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Thirty years of research on online learning

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Summary

This paper presents a personal account of developments in research on online learning over the past 30 years. Research on how to design online instruction represents an example of applying the science of learning to education. It contributes to the science of learning (as exemplified by developments in cognitive load theory, the cognitive theory of multimedia learning, and incorporating metacognitive, motivational, and affective aspects of learning), the science of instruction (as exemplified by the continuing development of research-based principles of instructional design), and the science of assessment (as exemplified by supplementing self-report surveys and retention tests with multilevel transfer tests, log file data during learning, and cognitive neuroscience measures of cognitive processing during learning). Some recurring themes are that learning is caused by instructional methods rather than instructional media, so research should focus on features that are uniquely afforded by digital learning environments; instructional practice should be grounded in rigorous and systematic research, including value-added experiments aimed at pinpointing the active ingredients in online instruction; research in online learning should identify boundary conditions under which instructional techniques are most effective; and research in online learning should test and contribute to learning theory.

KEYWORDS

digital learning, instructional design, multimedia learning, online learning, science of learning

1 | INTRODUCTION

1.1 | Applying the science of learning to education

The goal of this brief review is to provide a personal history of developments in research on online learning over the past 30 years, with a focus on contributions to the science of learning (i.e., how people learn), the science of instruction (i.e., how to help people learn), and the science of assessment (i.e., how to determine what people have learned). This review is intended as an example of applying the science of learning to education (Mayer, 2011) and fits under the larger umbrella of applied cognitive psychology.

1.2 | What is online learning?

Online learning (which also has been called e-learning, digital learning, or computer-based learning) can be defined as instruction delivered on a digital device that is intended to support learning (Clark & Mayer, 2016). This definition includes three parts concerning the what, how, and why of online learning: (a) concerning what, the material presented consists of words in spoken or printed form and/or graphics such as illustrations, diagrams, photos, animation, or video; (b) concerning how, the medium is a computer-based device such as a desktop computer, laptop computer, tablet, smartphone, or virtual reality; and (c) concerning why, the instructional objective is to cause specific changes in the learner's knowledge.

Online learning has garnered increasing attention because instruction is increasingly migrating from conventional media—such as books and face-to-face lectures—to computer-based media—such as narrated animations, instructional video, hypertext involving printed text, and illustrations, as well as educational games and simulations (Clark & Mayer, 2016; Mayer, in press). Online venues allow for many innovative approaches to support learning, but what is needed are research-based principles for how best to take advantage of these new possibilities. We are faced with the challenge that advances in instructional technologies have outpaced advances in instructional science needed to determine how best to use them. In short, just because something can be done with technology does not mean it should be done.

It is worthwhile to acknowledge that instructional media—even computer-based media—do not cause learning but rather instructional methods cause learning (Clark, 2001). It is possible that certain instructional technologies may afford instructional methods that are impractical or impossible with conventional media. For example, computer-based media enable instructional methods involving interactivity or dynamic graphics that are not easily afforded by conventional book-based media. However, the history of instructional technology is rife with examples of the rise and fall of cutting edge technologies in education, including motion pictures in the 1920s, radio in the 1930s, television in the 1950s, and programmed instruction in the 1960s (Cuban, 1986; Saettler, 1990). The lesson from this early history is the need to take a learner-centered approach by asking how technology can be adapted to support human learning rather than to take a technology-centered approach by asking how we can make humans adapt to the latest cutting edge technology.

Today, we are confronted with an array of online learning technologies that allow for the delivery of stunning graphics (including virtual reality), interactivity (including intelligent instructional systems), and geographic location (including GPS). Will the educational potential of online learning technologies vanish like past educational technologies, or will we be able to conduct appropriate scientific research that guides the effective use of online learning? This review summarizes our progress over the past 30 years in understanding how to help people learn in technology-rich environments and suggests some productive paths for future research. In particular, I provide a brief history of developments in creating a research-based theory of how people learn with media (i.e., science of learning), how to help people learn with media (i.e., science of instruction), and how to determine what people have learned with media (i.e., science of assessment.

2 | SCIENCE OF LEARNING

2.1 | Changing conceptions of learning

The science of learning is the scientific study of how people learn (Mayer, 2011). As shown in the first column of Table 1, three metaphors of learning developed during the 20th century (Mayer, 1992, 2001a, 2011). First, our starting point in the first half of the 20th century is the behaviorist-inspired metaphor of learning as response strengthening, in which learning consists of strengthening and weakening of associations to responses caused by rewards and punishments. Behaviorist theories of learning were based largely on studies of lab animals learning simple responses in contrived and impoverished situations, such as a rat running down an alley to obtain food.

