mayer RE. 2011. Applying the Science of Learning. Boston: Pearson.

Mayer RE, (ed.). 2014a. The Cambridge Handbook of Multimedia Learning. 2nd Ed. New York: Cambridge University Press.

Mayer RE. 2014b. Principles based on social cues in multimedia learning: personalization, voice, embodiment, and image principles. In: Mayer RE, editor. The Cambridge Handbook of Multimedia Learning: Second Edition. New York: Cambridge University Press. p 345–368.

Mayer RE. 2018. How to design multimedia presentations. How to design multimedia presentations. In: Bowe EA, Schell RM, DiLorenzo AN, editors. Education in Anesthesia: How to Deliver the Best Learning Experience. New York: Cambridge University Press. p 151–159.

Mayer RE. in press. How multimedia can improve learning and instruction. In: Dunlosky J, Rawson K, editors. The Cambridge Handbook on Cognition and Education. New York: Cambridge University Press.

Mayer RE, Estrella G. 2014. Benefits of emotional design in multimedia instruction. Learn Instr 33:12–18.

Mayer RE, Fennell S, Farmer L, Campbell J. 2004. A personalization effect in multimedia learning: students learn better when words are in conversational style rather than formal style. J Educ Psychol 96:389–395.

Mayer RE, Fiorella L. 2014. Principles for reducing extraneous processing in multimedia learning: coherence, signaling, redundancy, spatial contiguity, and spatial contiguity principles. In: Mayer RE, editor. The Cambridge Handbook of Multimedia Learning: Second Edition. New York: Cambridge University Press. p 279–315.

Mayer RE, Johnson C. 2008. Revising the redundancy principle in multimedia learning. J Educ Psychol 100:380–386.

Mayer RE, Griffith E, Naftaly I, Rothman D. 2008. Increased interestingness of extraneous details leads to decreased learning. J Exp Psychol-Appl 14:329–339.

Mayer RE, Pilegard C. 2014. Principles for managing essential processing in multimedia learning: segmenting, pre-training, and modality principles. In: Mayer RE, editor. The Cambridge Handbook of Multimedia Learning: Second Edition. New York: Cambridge University Press. p 316–344.

Mayer RE, Sims VK. 1994. For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. J Educ Psychol 86:389–401.

Parong J, Mayer RE. 2018. Learning science in immersive virtual reality. J Educ Psychol 110:785–797.

Pellegrino JW, Chudowsky N, Glaser R. 2001. Knowing What Students Know: The Science and Design of Assessment. Washington, DC: National Academies Press.

Rey GD. 2012. A review and a meta-analysis of the seductive details effect. Educ Res Rev 7:216–237.

Saettler P. 2004. The Evolution of American Educational Technology. Greenwich, CT: Information Age Press

Schneider S, Beege M, Nebel S, Rey GD. 2018. A meta-analysis of how signaling affects learning with media. Educ Psychol Rev 23:1–24.

Schroeder NL, Cenkci AT. in press. Spatial contiguity and spatial split-attention effect in multimedia learning environments: a meta-analysis. Educ Psychol Rev .

Stull A, Hegarty M, Mayer RE. 2009. Getting a handle on learning anatomy with interactive 3D graphics. J Educ Psychol 101: 803–816.

Stull AT, Hegarty M, Mayer RE. 2010. Anatomy learning with virtual objects. Cognitive Shape Processing: Papers from the AAAI Spring Symposium. Menlo Park, CA: AAAI Press. p 39–44.

Wang F, Li W, Mayer RE, Liu H. 2018. Animated pedagogical agents as aids in multimedia learning: effects on eye-fixations during learning and learning outcomes. J Educ Psychol 110:250–268.

Xie H, Wang F, Mayer RE, Zhou Z. in press. Coordinating visual and auditory cueing in multimedia learning. J Educ Psychol 110: 000–000.

Yue CL, Bjork EL, Bjork RA. 2013. Reducing verbal redundancy in multimedia learning: an undesired desirable difficulty? J Educ Psychol 105:266–277.