30  Multimedia Learning with Simulations and Microworlds

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Abstract

In this chapter, we discuss research on learning from simulations and microworlds. After providing working definitions and examples for these environments, we review research on their effectiveness and, where available, on specific questions of their information design, interaction design, and instructional guidance design. On the basis of the research findings, we propose extensions to current theories of multimedia learning to involve social and affective processes and outcomes, describe implications for instructional design, discuss limitations of the existing research, and outline areas for future research.

What Is Multimedia Learning with Simulations and Microworlds?

Simulations and microworlds are digital environments that enable users to interact with models of situations and phenomena (National Research Council, 2011; Plass, Homer, & Hayward, 2009b). As the user manipulates objects or parameters, the environment generates dynamic responses based on a set of underlying rules, models, or computations. Simulations and microworlds provide opportunities for active learning (Mayer, Mautone, & Prothero, 2002), affording exploration instead of providing explanation (Rieber, 2005).

Educators and researchers have posed a number of questions specifically linked to the pedagogical use of these resources: Are exploratory environments effective for learning? What support structures should be provided to make them effective? How can they be designed to engage the learner in meaningful learning activities? This chapter will review research that has provided some answers to these questions, propose extensions to cognitive theory in response to these research findings, and describe implications for
instructional design. We will then discuss limitations of existing research and suggest areas for future investigations of simulations and microworlds. First, however, we will provide working definitions of simulations and microworlds, used in compiling the research studies included in this review.

**Simulations.** Multimedia simulations are designed to depict specific phenomena, processes, or systems. Within a particular simulation, the user can adjust various parameters, and an underlying computational model responds by displaying the results of the user's input. Through repeated interactions, such as selecting a range of values for a variable and observing the resulting changes, the learner can arrive at an understanding of the model (de Jong & van Joolingen, 1998; National Research Council, 2011). Broad definitions of simulations distinguish conceptual models from operational models (de Jong & van Joolingen, 1998). Conceptual models focus on principles, concepts, or facts (e.g., how gases respond to changes in temperature), while operational models demonstrate a series of operations or procedures, such as how to perform a specific mechanical task. For the purpose of this chapter, we considered only interactive environments that are based on conceptual computational models to be simulations.

**Microworlds.** Beyond the exploration and investigation possible within a simulation environment, microworlds afford expanded opportunities for creation and production. Within a simulation, users are “controlling a system that someone else has built,” while in a microworld they are “building their own runnable system” (Laurillard, 2002, p. 162). This approach emphasizes active learning, which springs from the learner’s “exploration … of a microworld sufficiently bounded and transparent for constructive exploration and yet sufficiently rich for significant discovery” (Papert, 1980, p. 208). Microworlds have constraints of their own, since only actions foreseen by the creators of the program will be possible (Turkle, 2009), but they are designed to open many paths for students to explore rather than send them in one specific direction (Papert, 1980). It should be noted that, in practice, it can be difficult to distinguish simulations from microworlds, and the terms are sometimes used almost interchangeably (e.g., Gredler, 2004; Hegarty, 2004). For the purpose of this chapter, we considered environments to be microworlds if they were based on a conceptual model and gave learners the freedom to alter this model.

**Digital games.** Some digital games can be considered simulations or microworlds as well. In these types of games, the game engine may model a range of topics such as Newtonian physics, astronomy, history, urban planning, or evolution. Gamelike features such as levels, clear goals expressed as win states, feedback, reward systems, leaderboards, and message boards guide the way users explore these environments, making choices that amount to selecting values or constraints for a number of variables. Games often add social and affective components that may facilitate learning as well.
Examples of Multimedia Learning with Simulations and Microworlds

Let’s consider an individual who is studying to become a scuba diver and wants to learn about properties of gases, a topic important for diving safety. In order to explore the relationships among pressure, volume, and temperature of a gas, she uses a simulation of the ideal gas laws, depicted in Figure 30.1. On the left side of the screen, the learner sees a container filled with gas molecules. Sliders allow her to manipulate the variables of heat, temperature, and pressure. She can observe the values of the variables represented symbolically, by numbers in text boxes, as well as iconically, by depictions of burners and weights. On the right side of the screen is a graph that is dynamically linked to the container. If the learner decides, for example, to manipulate temperature while keeping pressure constant (Charles’s law), the simulation will automatically graph a point for each of the temperature values she selects, showing the corresponding volume. She can also choose to hold temperature constant and explore the relationship between pressure and volume (Boyle’s law). Through the exploration of the simulation and related learning activities, the learner can engage in the construction of knowledge, creating her own mental representation of the conceptual model on which the simulation is based and that is represented in the simulation interface.