Second, the advent of the information processing revolution in the 1950s and 1960s ushered in the cognitivist-inspired metaphor of learning as information acquisition, in which learning consists of adding information to memory. Cognitivist theories of learning were based largely on studies of humans learning to remember arbitrary material in contrived and impoverished situations, such as memorizing a word list.

Third, the next phase involved a constructivist metaphor of learning as knowledge construction, in which the learner actively builds a mental representation in working memory. Although constructivism gained momentum in the 1970s and 1980s, it has deep roots going back to research and theory on schema construction by Bartlett (1932) concerning prose comprehension, Piaget (1971) concerning cognitive development, and Wertheimer (1959) and other Gestalt psychologists concerning meaningful learning. The constructivist view is based on a reinterpretation of information processing (Mayer, 2014a). First, instead of information being seen as an objective commodity that can be transferred from the outside world to the human mind, the content of human learning becomes knowledge, which is personally constructed by the learner. Second, instead of processing being seen as a rigid set of algorithms or computations that can be applied to information as in a computer program or a mathematical operation, mental activity becomes construction. This involves active processing during learning aimed at meaning making, including attending to relevant material, mentally organizing it into a coherent structure, and integrating with relevant prior knowledge activated from long-term memory. Constructivist theories of learning were based largely on studies of people learning more realistic material, in both lab and field environments, such as learning from a science or math lesson.

As you can see, the progression from viewing learning as response strengthening to information acquisition to knowledge construction paralleled a shift in research methods from lab animals to humans and from contrived materials and settings to realistic materials and settings. Thus, the practical demands of research addressing educational issues have fostered advances in our theoretical conceptions of learning. Although all three visions of how learning works influence our field today, the constructivist view is recognized as the most relevant for academic learning.

2.2 | Recent advances in the conception of learning

During the past few decades, there have been continuing advances in the constructivist view of learning as a generative activity. Starting in the 1970s, Wittrock (Mayer & Wittrock, 1996, 2006; Wittrock, 1974; Wittrock, 1978; Wittrock, 1989; Wittrock, 1992) showed how

TABLE 1 Three phases in conceptualizing learning, instruction, and assessment

Phase	Learning	Instruction	Assessment
Behaviorist	Response strengthening	Drill and practice	Response execution
Cognitivist	Information acquisition	Direct instruction	Retention
Constructivist	Knowledge construction	Cognitive guidance	Transfer

a constructivist view of learning as a generative activity could advance educational theory and practice. The modern conception of constructivist learning is reflected in Wittrock's (1974, p. 89) argument that what is learned depends on assimilating what is presented with what the learner already knows: "Learning with understanding...is a process of generating...associations between stimuli and stored information." In particular, Wittrock's conception of generative learning emphasized the role of the learner's active cognitive processing during learning: "reading comprehension is facilitated when, during encoding, learners use their memory of events and experiences to construct meanings for the text" (Doctorow, Wittrock, & Marks, 1978, p. 109). In ensuing years, Wittrock (1992, p, 532) sharpened his focus on generative learning processes: "to selectively attend to events...and generating relations both among concepts and between experience or prior learning and new information."

Another advance in learning theory that is relevant for the instructional design of online learning is cognitive load theory, which emerged in the 1990s and continues to develop (Paas & Sweller, 2014; Sweller, 1999, 2005; Sweller, Ayres, & Kalyuga, 2011). A central tenet of cognitive load theory is that the cognitive capacity of working memory available to a learner is limited. The total cognitive load experienced by a learner consists of three demands on cognitive capacity during a learning: Extraneous cognitive load refers to cognitive processing that is not relevant to the learning goals and is caused by way the material is presented; intrinsic cognitive load refers to cognitive processing needed to achieve the learning goal and depends on the inherent complexity of the material for the learner; and germane cognitive load refers to cognitive processing caused by the learner's efforts including schema construction and automatization (Sweller, 1999, 2005). An important goal for instructional design that fostered much of the early research is summarized in the call: "The aim of instruction should be to reduce extraneous cognitive load caused by inappropriate instructional procedures" (Sweller, 2005, p. 27–28). Although recent adjustments have added an evolutionary flavor (Paas & Sweller, 2014) and the combined intrinsic and germane load, the central theme of cognitive load theory still concerns how to help people learn with a cognitive system that is characterized by limited processing capacity.

