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ORIGINAL ARTICLE

Interactive Multimodal Learning Environments

Special Issue on Interactive Learning Environments: Contemporary Issues and Trends

Roxana Moreno · Richard Mayer

Abstract What are interactive multimodal learning environments and how should they be designed to promote students' learning? In this paper, we offer a cognitive–affective theory of learning with media from which instructional design principles are derived. Then, we review a set of experimental studies in which we found empirical support for five design principles: guided activity, reflection, feedback, control, and pretraining. Finally, we offer directions for future instructional technology research.

Keywords Interactive · Multimodal · Learning · Environments

In this paper, we review the findings of our research on interactive multimodal[1] learning environments. The goal of our work is to contribute to the theory and practice of instructional design by testing a set of principles that are derived from cognitive theories of learning (Mayer 2001, 2005a; Mayer and Moreno 2003; Moreno 2005a, 2006a). Specifically, we address the following four questions: (1) What are interactive multimodal learning environments? (2) How do students learn from interactive multimodal environments according to cognitive theories of learning? (3) What are some instructional design principles that can be derived from cognitive theories of learning and what is their empirical support? (4) What are some productive directions for future research?

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[1] In previous writing we have used the adjective *multimedia* rather than *multimodal* to refer the use of words and pictures, that is, verbal and non-verbal modes of presentation (Mayer 2001, 2005a; Mayer and Moreno 2003). For continuity with our previous work, the terms can be used interchangeably.

R. Moreno (✉)
Educational Psychology Program, University of New Mexico, 123 Simpson Hall, Albuquerque, NM 87131, USA
e-mail: moreno@unm.edu

R. Mayer
Psychology Department, University of California, Santa Barbara, CA 93106, USA
e-mail: mayer@psych.ucsb.edu

Table 1 Distinction Between Modes and Modalities

Feature	Description	Examples
Mode	Code used to represent information	Verbal (e.g., printed words, spoken words) and non-verbal (e.g., illustrations, photos, video, and animation)
Modalities	Sense receptors used to receive information	Auditory (i.e., through the ears) and visual (i.e., through the eyes)

What are Interactive Multimodal Learning Environments?

We define *multimodal* learning environments as learning environments that use two different modes to represent the content knowledge: verbal and non-verbal[2] (Paivio 1986). In multimodal learning environments, students are presented with a verbal representation of the content and a corresponding visual representation of the content. Although the verbal mode of instruction has long dominated education, our research has focused on multimodal presentations, especially those that combine words and pictorial representations of knowledge, because according to the multimedia principle, student understanding can be enhanced by the addition of non-verbal knowledge representations to verbal explanations (Fletcher and Tobias 2005; Mayer 2001).

Presentation mode should not be confused with sensory modality. As shown in Table 1, mode refers to the code used to represent the material (i.e., verbal versus non-verbal) whereas modality refers to sense system used by which the learner receives the material (i.e., auditory versus visual; Penney 1989).[3] According to the modality principle of instructional design (Low and Sweller 2005; Mayer 2001, 2005c; Moreno 2006b; Moreno and Mayer 1999a, 2002a, b), the most effective learning environments are those that combine verbal and non-verbal representations of the knowledge using mixed-modality presentations. As we later explain within our theoretical framework, because human cognitive architecture includes independent, limited capacity, processing channels, the presentation of verbal and non-verbal materials in the visual modality alone is more likely to overload students' cognitive capacity during learning as compared to the presentation of verbal materials in the auditory modality and non-verbal materials in the visual modality (Low and Sweller 2005; Mayer 2005b).

An *interactive* multimodal learning environment is one in which what happens depends on the actions of the learner. In short, the defining feature of interactivity is responsiveness to the learner's action during learning. In a non-interactive multimodal learning environment, a multimedia message is presented in a pre-determined way irrespective of anything the learner does during learning. Examples of non-interactive multimodal learning environments include a narrated animation or a textbook passage containing text and illustrations. In an interactive multimodal learning environment, the presented words and pictures depend on the learner's actions during learning.

Although the term *interactive* means different things to different people in different contexts (McMillan 2002), in the context of this review we define interactivity as a characteristic of learning environments that enable multidirectional communication (Markus 1990). Underlying interactivity is the idea of a two-way action (between learner

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[2] In our work, the non-verbal mode is the pictorial mode, which includes static graphics (such as photos, illustrations, graphs, drawings, and maps) and dynamic graphics (such as video and animation).

[3] To reduce confusion, we could substitute "words/pictures" for "mode" and "sounds/images" for "modality."

and instructor) as opposed to a one-way action (i.e., from instructor to learner). However, we further qualify our definition of interactivity by clarifying that the goal of the participants' actions needs to be to foster learning, that is, to help the learner change his or her knowledge consistent with the instructional goal (Wagner 1994). In this regard, navigation alone, for example, would not be sufficient to make a learning environment interactive, unless navigating the environment can lead directly to the construction of knowledge or meaningful learning (Puntambekar *et al.* 2003; Rouet 2006; Rouet and Potelle 2005).