Consider another learning scenario in which an individual uses a microworld, such as the popular digital game Little Big Planet 2 (LBP 2), to
investigate Newtonian physics. This learner begins by solving some puzzles on game levels that were modified (“modded”) to allow the investigation of specific physics concepts (Figure 30.2, left panel). Once he has completed the available levels, the learner opens the LBP 2 level generator and builds his own game mod (Figure 30.2, right panel), applying what he has learned to create a level of his own. In playing his newly constructed puzzle, he may find that it does not work correctly. After reflecting on the problem, he develops a hypothesis as to what may have gone wrong and a plan to fix it. The student changes his level design accordingly and tries again, repeating these steps until his puzzle functions as expected. In this process, he constructs a deep mental model of the subject matter in a situated environment.

What Do We Know about Multimedia Learning with Simulations and Microworlds?

What we know about learning from simulations, microworlds, and related games is based on many of the same general theoretical foundations of multimedia learning environments discussed in previous chapters of this volume, especially in Part II, “Basic Principles of Multimedia Learning.” However, simulations and microworlds are by design set apart from other multimedia learning experiences in a theoretically significant way: simulations and microworlds are models of the phenomena they represent. These models are represented internally in symbolic form by the underlying code in which they are programmed and externally in multiple modalities via the user interface. The exploration of these environments is therefore a model-based inquiry that is situated in a specific explanatory framework (Schwartz, Milne, Homer, & Plass, in press). Like all models, simulations and microworlds are simplified or abstracted representations; specific features may be included, emphasized, or omitted in order to support particular activities or types of understanding (Schwartz et al., 2013).
Model-based inquiry typically involves a series of steps, often starting with the observation of real-world or imagined problems or phenomena (Linn et al., 2010). Learners may generate questions and hypotheses about the observed phenomena, plan an inquiry that allows for the verification or rejection of the hypotheses, implement that plan within the simulation or microworld, analyze results, and relate findings to the explanation of the phenomena originally observed; this in turn may generate new questions and hypotheses, thereby starting the inquiry process over again (Lehrer & Schauble, 2006; Windschitl, Thompson, & Braaten, 2008). In some approaches, this inquiry is seen as a participatory process of the creation of artifacts in a constructionist context (Barab, Hay, Barnett, & Keating, 2000; Papert, 1994).

Learning with Simulations

In this section we will discuss research on learning with simulations, beginning with a review of studies on the educational efficacy of simulations. We then consider research focusing on the design of simulations. This work aims to identify effective design patterns for simulations, systematically varying and comparing different features to arrive at conclusions on the most useful approaches for particular learners, contents, and settings. Since model-based inquiry in the context of a simulation involves manipulating the information represented in order to reach a learning goal, we discuss research on design patterns in terms of information design, that is, the way information is represented; interaction design, that is, the interactive opportunities that learners are afforded; and the design of instructional guidance, that is, how the simulation scaffolds specific learning strategies.

Effectiveness for Learning. An array of empirical studies, reviews, and analyses of available data provide strong support for the idea that simulations can be effective for learning in various content areas and for a range of learning objectives. Analyses include an exploration of the 1996 and 2000 National Assessments of Educational Progress (NAEP), which found better math and science scores for eighth graders who had learned with simulations rather than drill-and-practice programs (Wenglinsky, 2005). Several meta-analyses of empirical studies on simulations and games showed that, overall, the use of simulations resulted in better cognitive outcomes and attitudes toward learning than more traditional teaching methods (Bayraktar, 2002; Rutten, van Joelingen, & van der Veen, 2012; Vogel et al., 2006) or outcomes at least as good (Scalise et al., 2011; Smetana & Bell, 2012). Evidence from these aggregated studies indicated positive results not only for content learning, including gains in conceptual knowledge and science process skills, but for motivation and attitude as well.

Learning with a simulation can be a challenging process. The complexity of rich learning tasks, such as those encountered in an inquiry environment,
has the potential to overwhelm learners (van Merriënboer, Kirschner, & Kester, 2003); consequently, providing instructional guidance, or scaffolding, is essential in these environments (Rutten et al., 2012; Smetana & Bell, 2012). One review of studies on using simulations in scientific discovery learning, which found no clear pattern of superiority for these environments over other approaches, ascribed this finding to persistent skill deficits that can prevent learners from utilizing simulation environments effectively (de Jong & van Joolingen, 1998).

As with other teaching tools, the efficacy of a simulation is moderated by the way in which it is implemented within the educational context (Hegarty, 2004). Simulations were found to be most effective when used to supplement rather than replace traditional instructional models (Bayraktar, 2002; Rutten et al., 2012; Smetana & Bell, 2012), and results suggested that teachers need appropriate training to use simulations in the classroom to maximum effect (Rutten et al., 2012; Smetana & Bell, 2012). One of our own studies examined the implementation of a two-week chemistry curriculum unit based on the CREATE Lab simulation suite (create.nyu.edu/mm), finding differences in learning outcomes that resulted from factors including teacher attitudes, experience, and expectations; fidelity of implementation; technology infrastructure; and even the level of support from the school district (Plass et al., 2012). Such integration factors, much like design factors, can have a critical impact on simulation efficacy.