My own thinking about how learning theory applies to online learning was influenced by Wittrock's insights about generative learning as well as Sweller's insights about limitations on working memory capacity during learning. I (Mayer, 2001b) began with three basic cognitive principles that I used to guide the development of the cognitive theory of multimedia learning: (a) dual channels—people have separate channels for processing auditory/verbal and visual/pictorial information; (b) limited capacity—people are able to process only a limited amount of material in each channel at any one time; and (c) active processing—meaningful learning occurs when people engage in appropriate cognitive processing during learning, including selecting the relevant material, organizing it into a coherent structure, and integrating it with relevant knowledge activated from long-term memory. From this, I (Mayer, 2001b) proposed the flow chart shown in Figure 1, consisting of four boxes for where the material is being held (the multimedia presentation, sensory memory, working memory, and long-term memory), two channels (verbal as the top row and visual as the bottom row); and three kinds of arrows for cognitive processes applied to the material (selecting words and images brings the material from sensory memory to working memory; organizing words and images creates organized verbal and pictorial representations; and integrating involves connecting the verbal and pictorial representations with each other and with relevant prior knowledge activated from long-term memory).

This basic model developed over the past 30 years from predecessors in the 1990s that lacked sensory memory and consisted of only three arrows (selecting, organizing, and integrating) rather than five (Mayer & Sims, 1994), or lacked sensory memory and long-term memory (Mayer, 1997; Mayer, Steinhoff, Bower, & Mars, 1995). It first appeared in Mayer, Heiser, and Lonn (2001) and has been included in major reviews since then (Mayer, 2001b, 2005, 2009, 2014b; Mayer & Moreno, 2003). Over the past 30 years, the name has changed from "model of meaningful learning" (Mayer, 1989) to "dual-coding model" (Mayer & Anderson, 1991, 1992) or "dual-processing model" (Mayer & Moreno, 1998; Mayer, Moreno, Boire, & Vagge, 1999) to "generative theory" (Mayer, 1997; Mayer et al., 1995; Plass, Chun, Mayer, & Leutner, 1998), but the current term, "cognitive theory of multimedia learning," was first used in Mayer, Heiser, and Lonn (2001a) and has been used in all major reviews (Mayer, 2001b, 2005, 2009, 2014b; Mayer & Moreno, 2003). Although the basic model has remained constant for the past 20 years, the emphasis has shifted from the memory stores (i.e., the four boxes) and channels (i.e., the two rows) to the cognitive processes (i.e., the five arrows).

The focus on cognitive processing during learning highlights the need for better measures of cognitive processes during learning. Although most studies of online learning use subjective measures of cognitive load (Brunken, Seufert, & Paas, 2010; Paas, Tuovinen, Tabbers, & Van Gerven, 2003; Paas, Van Merriënboer, & Adam, 1994), their drawbacks include the need to measure after learning rather than during learning and a reliance on learners to give accurate assessments of their cognitive processes (DeLeeuw & Mayer, 2008). Some ongoing methodological developments in cognitive theories of online learning involve the use of objective measures of cognitive

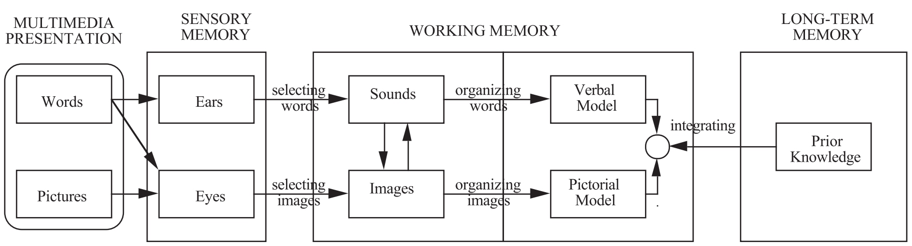

FIGURE 1 Flow chart representing the cognitive theory of multimedia learning

processing during learning including eye-tracking measures (Johnson & Mayer, 2012; Ponce & Mayer, 2014; Wang, Li, Mayer, & Liu, 2018) and brain measures such as EEG and fMRI (Mayer, 2017). The continuing development of objective techniques for measuring cognitive processing during learning holds promise for clarifying aspects of cognitive learning theory, particularly explaining the arrows in Figure 1.

Some ongoing expansions of cognitive theories of online learning include the incorporation of affect (Moreno & Mayer, 2007; Plass & Kaplan, 2016), motivation (Huang & Mayer, 2016; Mayer, 2014c), and metacognition (Azevedo, 2014; Azevedo & Aleven, 2013; Fiorella & Mayer, 2015). Concerning affect, Moreno and Mayer (2007) proposed the cognitive-affective model of learning with media, and Plass and Kaplan (2016) have shown how the emotional design of digital material can affect learning. Concerning motivation, researchers have shown how improvements in students' self-efficacy beliefs can improve their learning with multimedia lessons (Huang & Mayer, 2016; Mayer, 2014c). Concerning metacognition, researchers have shown how students' awareness and control of their learning processes and learning strategies can affect how they learn in multimedia environments (Azevedo, 2014; Azevedo & Aleven, 2013; Fiorella & Mayer, 2015). Such developments hold promise for broadening cognitive learning theories.