Table 2 lists five common types of interactivity: dialoguing, controlling, manipulating, searching, and navigating. In interactivity by dialoguing, the learner can ask a question and receive an answer, or can give an answer and receive feedback. For example, in the course of learning, the learner can seek help from an on-screen agent or can click on a highlighted word in a hypertext environment to get additional information. In interactivity by controlling, the learner is able to determine the pace and/or order of the learning episode. For example, with a narrated animation, the learner may be able to control the pace by using a pause/play key, or by using a continue (or forward) button when the material is presented in segments; and the learner is able to control the order by using a forward and back key, rewind key, slider bar, or a menu for direct access to a particular segment. In interactivity by manipulating, the learner can control aspects of the presentation, such as setting parameters before a simulation runs, zooming in or out, or moving objects around the screen. In interactivity by searching, the learner is able to engage in information seeking, such as by entering a query, receiving options, selecting an option, and so on, as in an Internet search. In interactivity by navigating, the learner is able to determine the content of a learning episode by selecting from various available sources, such as by clicking on a menu. In this review we focus mainly on dialoguing, controlling, and manipulating because they are central features of self-contained interactive multimodal learning environments. Searching and navigating types of interactivity can also be embedded in these environments, but are more typical of hypermedia and search engine programs such as the ones found in the Internet.

It is possible to think about a continuum of interactivity in learning environments ranging from highly interactive—which allow for strong communication between the learner and the

Table 2 Five Types of Interactivity in Multimodal Learning Environments

Type of interactivity	Description	Example
Dialoguing	Learner receives questions and answers or feedback to his/her input	Seek help from an on-screen agent, click on a hyperlink to get additional information
Controlling	Learner determines pace and/or order of presentation	Use pause/play key or forward (continue) button while watching a narrated animation
Manipulating	Learner sets parameters for a simulation, or zooms in or out, or moves objects around the screen	Set parameters in a simulation game and run the simulation to see what happens
Searching	Learner finds new content material by entering a query, receiving options, and selecting an option	Seek information in an Internet search
Navigating	Learner moves to different content areas by selecting from various available information sources	Click on a menu to move from one Internet page to another

instructional system, to non-interactive—which do not allow for communication between the learner and the instructional system. In the past, we have investigated instructional design issues using both extremes of the interactivity continuum. A non-interactive multimodal learning environment is a multimedia explanation: a linear presentation including verbal and visual representations of the scientific system to-be-learned. For example, students can listen about the causal chain of events leading to photosynthesis while they observe a corresponding animation illustrating how the process occurs inside a plant. This multimodal learning environment is non-interactive because it presents students with the information needed to understand the process of photosynthesis yet it does not allow for student input or control during learning (Jensen 1998; Morrison 1998).

Mayer (2001) has shown that it is useful to distinguish between two views of learning: information acquisition and knowledge construction.[4] In the information acquisition view, learning involves adding information to the learner's memory. The instructor's job is to present information and the learner's job is to receive the information. A typical learning environment is non-interactive, such as a narrated animation or a textbook lesson.

In contrast, in the knowledge construction view, learning involves building a mental representation. The learner is a sense-maker who works to select, organize, and integrate new information with existing knowledge. According to a knowledge construction approach to learning, the goal of instruction is to guide the learner to actively make sense of the instructional materials (Mayer 2005c). For example, an alternative to presenting a multimedia explanation to teach photosynthesis may consist of asking students to engage in mixed-initiative problem solving with a pedagogical agent (Lester *et al.* 1999). In this learning scenario, students try to infer the principles to-be-learned by experimenting with different plants and environmental conditions and receiving feedback and guidance from the agent. This multimodal learning environment is highly interactive because rather than unilaterally presenting the verbal and non-verbal information needed to understand the process of photosynthesis, it allows for student input, different learning paces, and system feedback contingent on students' responses (Moreno *et al.* 2001).[5]

We opt for the knowledge construction view, and therefore we are interested in whether interactivity is a feature than can be used to promote deep cognitive processing in the learner. It is worthwhile to make a distinction between behavioral activity and cognitive activity. Deep learning depends on cognitive activity—such as selecting relevant information from a lesson, mentally organizing it into a coherent structure, and integrating the new knowledge with existing knowledge. Although interactive environments promote behavioral activity, we are interested in how they can be designed to promote appropriate cognitive processing. In contrast, non-interactive environments do not promote behavioral activity, so the challenge is to design a presentation that primes learners to be cognitively active. Although an important area of our research has been to investigate methods to

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[4] It is important to distinguish between conceptions of how learning works (e.g., information acquisition versus knowledge construction) and conceptions of how to foster constructivist learning through instruction. Although we favor the knowledge construction view of learning, this does not necessarily mean that active methods of instruction (such as interactive multimedia simulations) are more effective than passive methods of instruction (such as static multimedia presentations). We have conducted research aimed at determining the conditions under which static multimedia presentations can lead to constructivist learning, but our focus in this review is on the conditions under which interactive multimedia simulations can lead to constructivist learning.