Many simulations employ gamelike features or are bona fide games, which may have both cognitive and affective consequences. For example, research on the use of the commercial simulation game Civilization III for learning history has provided initial evidence that giving students the opportunity to test their own hypotheses about historical topics, rather than maintaining the conventional focus on memorizing history facts, resulted in a unique form of engagement and rich conceptual learning (Squire, 2006). Research on other games specifically designed for learning showed initial evidence that those playing the games learned better than a non-playing control group, especially by engaging in authentic practices that led to a deeper understanding of scientific visualizations and scientific concepts (Jenkins, Klopfer, Squire, & Tan, 2003). However, many related studies lack the methodological rigor required to make general efficacy claims.

Some types of environments allow multiple participants, often in large numbers, to explore a simulation at the same time, either in collaboration or in competition with one another (Richter & Livingstone, 2011). These massively multi-player online games (MMOs) include several subgenres. The most popular MMOs, such as World of Warcraft and RuneScape for adults, and Habbo Hotel and Club Penguin for youth, were designed for entertainment purposes but have been the subject of research because of the opportunities for situated learning they provide (Thomas & Brown, 2009). More research on the impact of MMOs on learning, however, has been conducted.
with virtual worlds specifically designed for education. *Quest Atlantis*, for example, facilitates scientific inquiry on socially relevant problems, such as ecology, water quality, and astronomy (Barab, Thomas, Dodge, Carteaux, & Tazun, 2005). Research on related projects, such as *River City*, has shown that these environments can have an impact on learners’ self-efficacy (Ketelhut, 2007), support the transfer of students’ scientific inquiry processes into real-life processes (Ketelhut, Nelson, Clarke, & Dede, 2010), and do so for boys and girls alike (Nelson & Ketelhut, 2007). Exploratory studies on *Whyville*, an educational MMO that offers a range of science-based activities in which several million users participate at home or in school, suggest that users of this resource are motivated to investigate science topics in formal and informal settings (Kafai, Quintero, & Feldon, 2010; Neulight et al., 2006).

Though research on simulations is heavily weighted toward science and math, some studies have found that simulations can be useful in other content areas, such as economics (del Populo Pablo-Romero, Pozo-Barajas, & de la Palma Gómez-Calero, 2012), second-language learning (Ranalli, 2008), and career skills (Wall & Ahmed, 2008). In the field of medicine, evidence from the use of simulations developed for a number of procedures indicates that this emerging approach has the potential to increase surgical proficiency among doctors in training (Tobias & Fletcher, 2011). Looking at simulation games, an even broader range of content areas have been investigated, for example, social sciences, geography, educational psychology, and politics (Randel, Morris, Wetzel, & Whitehill, 1992).

To date, the overwhelming majority of empirical studies on simulations concern their general effectiveness for enhancing conceptual understanding, often investigating learning within a specific simulation environment (e.g., Cronjé & Fouche, 2008; Gazit, Yair, & Chen, 2005) or comparing learning outcomes and motivation between simulation and no-simulation conditions (e.g., Evans, Yaron, & Leinhardt, 2008; Renken & Nunez, 2013; Trundle & Bell, 2010). A first important overarching design principle for effective simulations has emerged from this research: clear goals for learning are essential (National Research Council, 2011), and simulations must be designed in line with these goals (Plass et al., 2009b). Specific learning objectives, such as teaching particular domain content, preparing students for future tasks, or changing learners’ affect, will influence what is included in a simulation and how it should be presented.

**Information design.** The presentation of information in an instructional multimedia environment involves a number of design decisions, such as whether and when to utilize visual representations and text, how to combine the two, and what types of graphics to select. In a simulation, these decisions affect how the user will be able to perceive and interrogate the underlying model and subsequently construct his or her own mental model. Users need support to select relevant items of visual and verbal information, organize them into coherent representations, and relate them to one another, making
connections to their prior knowledge as well (Mayer, 2001). The amount of
information presented at any one time must also be managed to avoid over-
loading working memory (Sweller, 1999). This is a particularly important
consideration given that simulations not only involve dynamic presentations,
but require the user to perform specific interactive behaviors, each of which
may demand significant cognitive resources (Domagk, Schwartz, & Plass,
2010). Three areas in which empirical studies have investigated the design of
information in the context of simulations are type of representation, cueing,
and the integration of multiple visual representations.