3 | SCIENCE OF INSTRUCTION

The science of instruction is the scientific study of how to help people learn (Mayer, 2011). The three metaphors of learning described in the previous section suggest different kinds of instructional methods, as summarized in the third column of Table 1 (Mayer, 1992, 2001b, 2011). In the early 20th century, when the response strengthening metaphor was dominant, a common instructional method was drill and practice (Cuban, 1986). For example, in a recitation exercise, the teacher asks a question that requires a short answer, calls on a student to make a response, and then rewards the student for a correct answer (e.g., by saying “right”) or punishes the student for an incorrect answer (e.g., by swatting him with a stick or having him sit in the corner). By the 1950s, when the information acquisition metaphor came into ascendency, the dominant instructional method turned into direct instruction such as through lectures, textbooks, and presentations. Next, since the rise of the knowledge construction metaphor in the 1980s, popular instructional methods have focused on active learning, such as discussion and guided practice on to-be-learned tasks.

The distinction between rote and meaningful instructional methods has a long history in psychology and education, as exemplified by the Gestalt psychologists in the first half of the 20th century (Katona, 1940; Wertheimer, 1959). Meaningful instructional methods lead to superior performance on transfer tests and retention tests, whereas rote instructional methods lead to superior performance on retention tests, so transfer tests are most useful in distinguishing learning outcomes produced by rote versus meaningful instructional methods (Mayer, 2011).

Methods like drill and practice and some forms of direct instruction were considered examples of rote instructional methods whereas guided practice and some forms of direct instruction were considered forms of meaningful instruction. With rote methods of instruction, learners receive material without trying to make sense of it (i.e., without trying to build a coherent mental model). With meaningful methods of instruction, learners engage in cognitive processes aimed at making sense of the material (i.e., trying to build a coherent mental model of the material).

An important change in the how scholars conceptualize rote and meaningful learning has occurred during the past 30 years. Initially, with the start of constructivist revolution, the focus was on behavioral activity during learning in which meaningful learning was associated with hands-on activity during learning as exemplified by discovery learning methods (Kirschner, Sweller, & Clark, 2006; Mayer, 2004). However, research in online learning over the past 30 years has shown that passive media—such as an online presentation—can result in active learning—in which the learner is cognitively active during instruction. Thus, the focus has shifted to cognitive activity during learning in which meaningful instruction is associated with guiding of cognitive processing even with passive media. An important advance is the recognition that the key to meaningful instructional methods rests not necessarily in the learner's behavioral activity during learning but in the learner's cognitive processing during learning. This has led to a shift in focus from purely hands-on activities to features of online lessons that guide active cognitive processing during learning (Skuballa, Dammert, & Renkl, 2018).

On the basis of cognitive theories of learning relevant to online learning such as cognitive load theory (Paas & Sweller, 2014; Sweller et al., 2011) and the cognitive theory of multimedia learning (Mayer, 2009, 2014b), Table 2 lists three instructional design goals for online learning. Although cognitive load theory has used the terms extraneous cognitive load, essential cognitive load, and germane cognitive load to describe three kinds of cognitive load during learning (Sweller, 1999; Sweller et al., 2011), the cognitive theory of multimedia learning uses parallel terms that highlight the kind of cognitive processing during learning—extraneous processing, essential processing, and generative processing, respectively (Mayer, 2001b, 2005, 2009, 2014b).

Extraneous processing is cognitive processing that does not serve the instructional goal, so a basic instructional design goal is to reduce extraneous processing. Much of the initial research on instructional design of online learning environments, starting the 1980s and 1990s, focused on techniques to reduce extraneous processing. The rationale was that if learners were using precious cognitive capacity on extraneous processing, they would have less capacity left over to engage in cognitive processing needed for meaningful learning, namely, essential and generative processing.

TABLE 2 Three instructional design goals for online learning

Instructional design goal description	
Reduce extraneous processing	Eliminate aspects of a lesson that prime the learner to engage in cognitive processing that does not serve the learning objective
Manage essential processing	Scaffold the lesson in ways that ensure the learner can process the relevant material
Foster generative processing	Include features in a lesson that prime the learner to exert effort to make sense of the material

Table 3 summarizes research on five instructional methods that are aimed at reducing extraneous processing and are applicable to online learning—coherence principle, signaling (or cueing) principle, redundancy principle, spatial contiguity principle, and temporal contiguity principle. The table provides a brief description of each principle and the median effect size based on published experimental comparisons in which the transfer or comprehension score of a group that learned from an online lesson with the feature was compared with a group that received the same online lesson without the feature. As can be seen, 30 years of research on techniques to reduce extraneous processing has generated a substantial research base and yielded several research-based design principles relevant to online learning (Ayres & Sweller, 2014; Kalyuga & Sweller, 2014; Mayer & Fiorella, 2014; Van Gog, 2014).