[5] Interactivity and the need for learners to make inferences is often not as effective as direct instruction in promoting meaningful learning (Mayer 2004), so it is especially important to determine the conditions under which interactivity promotes knowledge construction.

promote learning from non-interactive multimodal environments such as multimedia explanations, the present paper focuses on empirically-based principles for the instructional design of highly interactive learning environments due to the emphasis of this volume.

We must acknowledge that interactive multimodal mixed-modality learning environments do not automatically create understanding. By virtual of their interactivity, they can create excessive extraneous load that disrupts deep learning (Mayer and Moreno 2003). The world wide web and commercial software are full of examples with these characteristics, but it is fair to challenge whether or not they help people comprehend their messages. The goal of our research program has been to develop a sound theoretical framework that can guide designers in effectively using different representation modes and modalities to promote understanding. We describe this framework next.

How do Students Learn from Interactive Multimodal Environments?

In pursuing our research on technology-based learning, we have repeatedly faced the challenge of trying to promote meaningful learning by increasing students' active processing of the instructional materials while reducing cognitive load (Clark 1999; Sweller 1999; van Merrienboer 1997). The following is a theory of how people learn from instructional media, which highlights the potential for cognitive overload (Mayer and Moreno 2003).

The cognitive-affective theory of learning with media (CATLM; Moreno 2005a) that we describe expands the cognitive theory of multimedia learning (Mayer 2001, 2005a) to media such as virtual reality, agent-based, and case-based learning environments, which may present the learner with instructional materials other than words and pictures. CATLM is based on the following assumptions suggested by cognitive and motivational research: (a) humans have separate channels for processing different information modalities (Baddeley 1992); (b) only a few pieces of information can be actively processed at any one time in working memory within each channel (Sweller 1999); (c) meaningful learning occurs when the learner spends conscious effort in cognitive processes such as selecting, organizing, and integrating new information with existing knowledge (Mayer and Moreno 2003); (d) long-term memory consists of a dynamic, evolving structure which holds both, a memory for past experiences and a memory for general domain knowledge (Tulving 1977); (e) motivational factors mediate learning by increasing or decreasing cognitive engagement (Pintrich 2003); (f) metacognitive factors mediate learning by regulating cognitive processing and affect (McGuinness 1990); and (g) differences in learners' prior knowledge and abilities may affect how much is learned with specific media (Kalyuga *et al.* 2003; Moreno 2004; Moreno and Durán 2004).

Figure 1 presents a model for learning with an interactive multimodal environment according to a CATLM. As can be seen in the figure, the instructional media may consist of verbal explanations presented with spoken or written words combined with non-verbal knowledge representations such as pictures and sounds. For meaningful learning to occur, students need to first attend to and select relevant verbal and non-verbal information for further processing in working memory. Then, students need to organize the multiple representations into a coherent mental model and integrate the organized information with their prior knowledge. In interactive learning environments these cognitive processes are guided partially by prior knowledge activated by the learner (as illustrated by the top–down arrows from long term memory to attention, perception, and working memory) and partially by the feedback and instructional methods embedded in the learning environment. As can be seen from the model, learners may also use their metacognitive skills to regulate their

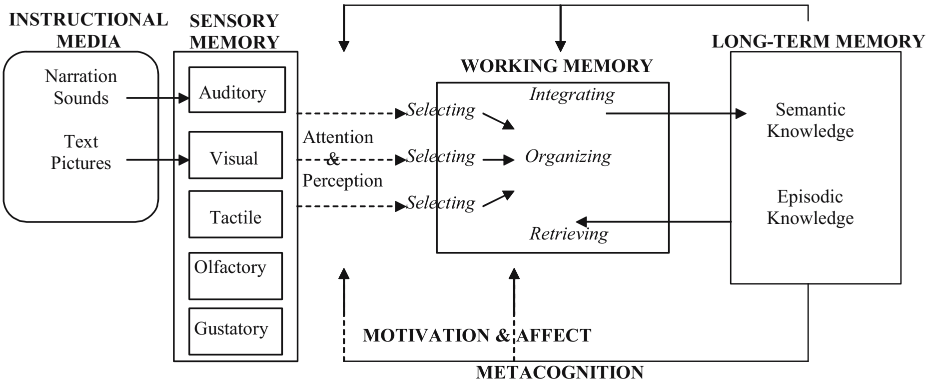

Fig. 1 A cognitive–affective model of learning with media.

motivation and cognitive processing during learning. Students who are aware of the strengths and limitations of their knowledge, strategies, affect and motivation, are better able to regulate their learning by planning and monitoring the cognitive processes needed for understanding (Bruning *et al.* 1999). The influence of metacognition, motivation, and affect on learning is illustrated by the bottom–up arrows from long-term memory to working memory.