**Type of representation.** The cognitive theory of multimedia learning
(Mayer, 2001; see also Chapter 3) suggests that information can be repre-
sented as words or pictures, perceived visually or auditorily. The integrated
model of text and picture comprehension (Chapter 4) further distinguishes
between descriptive (verbally based) and depictive (pictorially based) rep-
resentations used by learners when they select, process, and integrate infor-
mation. Consistent with these theoretical approaches, several studies have
asked how information should be represented in a simulation to best sup-
port learning.

One line of research that explored this issue compared the use of iconic
(pictorial) versus symbolic (textual) representations of key information in
chemistry simulations for high school learners (Lee et al., 2006; Plass et al.
2008; Plass et al. 2009b). Iconic representations depicted temperature and
pressure by small images of burners and weights, while symbolic representa-
tions indicated these variables by text stating “temperature” and “pressure.”
Results showed that comprehension and transfer were higher for students in
conditions that utilized iconic representations; this icon effect was particu-
larly strong for individuals with low prior knowledge (Homer & Plass, 2010;
Plass et al. 2009b). These findings suggest that processing icons requires less
cognitive effort than processing symbolic representations, thus freeing cogni-
tive capacity for the construction of a mental model.

Research has also investigated whether graphic representations contain-
ing equivalent information can differ in computational efficiency based on
the visual design of the information presentation (Rasch & Schnitz, 2009;
Schnitz & Bannert, 2003). In one such study, learners interacted with dif-
f erent visualizations on the topic of time differences, after which they were
tested on two distinct types of computational tasks. The results confirmed
that different visualizations supported performance on different tasks
(Schnitz & Bannert, 2003). This structure mapping effect suggests that fea-
tures of a graphic representation have a direct effect on a learner’s men-
tal model (Rasch & Schnitz, 2009; Schnitz & Bannert, 2003; Schnitz &
Kürschnner, 2007). Similarly, in a simulation on identifying geological fea-
tures, the main task – which was primarily visual – was best supported by
visually rather than verbally based scaffolds, with a medium to large effect
size (Mayer et al., 2002).
Multiple representations. One powerful affordance of multimedia simulations is the capacity to provide learners with multiple representations, as in the gas laws example shown in Figure 30.1, which represents the behavior of a gas pictorially as well as symbolically (Plass et al. 2013a, 2013b). Multiple representations provide information that may allow learners to construct more accurate mental models; in many content areas, the ability to move fluidly between multiple representations is an attribute of expertise (Schwartz et al., 2013). Van der Meij and de Jong (2006) found that linking multiple representations by physical integration (keeping related elements together) as well as dynamic linking (changes in one representation automatically appear in another) resulted in significantly better outcomes than a condition in which representations were not linked. Another study utilized eye-tracking technology to examine learners’ interactions with multiple representations in a CREATE Lab simulation on the ideal gas laws (O’Keefe et al., 2012). Researchers observed that specific patterns of visual transitions between the explanatory model and dynamically linked graph were associated with learning gains. This suggests the potential to foster improved learning outcomes by scaffolding students in making this type of transition, a hypothesis explored in Milne et al. (2012), as described in the next section.

Cueing. Cueing, or signaling, refers to the manipulation of visual or textual elements in order to direct learners’ attention to specific features in the learning environment (de Koning, Tabbers, Rikers, & Paas, 2010). The benefits of this approach for helping learners select, organize, and integrate information have been well established in studies of static visuals and animation (de Koning et al., 2010; Paik & Schraw, 2012; see also Chapter 12). Because attending to the transitory elements of a simulation can place significant demands on the learner, cueing is a promising strategy for simulations as well (Plass et al., 2009b). In a recent series of studies, high school students used the simulation on the ideal gas laws in Figure 30.1 (Plass et al., 2013a, 2013b), which displays a container with gas particles as well as an accompanying graph. When the user manipulates a variable using a slider, a corresponding point is dynamically added to the graph. An analysis of gaze data confirmed that learners made transitions between the sliders and the graph more frequently when cued (Plass et al., 2013b), and students in the cued condition learned better than students who received no cueing (Plass et al., 2013a). Another study stressed the importance of cueing for novice users, who are not able to distinguish between critical and peripheral features of simulations (Adams et al., 2008).

Emotional design. An emerging area of research in simulations is concerned with emotional design – the question of how information design can influence emotion and, in turn, learning. Although investigations to date have focused on interactive multimedia lessons rather than simulations, these studies have shown that materials designed to evoke positive emotions can facilitate both comprehension and transfer (Plass et al., 2014; Um et al.,
This suggests that emotional design in simulations may be a fruitful area for further investigations.