For example, an introductory online lesson describing how the human circulatory system works could be improved by deleting interesting by irrelevant facts (coherence principle), using black-ink line drawings rather that photo-realistic images of the heart and lungs (coherence principle), having part of the illustration turn red when the narration mentions it (signaling principle), placing more voice stress on the key terms in the narration (signaling principle), not adding captions on the screen that duplicate what the narrator is saying (redundancy principle), printing the name next to the corresponding part in the onscreen graphic (spatial contiguity principle), and showing actions or objects in the graphic at the same time as the narration is describing them (temporal contiguity principle).

Even if most or all extraneous processing is eliminated, learners' cognitive systems could become overloaded when the lesson is overly complex for them. Therefore, the next major advance was to include research on techniques to manage essential processing—cognitive processing needed to mentally represent the relevant material. Table 4 summarizes research, much dating from the 2000s, on three instructional methods for managing essential processing—segmenting principle, pretraining principle, and modality principle. As can be seen, 20 years of research on techniques to manage essential processing have generated a substantial research base that supports several research-based design principles relevant to online learning (Low & Sweller, 2014; Mayer & Pilegard, 2014).

For example, an animation describing how the human circulatory system works could be improved by breaking the lesson into meaningful segments each ending with a CONTINUE key that allows the learner to move on to the next segment (segmenting principle), providing the names and definitions of each part in the circulatory system before the animation begins (pretraining principle), and presenting the words in spoken form as narration rather than in printed form as onscreen text (modality principle).

The most recent target of instructional design research is instructional methods for fostering generative processing—cognitive processing aimed at making sense of the material. This approach, which has been gaining attention since the 2000s, focuses on instructional features that motivate the learner to exert effort to understand the material. As summarized in Table 5, these include the personalization principle, embodiment principle, and voice principle. Overall, the last 20 years are beginning to yield enough experiments to produce several initial design principles based on social cues, with more expected in the years ahead (Mayer, 2014d).

For example, a narrated animation describing how the human circulatory system works could be improved by using conversational language involving “you” and “I” rather than formal language (personalization principle), having the lesson presented by an onscreen character who uses human-like gesture and facial expression (embodiment principle), and having the narration presented in an appealing human voice rather than a machine-synthesized voice (voice principle).

As can be seen, researchers initially focused on reducing extraneous processing, then added managing essential processing, and more recently have emphasized fostering generative processing. For example, a 2001 review of evidence-based principles for the design of online instruction contained four of the five methods for reducing extraneous processing but only one of the three methods for managing essential processing, and no methods for fostering generative processing (Mayer, 2001b). Later reviews contained all except one method for fostering generative processing (Mayer, 2005, 2009), and

TABLE 3 Five instructional methods for reducing extraneous processing during learning

Instructional method	Description	ES	N
Coherence principle	Eliminate unneeded material	0.86	23
Signaling principle	Highlight essential material	0.41	28
Redundancy principle	Do not add onscreen text to narrated graphics	0.86	16
Spatial contiguity principle	Place onscreen text near corresponding graphics	1.10	22
Temporal contiguity principle	Present corresponding speech and graphics at the same time	1.22	9

Note. ES = median effect size; N = number of experiments. Adapted from Mayer and Fiorella (2014).

TABLE 4 Three instructional methods for managing essential processing during learning

Instructional method	Description	ES	N
Segmenting principle	Break lesson into user-paced parts	0.79	10
Pretraining principle	Provide names and definitions of key components before the lesson	0.75	16
Modality principle	Present words in spoken form	0.76	61

Note. ES = median effect size; N = number of experiments. Adapted from Mayer and Pilegard (2014).

TABLE 5 Three instructional methods for managing essential processing during learning

Instructional method	Description	ES	N
Personalization principle	Use conversational language	0.79	17
Embodiment principle	Use human-like gesture for on-screen instructor	0.36	11
Voice principle	Speak with friendly human voice	0.74	6

Note. ES = median effect size; N = number of experiments. Adapted from Mayer (2014d).

the most recent review contained all of them (Mayer, 2014b). In the years to come, I expect to see additional principles including techniques for helping students overcome anxiety, develop productive beliefs, manage their learning strategies, and feel positive emotions.

The research base on instructional methods for online instruction has shown strong growth over the past 30 years. By 2001, there were enough studies for a meta-analysis containing five of the principles listed in the foregoing three tables based on 30 experimental comparisons (Mayer, 2001b). By 2009, there were enough studies for a meta-analysis containing 10 of the principles listed in the foregoing three tables based on 72 experimental comparisons (Mayer, 2009). By 2014, all 11 principles were included in meta-analyses based on 219 experimental comparisons (Mayer, 2014d; Mayer & Fiorella, 2014; Mayer & Pilegard, 2014). In the last few years, the pace has continued for research on the instructional design of online instruction, including emerging research on instructional design to enhance learning in virtual reality (Parong & Mayer, 2018).