A potential challenge when learning from interactive multimodal environments is that the processing demands may exceed the processing capacity of the cognitive system, a situation we call cognitive overload. Therefore, it is useful to carefully examine the relationship between the cognitive demands imposed by the learning environment and the desired learning outcomes. To this end, we have proposed to distinguish between extraneous processing, representational holding, essential processing, and generative processing during learning (Mayer 2005a; Mayer and Moreno 2003). We define *extraneous processing* as the cognitive processes that are not necessary for making sense of the new information but are instead originated from poorly designing the learning task. For example, students are forced to engage in extraneous processing when an instructional environment presents mutually referring text and graphics in separate pages or computer screens, producing a visual split-attention effect that hurts learning (Ayres and Sweller 2005; Mayer and Moreno 1998; Moreno and Mayer 1999a). In this case, the learner must waste precious cognitive capacity on the cognitive process of scanning between the words and pictures.

A special subclass of extraneous processing is *representational holding*—the cognitive processes aimed at holding a mental representation in working memory during the meaning-making process. For example, students are forced to engage in representational holding when a narration is presented before a corresponding animation. In this situation learners must hold a spoken explanation in working memory's articulatory loop (Baddeley 1992) until they are able to identify a corresponding illustration in the subsequent animation. Extraneous processing—including representational holding—wastes the learner's limited processing capacity, so a goal of instructional design is to reduce extraneous processing and representational holding.

We define *essential processing* as the cognitive processes that are required to mentally select the new information that is represented in working memory. When the material is complex and unfamiliar to the learner, the amount of required essential processing can become overwhelming. In this case, the goal of instructional design is to manage essential processing.

We define *generative processing* as making sense of the new information, such as the processes of mentally organizing the new information into a coherent structure and integrating the new knowledge representations with prior knowledge. Together, essential and generative processing result in the creation of a meaningful learning outcome. When learners lack motivation they may fail to engage in generative processing even when cognitive capacity is available. In this case, the goal of instructional design is to foster generative processing.

The total amount of cognitive processing during a learning episode consists of the sum of the four processing activities described. In the next section we introduce a set of instructional design principles aimed at optimizing learning by reducing extraneous processing and representational holding so that the learner's available cognitive resources can be used to engage in essential and generative processing activities.

What are some Instructional Design Principles for Interactive Multimodal Learning Environments and what is their Empirical Support?

From the assumptions underlying a CATLM, it is possible to derive cognitive principles of instructional design. For example, using non-interactive multimodal environments we have found empirical support for the following set of principles: verbal information should be presented in the auditory modality alone—*modality* and *verbal redundancy* principles (Moreno and Mayer 1999a, 2002a, b); explanations should be presented using a conversational style—*personalization principle* (Moreno and Mayer 2000a, 2004); verbal and non-verbal information need to be synchronized in time and space—*temporal contiguity* and *spatial contiguity principles*, respectively (Mayer and Moreno 1998, 1999; Moreno and Mayer 1999a); information that is not necessary to make a lesson intelligible and redundant information should be excluded—*coherence* and *redundancy principles*, respectively (Moreno and Mayer 2000b, 2002b).

Although several of these instructional principles have been also supported in high-tech interactive multimodal learning environments (Moreno 2006a), further research is needed to investigate the potential interaction between particular interactive methods and non-interactive design principles. For example, Tabbers (2002) found that written explanatory text was more effective than spoken explanatory text when learners had control over the pacing of a multimedia presentation, presumably because the absence of time pressure offered students the possibility to process the written text strategically. Due to the focus of this volume, we now describe in more detail principles that apply exclusively to the design of interactive multimodal learning environments, i.e., learning environments that allow for interactions between the learner the instructional system. Table 3 summarizes five empirically based principles for the design of interactive multimodal learning environments, along with their corresponding theoretical rationales: guided activity, reflection, feedback, pacing, and pretraining.

Guided activity principle Guided activity enables students to interact with a pedagogical agent who guides their cognitive processing during learning. According to the guided activity principle, students learn better when they interact with a pedagogical agent who guides their cognitive processing rather than when they receive direct instruction without any guidance concerning how to process the presented information or when they engage in pure discovery (Mayer 2004). This principle is similar to the guided discovery principle in multimedia learning (de Jong 2005), in which students learn better when an agent guides

Table 3 Five Design Principles and Corresponding Theoretical Rationale

Principle and Description	Theoretical Rationale
Guided activity	
Students learn better when allowed to interact with a pedagogical agent who helps guide their cognitive processing	Guided activity encourages essential and generative processing by prompting students to engage in the selection, organization, and integration of new information
Reflection	
Students learn better when asked to reflect upon correct answers during the process of meaning making	Reflection promotes essential and generative processing by encouraging more active organization and integration of new information
Feedback	
Students learn better with explanatory rather than corrective feedback alone	Explanatory feedback reduces extraneous processing by providing students with proper schemas to repair their misconceptions
Pacing	
Students learn better when allowed to control the pace of presentation of the instructional materials	Pace control reduces representational holding by allowing students to process smaller chunks of information in working memory
Pretraining	
Students learn better when they receive focused pretraining that provides or activates relevant prior knowledge	Pretraining helps guide the learner's generative processing by showing which aspects of prior knowledge to integrate with incoming information

their cognitive processing during learning. The theoretical rationale for the guided activity principle is that prompting students to actively engage in the selection, organization, and integration of new information, encourages essential and generative processing. This processing leads to deeper understanding than having students passively process identical instructional materials (Mayer and Moreno 2003) or having students engage in pure discovery (Mayer 2004).