**Interaction design.** Interaction design describes the activities, or types of engagement, available to the learner in a multimedia environment. Within a simulation, the user's interactions are the basis for the exploration and inquiry that will lead to the construction and elaboration of a mental model (Domagk et al., 2010). Commonly explored aspects of interactivity include learner control, feedback, and guidance.

**Learner control.** A number of studies have demonstrated that learner control over pace, content, or representation in a multimedia environment can have beneficial effects (Mayer & Chandler, 2001; Schwan & Riempp, 2004; see also Chapter 21). Users of a simulation, by definition, always have a certain degree of control, since their role is to conduct investigations in the learning environment that will lead to an understanding of the underlying model, and in fact this control is seen as an essential aspect of learning with simulations (Plass et al., 2012). Several studies have investigated types of learner control within simulations. One study of a simulation on the cardiovascular system examined outcomes for users who either explored the environment freely or followed a set of explicit directions (Windschitl & Andre, 1998). The exploratory condition helped support conceptual change better than the directions condition, but it was more difficult for less cognitively advanced students. A similar study that compared users who were free to choose their own course through a simulation on electrical circuits with others whose paths were constrained by the system found no significant differences in outcome between the two conditions. The authors suggest that the specific assignment given to all users had the effect of structuring interaction in either condition (Swaak & de Jong, 2001).

To further investigate the effects of levels of user control in a simulation environment, Plass et al. (2008) compared a version of a computer simulation in which users freely explored the environment with another version in which learners followed detailed steps of manipulating simulation parameters (i.e., worked simulations). The results indicated that the exploration group outperformed the worked simulation group on tests of comprehension. Transfer test results showed that learners with high levels of executive functions performed better with the exploratory simulation, whereas learners with low levels of executive functions performed better when they used the worked simulations (Plass et al., 2008).

**Feedback.** Feedback can provide additional informational content within a simulation or can correct, evaluate, and make suggestions about a learner's progress through the environment (see Chapter 19). A number of studies have considered the effects of different types and amounts of feedback in simulation environments.

In a simulation on thermal equilibrium, eighth grade students explored temperature and heat flow by clicking on various images (Clark & Jorde,
Learners in the tactile condition received additional audio, text, and visual feedback about the objects, such as “This feels burning hot!” Students in the tactile group performed significantly better than those in the control group on post-tests of content knowledge. Despite some methodological questions about the equivalency of the two treatments, this suggests that the interaction between the learning environment and the learner activated not only cognitive but emotional responses, with resulting changes in the learner’s conceptual model.

Like all information within a simulation, feedback can be delivered using different representations of information. In a physics simulation environment dealing with Newton’s laws, college students received either graphical feedback (animated representations) or textual feedback (numerical reports) on their interactions (Rieber et al., 2004). Consistent with results from previous studies utilizing the same environment (Rieber, 1996), users in the graphical feedback group did better on outcome measures, in particular when evaluation tasks were structurally similar to the simulation tasks. This result is consistent with the structure mapping effect discussed earlier.

Other aspects of feedback that have been investigated in simulation environments include the use of personalized versus impersonal feedback messages (Moreno & Mayer, 2000), with benefits demonstrated for personalized feedback.

**Instructional guidance.** Simulations are complex learning environments that pose a number of challenges for learners (van Merriënboer et al., 2003). Students may have difficulty with aspects of inquiry such as generating hypotheses, designing systematic experiments, or analyzing results, all of which are crucial to the process of understanding the underlying model in a simulation environment (de Jong & van Joolingen, 1998). The guided discovery principle in multimedia learning suggests that to help students learn successfully with simulations, the learning environment should include appropriate guidance or support (Mayer, 2004; see also Chapter 15).

Guidance, or scaffolding, can be introduced into simulations in a number of forms, including specific information on the learning domain, tips on when or how to perform certain procedures, or tools that enable learners to record information (Plass et al., 2009b). One typology suggests that scaffolding should be targeted to address three interlinked aspects of inquiry: sense making, process management, and articulation and reflection (Quintana et al., 2004).

**Sense making.** Sense making encompasses basic processes, such as making connections between intuitive, everyday knowledge and formal scientific representations, as well as selecting and applying information from the simulation to the inquiry process, including the formulation of hypotheses (Quintana et al., 2004).

A common issue in education is bridging the gap between what learners know – or think they know – and the formal expression of knowledge.
The use of narrative to link experiential and abstract knowledge was explored by Milne et al. (2011). Learners used a simulation with either an expository introduction, typical of science textbooks, or a narrative introduction based on an everyday situation. While learners with high levels of prior knowledge performed better in the narrative condition, students with low prior knowledge showed no differences between conditions. This suggests that while making connections to prior knowledge can be important to support learning, the overall burden on learners of different ability levels must be taken into account. A follow-up study examined problematizing — challenging students on how much they really understood about a familiar phenomenon in order to create a motive for exploration (Milne et al., 2012). Students in the problematizing condition showed significantly better scores on both comprehension and transfer than those in the non-problematizing condition. Problematizing may have supported sense making not only by motivating students to explore an everyday experience in a formal science context, but by helping learners formulate the questions or hypotheses they needed to investigate within the simulation.