Another important advance over the past 30 years of instructional research has been the emergence of boundary conditions for each instructional design principle, particularly in the past decade (Mayer, 2009, 2014d; Mayer & Fiorella, 2014; Mayer & Pilegard, 2014). The most common boundary condition involves the level of prior knowledge of the learner, with principles listed in the foregoing tables sometimes working best for learners with low rather than high-prior knowledge (Kalyuga, 2014). Spelling out the boundary conditions for each principle is an important continuing task for future research, including for whom, for which kinds of learning objectives and materials, and for which media venues.

4 | SCIENCE OF ASSESSMENT

The science of assessment is concerned with the scientific study of determining what students have learned (Mayer, 2011). As noted in the rightmost column of Table 1, the initial focus of learning outcome assessment was on response execution (based on the response strengthening metaphor), then shifted to retention of presented information (based on the information acquisition metaphor), and more recently returned to transfer performance (based on the knowledge construction metaphor). Bloom's taxonomy (Bloom, Engelhart, Furst, Hill, & Krathwohl, 1956) initiated the shift to add tests of transfer to the existing tests of retention in educational assessment, and an updated version (Anderson et al., 2001) showed transfer could be applied to different kinds of knowledge. Future work is needed to refine computer-based dynamic assessment (or performance assessment) in which students are given challenging tasks as well as stealth assessment in which the assessment is seamlessly built into the online lesson and used to adapt it to the learner's needs (Shute & Ventura, 2013). Also, future work on assessment of learning processes involves moving beyond self-report ratings to include analysis of log data and other behaviors during learning as well as analysis of brain and physiological data during learning such as EEG, fMRI, and eye tracking.

5 | AN AGENDA FOR FUTURE RESEARCH ON ONLINE INSTRUCTION

In summary, it is likely that students will be increasing exposed to online learning—both in formal and informal contexts—so the design of online instruction will continue to be an important practical and theoretical challenge. This brief history provides an example of applied cognitive psychology by focusing on applying the science of learning to the practical problem of online instruction. From my vantage point as an educational psychologist, I foresee several areas for future advances.

Concerning the science of learning, current cognitive theories of online learning would benefit from stronger incorporation of affect, motivation, and metacognition, as well as from a better understanding of how to use objective measures of cognitive processing during learning.

Concerning the science of instruction, we need to continue the growth of the research base on replicating existing principles of instructional design, developing boundary conditions for existing principles, and creating new principles (including for new venues such as games, simulations, virtual reality, and portable media).

Concerning the science of assessment, we need improvements in online assessment of learning processes and outcomes as part of the online learning experience, allowing for adapting instruction to the needs of individual learners.

Overall, this line of research demonstrates the value of conducting research that has both a practical goal (e.g., to improve online instruction) and a theoretical goal (e.g., to understand how learning works) as suggested by Stokes (1997). In short, this review shows why applied cognitive psychology is and will continue to be an exciting and productive area of research.

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REFERENCES

Anderson, L. W., Krathwohl, D. R., Airasian, P. W., Cruikshank, K. A., Mayer, R. E., Pintrich, P. R., … Wittrock, M. C. (2001). *A taxonomy for learning. Teaching, and assessing: A revision of Bloom's taxonomy of educational objectives*. New York: Longman.

Ayres, P., & Sweller, J. (2014). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia* *learning* (2nd ed.) (pp. 206–226). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.011

Azevedo, R. (2014). Multimedia learning of metacognitive strategies. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 647–672). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.032

Azevedo, R., & Aleven, V. (Eds.) (2013). *International handbook of metacognition and learning technologies*. New York: Springer. https://doi.org/10.1007/978-1-4419-5546-3

Bartlett, F. C. (1932). *Remembering*. New York: Cambridge University Press.

Bloom, B. S., Engelhart, M. D., Furst, E. J., Hill, W. H., & Krathwohl, D. R. (1956). *Taxonomy of educational objectives: Cognitive domain*. New York: David McKay Company.

Brunken, R., Seufert, T., & Paas, F. (2010). Measuring cognitive load. In J. L. Plass, R. Moreno, & R. Brunken (Eds.), *Cognitive load theory* (pp. 181–202). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511844744.011

Clark, R. C., & Mayer, R. E. (2016). *E-learning and the science of instruction* (4th ed.). Hoboken, NJ: Wiley. https://doi.org/10.1002/9781119239086

Clark, R. E. (2001). *Learning from media*. Greenwich, CT: Information Age Publishing.