In our research program, we tested the guided activity principle by comparing the learning and perceptions about learning of two groups of students (Moreno *et al.* 2001). One group learned about botany with an instructional program called *Design-A-Plant* (Lester *et al.* 1999), in which students are presented with a set of different environmental conditions (e.g., low rainfall, light sunlight) and asked to infer the characteristics of plants that would flourish in those conditions by designing appropriate roots, stems, and leaves. The *Design-A-Plant* program includes an animated pedagogical agent named Herman-the-Bug who provides students with feedback on the choices they make in the process of designing plants (see Moreno 2005b for a review of pedagogical agent effects). In contrast, the second group of students learned in a direct instruction environment, where they see the same set of example plants and receive the same instructional words as in the first condition, but are not able to interact with an agent by designing the plant before listening to the explanations. Across two experiments (one with college students and one with seventh grade students), participants who were allowed to design the plants (i.e., manipulating interactivity) had higher far problem solving transfer scores (effect sizes of d=1.49 and 1.34, respectively) and perceived the learning experience as more interesting (effect sizes of d=0.85 and 0.78, respectively) than those who learned with direct instruction (Moreno *et al.* 2001). It is important to note that the animated pedagogical agent provided structure and guidance for the learner's activity rather than open-ended exploration, which could create extraneous cognitive processing. These findings are consistent with CATLM's assumption (c), according to which meaningful learning occurs when the learner spends conscious effort in cognitive processes such as selecting, organizing, and integrating new information with existing knowledge, and with CATLM's assumption (e), according to which motivational factors mediate learning by increasing or decreasing cognitive engagement (Pintrich 2003).

Reflection principle Despite the fact that interactive multimodal learning environments allow students to manipulate the instructional materials, deep learning from these environments depends on opportunities for students to reflect on their actions (Azevedo 2005; Jacobson *et al.* 1996)—a component that is often absent. Therefore, the guided activity principle needs to be combined with the reflection principle: Students learn better when asked to reflect upon correct answers during the process of meaning making. Priming students to reflect is an example of dialoguing interactivity. For example, using the *Design-A-Plant* program in a later experimental study (Moreno and Mayer 2005), we found that the transfer benefits of interactivity disappeared when we asked learners to provide explanations for their choices while they interacted with the program. More specifically, we used a two-factor design to examine the relative contribution of asking students to manipulate or not manipulate (factor 1) the instructional materials before receiving explanatory words from a pedagogical agent, and asking students to reflect or not reflect (factor 2) on the principles underlying their plant designs (interactive programs) or the worked-out example designs presented by the pedagogical agent (non-interactive programs). We operationalized reflection by using a form of elaborative interrogation (Woloshyn *et al.* 1994), a method that has shown to improve students' reading comprehension (Chi *et al.* 1994; Seifert 1993). Our findings showed a significant interaction between students' ability to manipulate the instructional materials and the elaborative interrogation method. Specifically, for non-interactive learning conditions, students who were prompted to reflect on the worked-out examples presented by the agent had higher far-transfer scores than those who were not prompted to reflect on the examples (effect size of d=0.98). However, for interactive learning conditions, there were no significant differences between reflective and non-reflective treatments on far-transfer (Moreno and Mayer 2005; experiment 2). In addition, a follow-up study revealed that, for reflection to be effective, students must be asked to reflect on correct models of the new information (Moreno and Mayer 2005; experiment 3).

Although these findings are consistent with CATLM's active learning and metacognitive mediation assumptions (c and f, respectively), they suggest that caution should be taken when transferring design principles form non-interactive to interactive learning environments. When learning environments are not interactive, it might be necessary to help students regulate their cognitive processing by prompting them to become more mentally active during the lesson (Azevedo 2005). On the other hand, manipulation interactivity may be sufficient to prime active learning, making additional reflective methods unnecessary (Moreno and Mayer 2005).

Nevertheless, even when instructional environments are interactive, it is most important to carefully examine whether the design of students' interaction is aimed at promoting superficial or deep processing of the instructional materials (Bangert-Drowns *et al.* 1991). For example, using an interactive learning program on environmental science, Moreno and Valdez (2005) found that asking students to organize the steps corresponding to a causal chain of events (i.e., manipulating interactivity) was not sufficient to improve their understanding about the topic as compared to having students study the organized chain of events. Only when the interactive version of the program was modified to prompt students to reflect on the product of their interaction did it promote students' problem solving transfer as compared to the non-interactive version of the program (effect size of d=0.71). In short, different interactivity methods may prompt the student to process instructional materials mindfully or not mindfully. The reflection principle seems to provide a learning advantage when students are not likely to reflect on relevant aspects of the materials, either because the instructional media is passive (i.e., non-interactive instructional presentations, textbooks) or because the interactivity embedded in the lesson can be performed in a superficial or automatic fashion.