Some studies have been concerned with the cognitive load imposed by the task of discovering the information needed to operate a simulation. While discovery is considered a valuable aspect of the learning process, such tasks may sometimes impede the learner in acquiring domain knowledge. In some cases, having the system provide adaptive advice as needed during exploration helped learners to acquire content knowledge, though it interfered with learning to play the game (Leutner, 1993).

**Process management.** Process management involves decision making about how to proceed through an investigation, particularly important in the kind of complex tasks or phenomena that may be represented in a simulation (Quintana et al., 2004). In order to successfully carry out the necessary experimentation in an inquiry environment, a student must be able to generate hypotheses as well as plan and monitor appropriate investigations. A number of approaches to supporting these processes have been investigated — for example, structured assignments or templates (Chang, Chen, Lin, & Sung, 2008; Manlove, Lazonder, & de Jong, 2007), feedback or advice (Moreno, 2004; Moreno & Mayer, 2005), or model progression, which involves structuring the learning environment itself to support the user’s growing level of competency (Frederickson, White, & Gutwill, 1999; Swaak, van Joolingen, & de Jong, 1998).

Feedback or hints provided by the learning environment can be designed to guide the learner’s progress through the inquiry process. One line of research examined different types of feedback, comparing the performance of learners who received only corrective feedback, which informed them of whether their responses were correct, and learners who also received explanatory feedback, which explained why each response was correct or incorrect (Moreno, 2004; Moreno & Mayer, 2005). The learning environment was a
simulation game on plant structure, with feedback provided by a pedagogical agent within the game. The results showed that explanatory feedback was significantly more effective in supporting learners.

Model progression is an approach that supports learners’ use of simulations by allowing them to begin their investigations with a simplified version of the environment. As the learner gains expertise, the complexity of the environment increases. This approach allows the learner to explore the environment without experiencing an overwhelming cognitive burden. Swaak et al. (1998) investigated learning with a simulation on oscillation in which support was provided by a model progression approach as well as by assignments that helped structure learners’ interactions. Assignments included feedback with hints on how to proceed. Both model progression and assignments resulted in gains on a test of intuitive knowledge.

Several variations in types of model progression have also been investigated. One study showed an advantage for model order progression, which scaffolds learners in an increasingly complex understanding of relationships between variables, over model elaboration, which gradually introduces a greater number of variables into the model (Mulder, Lazonder, & de Jong, 2011). In another approach, high school students used a simulation on electrical circuits that presented only the initial and final stages of a model or a sequence that included transient states between the initial and final stages. Students who viewed the transient states developed a better understanding of the content area (Frederiksen, White, & Gutwill, 1999).

**Articulation and reflection.** Articulation and reflection center on having learners express and evaluate their experiences throughout the inquiry process (Quintana et al., 2004). One approach to this process is to provide opportunities for self-explanation. In order to generate such an explanation, students must not only attend to the material, but also monitor their own developing understanding (see also Chapter 17).

A comparison of self-explanation, inquiry learning, observational learning, and hypermedia learning environments showed that self-explanation and inquiry environments were most effective for teaching high school students about probability; self-explanation resulted in the best outcomes overall, but the inquiry environment was more time-efficient (Eysink et al., 2009). On the basis of these findings, the authors suggest that multimedia instruction should combine inquiry learning with prompts for self-explanation. However, another study suggests that while self-explanation may be a productive strategy, its effectiveness depends on what students are explaining. In a simulation environment on designing plants, college students who reflected on their own solutions – which were sometimes incorrect – did not do as well as those who reflected on correct information supplied by the program (Moreno & Mayer, 2005).

Van der Meij and de Jong (2011) examined self-explanation by users of SimQuest, a simulation environment utilizing multiple representations. Two
versions of a simulation on physics were compared: one with general self-
explanation prompts and one with prompts specifically directing learners to
explain how dynamically linked multiple representations within the simu-
lation were related. Students’ knowledge improved under both conditions.
Specific directive prompts resulted in better outcomes for domain knowl-
edge, though not for transfer knowledge, than general prompts. This sug-
gests than scaffolding students to articulate conceptual relationships may in
fact be a promising approach.