Cuban, L. (1986). *Teachers and machines: The classroom use of technology since 1920*. New York: Teachers College Press.

DeLeeuw, K. E., & Mayer, R. E. (2008). A comparison of three measures of cognitive load: Evidence for separable measures of intrinsic, extraneous, and germane load. *J Educ Psychol*, *100*, 223–234. https://doi.org/10.1037/0022-0663.100.1.223

Doctorow, M., Wittrock, M. C., & Marks, C. (1978). Generative processes in reading comprehension. *J Educ Psychol*, *70*, 109–118. https://doi.org/10.1037/0022-0663.70.2.109

Fiorella, L., & Mayer, R. E. (2015). *Learning as a generative activity*. New York: Cambridge University Press. https://doi.org/10.1017/CBO9781107707085

Huang, X., & Mayer, R. E. (2016). Benefits of adding anxiety-reducing features to a computer-based multimedia lesson. *Computers in Human Behavior*, *63*, 293–303. https://doi.org/10.1016/j.chb.2016.05.034

Johnson, C., & Mayer, R. E. (2012). An eye movement analysis of the spatial contiguity effect in multimedia learning. *J Exp Psychol-Appl*, *18*, 178–191. https://doi.org/10.1037/a0026923

Kalyuga, S. (2014). The expertise reversal principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 576–597). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.028

Kalyuga, S., & Sweller, J. (2014). The redundancy principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 247–262). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.013

Katona, G. (1940). *Organizing and memorizing*. New York: Columbia University Press.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, *41*(2), 75–86. https://doi.org/10.1207/s15326985ep4102_1

Low, R., & Sweller, J. (2014). In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 227–246). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.012

Mayer, R. E. (2005). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 31–48). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511816819.004

Mayer, R. E. (1989). Systematic thinking fostered by illustrations in scientific text. *J Educ Psychol*, *81*, 240–246. https://doi.org/10.1037/0022-0663.81.2.240

Mayer, R. E. (1992). Cognition and instruction: On their historic meeting within educational psychology. *J Educ Psychol*, *84*, 405–412. https://doi.org/10.1037/0022-0663.84.4.405

Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? *Educational Psychologist*, *32*, 1–19. https://doi.org/10.1207/s15326985ep3201_1

Mayer, R. E. (2001a). Changing conceptions of learning: A century of progress in the scientific study of education. In L. Corno (Ed.), *Education across a century: The centennial volume. Hundredth yearbook of the National Society for the study of education* (pp. 34–75). Chicago: National Society for the Study of Education.

Mayer, R. E. (2001b). *Multimedia learning*. New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139164603

Mayer, R. E. (2004). Should there be a three strikes rule against pure discovery? The case for guided methods of instruction. *Am Psychol*, *59*(1), 14–19. https://doi.org/10.1037/0003-066X.59.1.14

Mayer, R. E. (2009). *Multimedia learning* (2nd ed.). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511811678

Mayer, R. E. (2011). *Applying the science of learning*. Boston: Pearson.

Mayer, R. E. (2014a). Cognitive revolution and information processing perspective. In D. C. Phillips (Ed.), *Encyclopedia of educational theory and philosophy* (pp. 142–149). Thousand Oaks, CA: SAGE.

Mayer, R. E. (2014b). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 43–71). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.005

Mayer, R. E. (2014c). Incorporating motivation into multimedia learning. *Learning and Instruction*, *29*, 171–173. https://doi.org/10.1016/j.learninstruc.2013.04.003

Mayer, R. E. (2014d). Principles based on social cues in multimedia learning: Personalization, voice, image, and modality principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 345–368). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.017

Mayer, R. E. (2017). How can brain research inform academic learning and instruction? *Educational Psychology Review*, *29*, 835–846. https://doi.org/10.1007/s10648-016-9391-1

Mayer, R. E. (in press). Using multimedia for e-Learning. *Journal of Computer Assisted Learning*.

Mayer, R. E., & Anderson, A. B. (1991). Animations need narrations: An experimental test of a dual-coding hypothesis. *J Educ Psychol*, *83*, 484–490. https://doi.org/10.1037/0022-0663.83.4.484

Mayer, R. E., & Anderson, A. B. (1992). The instructive animation: Helping students build connections between words and pictures in multimedia learning. *J Educ Psychol*, *84*, 444–452. https://doi.org/10.1037/0022-0663.84.4.444

Mayer, R. E., & Fiorella, L. (2014). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 279–315). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015

Mayer, R. E., Heiser, J., & Lonn, S. (2001). Cognitive constraints on multimedia learning: When presenting more material results in less understanding. *J Educ Psychol*, *93*, 187–198. https://doi.org/10.1037/0022-0663.93.1.187