Feedback principle The direct practical implication of the guided activity and reflection principles is that instructional technologies promote meaningful learning when learners are prompted to mindfully interact with or reflect upon the essential material in a learning environment. However, according to a CATLM, the effectiveness of interactive learning environments is also dependent on the relationship between the quality of feedback given by the system and the student's prior knowledge (Moreno 2004). Feedback is another example of dialoguing interactivity. For instance, the limited capacity assumption (c) suggests that the free exploration of a complex multimodal environment may generate a heavy cognitive load that is detrimental to learning (Sweller 1999; Paas *et al.* 2003), especially for novice learners, who according to CATLM's assumption (d), lack sufficient background knowledge to guide their meaning-making process (Tuovinen and Sweller 1999).

According to the feedback principle, novice students learn better with explanatory rather than corrective feedback alone. Explanatory feedback (EF) consists of providing a principle-based explanation for why students' answers are correct or incorrect whereas corrective feedback (CF) consists of only communicating whether students' answers are correct or incorrect. Past research indicates that different types of feedback have different influences on performance (Hogarth *et al.* 1991). In our own research, we have found empirical support for the feedback principle across four experimental studies. First, we investigated feedback effects on teaching elementary school students how to add and subtract integers. To this end, children were asked to solve a set of 64 practice problems over four training sessions with two feedback methods. One group of children was given CF alone after their responses to the practice problems. In addition to CF, a second group of children was given EF consisting of a verbal explanation relating the arithmetic procedure to a set of movements along a number line, a visual metaphor for the procedure to-be-learned (Lakoff and Nunez 1997). Students who learned with EF showed greater gain on difficult problems (effect size of d=0.47); learned faster during training (effect size of d=0.38); and showed a greater pretest to posttest reduction in the use of conceptual bugs (effect size of d=1.46) than those who learned with CF alone (Moreno and Mayer 1999b).

In the second study, we modified the instructional program used in the first study to discriminate between the feedback benefits of the number line animation and its corresponding verbal explanation. To this end, we included the following two conditions: one group of children received CF along with the animated number line (i.e., visual feedback or VF group) and a second group of children received CF, VF, and additional EF in English, or optionally in Spanish (Moreno and Durán 2004). Students who learned with EF showed larger posttest scores than those who did not receive EF (effect size of d=0.50).

The third and fourth studies supporting the feedback principle used the interactive *Design-A-Plant* learning environment (Lester *et al.* 1999). The third study, compared students learning about botany with CF alone or CF and EF (Moreno 2004). Compared to students who received CF alone, students who received EF produced higher transfer scores (effect sizes of d=1.16 and 1.58, respectively) and perceived the program as being more helpful (effect sizes of d=.57 and .68, respectively) and less difficult (effect sizes of d=.78 and .67, respectively). Finally, in the fourth study (Moreno and Mayer 2005) we found that students who learned with EF produced higher transfer scores (effect sizes of d=.75 and 1.87, for close and far transfer, respectively), gave fewer wrong answers during learning (effect size d=.94), and showed a greater reduction of their misconceptions over time than those who learned with CF alone (effect size d=1.88).

In sum, the reported findings are consistent with CATLM's assumptions (b) and (d), which emphasize the limited capacity of cognitive resources during the meaning-making process and the guiding power of prior knowledge in learning, respectively. Novice learners, often become lost and frustrated and eventually resort to ineffective trial-and-error strategies when asked to discover scientific principles without guidance (Moreno and Valdez 2005). Providing students with EF, therefore, reduces the extraneous processing of attempting to find a meaningful explanation when no mental model is available to the learner (Schauble 1990; Singley and Anderson 1989). The fact that students were more likely to choose EF in their home language, and that higher computer experience and longer latency to respond was associated with learning further supports this idea.

Pacing principle Another challenge to learning from interactive multimodal environments is the processing of dynamic visual displays such as instructional animations and videos. Imagine that an interactive learning environment presents a novice student with a narrated animation that explains how a scientific phenomenon works. In this example, some of the narration will be selected and processed in the auditory channel and some of the animation will be selected and processed in the visual channel. According to CATLM's assumptions (a) and (b), this mixed-modality presentation is most efficient because it takes advantage of the existence of independent visual and auditory channels, therefore expanding effective working memory capacity (Moreno 2006b). However, if the animation is complex, such as the case of illustrating reciprocal interactions between multiple system components, and the pace of presentation is fast, learners may not have enough time to organize the words and images into a mental model and integrate the model with prior knowledge. By the time that the learner selects relevant words and images from one segment of the presentation, the next segment begins, thereby cutting short the time needed for deeper processing. A potential solution to allow sufficient time for processing is to break down the animation and corresponding explanation into smaller segments. In this way, students are able to select words and images from one segment and organize them before moving to the next segment. Pacing is an example of controlling type of interactivity.