Learning with Microworlds

Microworlds aim at providing learners with situated experiences, via the
exploration of simulation models that can be modified, to engage them in
deep thinking and foster rich understanding (diSessa, 1997; Laurillard, 2002;
Papert, 1980). Whereas original conceptions of microworlds saw their use of
programming languages as a defining feature (diSessa, 1997; Papert, 1980;
Resnick, 1994), more recent approaches provide alternative ways to manip-
ulate Papert’s “objects-to-think-with” (1980, p. 11), such as direct object
manipulation, icon-based interfaces, and the use of games as microworlds.

Compared with the relatively large body of research on simulations, much
less robust evidence has been accumulated on the effectiveness and design
patterns of microworlds. This may stem in part from Papert’s dislike for
experimental research in microworlds and his call for other forms of evi-
dence to support their effectiveness (Papert, 1994). Yet to date no such evi-
dence in support of the general efficacy of microworlds has emerged.

Effectiveness of microworlds. Early microworlds were built around pro-
gramming languages such as LOGO, and research initially focused on the
effects of learning to program, which many expected would have a funda-
mental impact on children’s learning and cognitive development (Harel &
Papert, 1991; Papert, 1994; Pea & Kurland, 1984; Resnick, 1994). Some stud-
ies provided support for these expectations. After 12 weeks of computer pro-
gramming, for example, one group of 6-year-olds demonstrated increased
creative thinking skills (fluency and originality) and higher levels of reflective
thinking than a control group that received computer-assisted instruction.
The programming group also performed better on metacognitive measures
and tasks of giving directions (Clements & Gullo, 1984). Similarly, fourth
graders using LOGO to design instructional software on fractions learned
more about fractions than two control groups (Harel & Papert, 1991). There
is also some support for the claim that learning with LOGO results in bet-
ter transfer performance than traditional approaches (Lehrer, Randle, &
Sancilio, 1989). However, other studies identified significant problems and
misconceptions related to programming among children (Mayer, 1976; Pea
& Kurland, 1984) and failed to find evidence that programming experience
would transfer to other tasks (Kurland, Pea, Clement, & Mawby, 1986).
Comprehensive reviews of the literature have found that the evidence for a general impact of programming on learning is inconclusive (Jonassen & Reeves, 2000; Pea & Kurland, 1984) and the evidence for effective discovery learning with LOGO is negative (Mayer, 2004).

Microworlds quickly expanded beyond programming languages to allow learners to explore and build models through the direct manipulation of objects on the screen. One early example of this type of microworld, ThinkerTools, enabled students to investigate Newtonian physics, either by interacting with existing models or by building their own, which was shown to improve students’ ability to solve Newtonian dynamics problems (White, 1984). Exploratory research has examined other areas, such as the use of microworlds to help students develop a rich understanding of astronomical phenomena by building dynamic three-dimensional models of the solar system (Barab et al., 2000) or learn about complex dynamic systems by modeling with StarLogo (Klopfer, Yoon, & Um, 2005). However, the empirical evidence for the effectiveness of most of these systems is weak. Some researchers have expressed concerns about the amount of time students spent learning the modeling tool rather than the subject and the limited opportunities for interactions among students within microworlds (Roth, Woszczyna, & Smith, 1996).

A number of commercial games now allow for modding, which permits players to modify a game along with its underlying rules and models, effectively turning the game into a microworld. Research on the impact of modding is in its early stages. Exploratory studies are investigating topics such as the values expressed by modders of a history game (Moshirnia & Walker, 2007; Owens, 2011) and the potential benefits of acquiring computer science skills through modding of games using engines such as War Craft III and Unreal Tournament (El-Nasr & Smith, 2006). In an extension of the idea of modding games, there is a growing interest in investigating the impact of game design curricula, often offered in after-school programs, on a variety of learning outcomes (deVane, Durga, & Squire, 2010; Kwah, Milne, Goldman, Tsai, & Plass, 2012).

**Microworld design factors.** Many microworld designers have offered heuristics on design factors related to the information and interaction design of microworlds for their specific implementations (Resnick & Silverman, 2005; White, 1984), but there are few cases in which design factors were the subject of the research investigation. Discussions of microworld design focus mainly on instructional and learning strategies that support students in using microworlds to comprehend powerful ideas. Research has shown that microworlds cannot achieve this type of learning outcome unless learning objectives are well specified and the related context of the activity well designed (Miller, Lehman, & Koedinger, 1999). In a microworld about the behavior of charged particles in an electrical field, for example, students learned best when they were asked to explore the model by setting their own goals rather than when...
they were provided with goals. However, when gamelike goals were added, students learned best when they received very specific rather than general guidance (Miller et al., 1999).