Mayer, R. E., & Moreno, R. (1998). A split-attention effect in multimedia learning. *J Educ Psychol*, *90*, 312–320. https://doi.org/10.1037/0022-0663.90.2.312

Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist*, *38*, 43–52. https://doi.org/10.1207/S15326985EP3801_6

Mayer, R. E., Moreno, R., Boire, M., & Vagge, S. (1999). Maximizing constructivist learning from multimedia communications by minimizing cognitive load. *J Educ Psychol*, *91*, 638–643. https://doi.org/10.1037/0022-0663.91.4.638

Mayer, R. E., & Pilegard, C. (2014). Principles for managing essential processing in multimedia learning: Segmenting, pre-training, and modality principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 316–345). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.016

Mayer, R. E., & Sims, V. K. (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. https://doi.org/10.1037/0022-0663.86.3.389

Mayer, R. E., Steinhoff, K., Bower, G., & Mars, R. (1995). A generative theory of textbook design: Using annotated illustrations to foster meaningful learning of science text. *Educational Technology Research and Development*, *43*, 31–43. https://doi.org/10.1007/BF02300480

Mayer, R. E., & Wittrock, M. C. (1996). Problem solving and transfer. In D. Berliner, & R. Calfee (Eds.), *Handbook of educational psychology* (pp. 45–61). New York: Cambridge University Press.

Mayer, R. E., & Wittrock, M. C. (2006). Problem solving and transfer. In P. Alexander, P. Winne, & G. Phye (Eds.), *Handbook of educational psychology* (2nd ed.) (pp. 287–303). Mahwah, NJ: Erlbaum.

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review*, *19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2

Paas, F., & Sweller, J. (2014). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 27–42). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.004

Paas, F., Tuovinen, J. E., Tabbers, H., & Van Gerven, P. W. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist*, *38*(1), 63–71. https://doi.org/10.1207/S15326985EP3801_8

Paas, F., Van Merriënboer, J. J. G., & Adam, J. J. (1994). Measurement of cognitive load in instructional research. *Percept Mot Skills*, *79*(1), 419–430. https://doi.org/10.2466/pms.1994.79.1.419

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *J Educ Psychol*, *110*, 785–797.

Piaget, J. (1971). *Science of instruction and the psychology of the child*. New York: Viking Press.

Plass, J. L., Chun, D. M., Mayer, R. E., & Leutner, D. (1998). Supporting visual and verbal learning preferences in a second language multimedia learning environment. *J Educ Psychol*, *90*, 25–36. https://doi.org/10.1037/0022-0663.90.1.25

Plass, J. L., & Kaplan, U. (2016). Emotional design in digital media for learning. In S. Y. Tettegah, & M. Gartmeier (Eds.), *Emotions, technology, design, and learning* (pp. 131–161). San Diego, CA: Academic Press. https://doi.org/10.1016/B978-0-12-801856-9.00007-4

Ponce, H., & Mayer, R. E. (2014). An eye-movement analysis of highlighting and graphic organizer study aids for learning from expository text. *Computers in Human Behavior*, *41*, 21–32. https://doi.org/10.1016/j.chb.2014.09.010

Saettler, P. (1990/2004). *The evolution of American educational technology*. Greenwich, CT: Information Age Publishing.

Shute, V., & Ventura, M. (2013). *Stealth assessment*. Cambridge, MA: MIT Press.

Skuballa, I. T., Dammert, A., & Renkl, A. (2018). Two kinds of meaningful multimedia learning: Is cognitive activity alone as good as combined behavioral and cognitive activity? *Learning and Instruction*, *54*, 35–46. https://doi.org/10.1016/j.learninstruc.2018.02.001

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

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

Sweller, J. (2005). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 19–30). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511816819.003

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York: Springer. https://doi.org/10.1007/978-1-4419-8126-4

Van Gog, T. (2014). The signaling (or cueing) principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed.) (pp. 263–278). New York: Cambridge University Press.

Wang, F., Li, W., Mayer, R. E., & 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. https://doi.org/10.1037/edu0000221

Wertheimer, M. (1959). *Productive thinking*. New York: Harper & Row.

Wittrock, M. C. (1974). Learning as a generative process. *Educational Psychologist*, *11*, 87–95. https://doi.org/10.1080/00461527409529129

Wittrock, M. C. (1978). The cognitive instruction movement. *Educational Psychologist*, *13*, 15–29. https://doi.org/10.1080/00461527809529192

Wittrock, M. C. (1989). Generative processes of comprehension. *Educational Psychologist*, *24*, 345–367. https://doi.org/10.1207/s15326985ep2404_2

Wittrock, M. C. (1992). Generative processes of the brain. *Educational Psychologist*, *26*, 109–116.

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