A simple way to allow students to control the pace of presentation of complex dynamic multimodal materials in computer-based learning is to include a *Continue* button on the computer screen. Students can process the first segment of the presentation and, once the first segment is understood, they can click on the *Continue* button to move to successive segments. Using this technique, Mayer and Chandler (2001, experiment 2) broke a narrated animation explaining the process of lightning formation into 16 segments, with each segment containing one or two sentences of narration and approximately 8 to 10 s of animation. Students who had control over the pace of the presentation performed better on subsequent tests of problem-solving transfer than those who received a continuous presentation (effect size of d=1.36).

In another study, Mayer *et al.* (2003) allowed students to learn how an electric motor works by selecting specific questions to be answered by a narrated animation segment (i.e., having control over the pace and order of presentation) or by viewing the entire narrated animation as a continuous presentation (i.e., not having control over the pace or order of presentation). In two separate experiments students who could control the pace and ordering of the segments performed better on a subsequent transfer test than did students who had no control (d=0.70 and d=1.03 for experiments 2a and 2b, respectively).

A more recent study (Moreno 2006c) extended this research to the teacher education domain. Prospective teachers learned about teaching principles either with a video (experiment 1) or classroom animation (experiment 2) showing how an expert teacher applied the principles in her classroom. Similar to Mayer and Chandler's (2001) study, some students were able to control the pace of the video presentation whereas others were not. Across both experiments, paced presentations promoted students' retention (effect sizes were d=0.68 and 0.74, for experiment 1 and 2, respectively) and transfer (effect sizes were d=0.40 and 0.61, for experiment 1 and 2, respectively). Furthermore, students' who learned with paced presentations gave lower ratings of difficulty than those presented with continuous presentations (effect sizes were d=0.65 and 1, for experiment 1 and 2, respectively), suggesting that the benefits of paced presentations resides on cognitive load reduction. Similar benefits for pacing were obtained in a study where participants learned to tie nautical knots of different complexity by watching videos (Schwan and Riempp 2004). Participants who were allowed to pace the video demonstration needed substantially less time to acquire the necessary skills for tying the knots than those who viewed a non-interactive video.

To summarize, allowing students to control the pace of presentation of instructional materials in interactive multimodal environments is consistent with CATLM's assumption of limited capacity (b). Pacing a presentation allows novice students to reduce representational holding by minimizing the amount of information that needs to be processed in working memory at one time. Within non-interactive instructional presentations, we found evidence for this interpretation in a study where students who viewed segments of a narrated animation depicting the process of lightning formation outperformed students who were presented with the whole narrated animation on retention, visual–verbal matching, and transfer tests (Mayer *et al.* 1999).

Pretraining principle Finally, consider an educational game—called the Profile Game—in which students sit at a computer screen showing a section of a planet's surface. They can draw a line and the computer will show them a profile line, indicating how far above and below sea level the surface is at each point on the line. By drawing many lines, the learner can determine whether the section contains a mountain, a valley, a ridge, a trough, an island, and so forth. Using the Profile Game, Mayer *et al.* (2002b) found that students made fewer errors during learning (d=0.57 and d=0.75, in experiments 2 and 3, respectively) and performed better on subsequent transfer tests (d=0.85 in experiment 3) when they received pretraining in which they saw pictures of each type of geological formation.

Prior knowledge can be an important element in interactive multimodal learning, so students who lack appropriate prior knowledge may benefit from highly focused pretraining. The *pretraining principle* is that students learn better from interactive multimodal learning environments when they receive pretraining that activates or provides relevant prior knowledge. The theoretical rationale is that pretraining helps students engage in generative processing by showing them which pieces of prior knowledge they should integrate with incoming information. Pretraining can be also embedded in non-interactive multimodal learning environments (Mayer *et al.* 2002a; Pollock *et al.* 2002). However, in interactive environments, it is a form of dialoguing interactivity, where students may ask to learn about the components of a system or a pedagogical agent may offer an explanation about the system components, if needed.

What are some Productive Directions for Future Research?

In a review of what cognitive science says about how people learn, Bransford *et al.* (1999) noted two important features of new instructional technologies that are consistent with the principles of a new science of learning: visual modes of presentation and interactive modes of presentation. First, "technologies can help people visualize difficult-to-understand concepts... [so] students are able to work with visualization...software" (p. xix). This feature corresponds to the multimodal learning environments. Second, "new technologies are interactive [so] it is easier to create environments in which students learn by doing" (p. xix). This feature corresponds to interactive learning environments. Overall, interactive multimodal learning environments represent an important venue for rigorous research aimed at improving how people learn.

The theme of this chapter is that interactivity and multimodal presentations do not cause learning, but rather that there are a growing set of research-based principles for using interactive multimodal learning environments in ways that promote learning. A continuing challenge for instructional designers who develop interactive multimodal learning environments is to reduce the extraneous cognitive processing that can be caused by interactivity and to maximize the learner's motivation to engage in generative cognitive processing that can be fostered by interactivity. In this final section we look to the future by suggesting several kinds of interactive multimodal learning environments that warrant rigorous study.

Games and simulations Proponents argue that interactive simulations and games hold potential for improving web-based learning, because users find them entertaining and motivating (Gee 2004; Prensky 2001; Rieber 2005; Schank 2002). However research examining this claim is in its infancy (Gredler 2004; Moreno and Mayer 2005; Rieber 2005). For example, considerable effort has gone into developing computer-based games and simulations intended to help people learn scientific material (Gredler 2004; Jacobsen and Kozma 2000; Lajoie 2000; Linn *et al.* 2004; Rieber 2005), but there is a need for such development efforts to be consistent with research-based principles of multimedia design and grounded in a research-based theory of how people learn. Although we have made progress in developing research-based principles for the design of simple multimodal learning environments, much of the empirical research base comes from studies using non-interactive instructional presentations (Clark and Mayer 2003; Mayer 2001; Mayer and Moreno 2003; Sweller 1999). An important goal for future research is to determine which features of games and simulations improve learning of which kinds of knowledge for which kinds of learners. Squire (2007, this volume) presents productive suggestions in this regard.

Pedagogical agents On-screen pedagogical agents are designed to guide student learning by providing guidance, advice, feedback, and support appropriate to the needs of the learner. Proponents argue that on-screen pedagogical agents can serve as individualized tutors that not only help students learn but also help them build effective learning strategies (Cassell *et al.* 2000; Lester *et al.* 1999). However, research on the cognitive consequences of learning with pedagogical agents is just beginning (Moreno 2005b). In particular, research is needed that pinpoints the features of agents that hurt learning and those that improve learning.

In this regard, Moreno (2005b) distinguished between agents' internal properties—the instructional methods that the agent uses during instruction, and external properties—agents' voice and image characteristics. Although much more is known about effective methods that computer tutors may use to promote learning (Aleven and Koedinger 2002), less is known about the effects of pedagogical agents' external properties. For example, Nass and Brave (2005) have shown that aspects of the agent's voice can have strong effects on performance. In addition, Moreno and Flowerday (2006) found that students' learning is hurt when they choose to learn from an agent of their same ethnicity. This last finding suggests that, although allowing students to make choices may promote their development of self-regulation (Randi and Corno 2000) and positive affect (Ryan and Deci 2000), if the choices are extraneous (i.e., not necessary to make the lesson intelligible), they may hurt learning by means of cognitive distraction.

Digital libraries Students have access to an amazing amount of information through various digital libraries—with the World Wide Web as the most popular, if not the most useful (Marchionini and Long 1997). Proponents envision that digital libraries will become indispensable learning aids for students (Borgman *et al.* 2000; Dillon and Jobst 2005; Marchionini and Long 1997). However, preliminary research on the use of digital libraries indicates that students need a great deal of guidance (Dillon and Jobst 2005; Rouet 2006). Therefore, there is a need for rigorous research that focuses on the kinds of scaffolds and guidance that aid learning with digital libraries. Of particular importance is the examination of interactivity methods that are germane to any engine or hypermedia program, such as searching and navigating.

Case-based learning There is an increasing trend in education to develop and use case materials in teaching concepts and problem-solving strategies in many disciplines (Copeland and Decker 1996; Kolodner and Guzdial 2000). These instructional tools are usually presented in text or video formats and used either in the classroom or presented in interactive multimodal learning environments (Beck *et al.* 2002; Lampert and Ball 1998). For example, videocases have been used as models, to demonstrate how an expert applies knowledge to solve a problem (Moreno and Ortegano-Layne 2007; Moreno and Valdez 2007; Wouters *et al.* 2007) and to encourage the application of principles and theories to analyze a richly contextualized problem (Derry and Hmelo-Silver 2005; Wilkerson and Gijselaers 1996). Despite their popularity, only recently has research started to examine whether and how do students learn from cases (Lundeberg *et al.* 1999). A fruitful area for future research, therefore, consists of investigating the conditions for designing effective learning from interactive multimodal environments that include cases in video and other formats. Because the nature of case-based learning is complex (Spiro and Jehng 1990; Spiro *et al.* 1992), special attention should be given to examine dialoguing interactivity methods that can guide students to engage in effective essential and generative processing.

Embedded authentic assessment Another novel multimodal interactive environment for learning consists of asking students to take part in a simulation of an authentic task, which gauges their performance as a form of assessment (Ridgway *et al.* 1999). In this scenario, teachers can gauge preexisting knowledge from the questions that children generate for investigation and, based on this information, decide how to help a particular student learn about science. This interactive learning environment imposes high cognitive demands for both, teachers and students. On one hand, students need to engage in multiple interactions by dialoguing, searching, and manipulating. On the other hand, teachers need to engage in customized dialoguing by prompting students when they are not making progress, responding to their answers to simulation questions, analyzing students' entries to journals, and evaluating students who use presentation software to communicate their understanding. Consequently, research is needed to determine whether this type of interactive learning environment can serve as a venue for valid, reliable, and efficient assessment of student knowledge.

Overall, there is much work to be done to determine when, where, how, for what material, and for whom various aspects of interactivity and multimodal presentation can improve learning.

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