**Agent-based microworlds.** Other research has focused on agent-based microworlds, using modeling environments such as NetLogo, for learning various science subjects, including chemistry (Stieff & Wilensky, 2003), material science (Blikstein & Wilensky, 2009), and electricity (Sengupta & Wilensky, 2009). Agent-based modeling allows for the use of simple, individual-level rules to create complex collective behaviors, thereby revealing the underlying logic of the model (Blikstein & Wilensky, 2009). In NetLogo, for example, the learner/developer may specify the rules for the behavior of one agent, such as a molecule. The user can then observe how the system models the way in which multiple instances of this agent interact with one another, in this case as an ideal gas. In exploratory studies, researchers have begun collecting evidence on whether learning with these environments can foster students’ ability to transition between multiple levels of representations, conceptual reasoning, and logical justifications in the inquiry process (Stieff & Wilensky, 2003). Although scholars have offered a number of theory-based design features for agent-based microworlds (e.g., Blikstein & Wilensky, 2009; Jacobson & Wilensky, 2006), research with these environments focuses largely on making meaning in complex systems in science education, and virtually no research exists that critically investigates specific aspects of microworld design.

**Gamelike elements.** Another feature of modern microworlds is their incorporation of gamelike elements. The idea of using games for this purpose is not new (White, 1984); however, only in recent years have games become popular implementations of microworlds. In one study involving the game Rapunsel, for example, players used Java-like programming to create a personalized avatar that would interact with the world via custom dances. After four weeks of playing this game once a week for 40 minutes, middle school girls showed significantly increased general self-efficacy and programming-related self-efficacy, and both boys and girls showed significantly increased self-esteem (Plass, Goldman, Flanagan, & Perlin, 2009a). In the same vein, a class on developing and playing games for middle and high school girls also led to increased computer-related self-efficacy (Tapia, El-Nasr, Yucel, Zuko, & Maldonado, 2007). However, no strong evidence linking cognitive learning outcomes to gamelike features in microworlds exists to date.

**Social elements of microworlds.** One of the significant features of modern microworlds is their conceptualization as social environments in which learners actively make meaning and construct their own knowledge. For example, the success of Scratch has been linked to the creation of a culture of affinity groups in which learners support one another, learn from one another, and reuse and remix each other’s code (Brennan, Monroy-Hernandez, &
Resnick, 2010). The use of such microworlds has been linked to the acquisition and practice of interpersonal social-behavioral competence (Young & Upitis, 1999). In fact, even for simulation games such as Civilization III that had not been designed as microworlds, that is, did not permit modding, online communities formed in which learners analyzed, among other things, the game’s key algorithms, eventually helping to build the next version of the game (Squire & Gionanetto, 2008). Ethnographies and other qualitative analyses of such online communities have suggested that they foster deep social knowledge construction, systems-based thinking, and application of an evaluative epistemology (Squire & Gionanetto, 2008; Steinkuehler & Duncan, 2008), but these findings have yet to be validated.

Another aspect of social features is represented in participatory simulations, in which learners use wearable or handheld computers to take part in collaborative computer simulations of complex dynamic systems, often situated in the real world (Colella, 2000). In one example, teams of learners fought virtual outbreaks of viruses that could infect virtual or real characters (Rosenbaum, Klopfer, & Perry, 2006). Studies showed that the virus simulation engaged learners in the subject matter and facilitated various aspects of scientific inquiry (Colella, 2000). Augmented reality simulations utilize location-aware handheld computers to place learners in large-scale complex investigations, such as environmental or health-related topics, which has been shown to enhance the authenticity of, and personal involvement in, the experience; personalize learners’ goals; and foster their understanding of the dynamic system (Rosenbaum et al., 2006). Among the most popular features of these environments were those fostering social interactions (Klopfer, Yoon, & Rivas, 2004). Research supporting the effectiveness of these environments is lacking, however.

### Implications for Cognitive Theory

#### Summary of Implications

Research on simulations shows that these exploratory environments are at least as effective as traditional methods (Scalise et al., 2011; Smetana & Bell, 2012) and often result in higher cognitive outcomes, with mean effect sizes reported from 0.39 (Bayraktar, 2002) up to 1.5 (Rutten, van Joolingen, & van der Veen, 2012). Higher affective outcomes (attitude and motivation) have also been reported, with mean effect sizes larger than 2.0 (Rutten et al., 2012). For research on microworlds, the empirical evidence does not yet allow similar efficacy claims to be made. These findings have several important implications for cognitive theory that are related to the paradigm of active learning through model-based inquiry, the importance of considering affect during learning, and the importance of considering social aspects of learning.
**Active exploration through model-based inquiry.** Most important, research in simulations and microworlds supports the active learning assumption of the cognitive theory of multimedia learning (Chapter 3) and expands it to model-based inquiry. Model-based inquiry in simulations and microworlds begins with the observation of real-world or imagined problems or phenomena by individual learners or groups of learners (Linn et al., 2010). If properly supported, learners then generate questions and hypotheses about their observations, plan an inquiry that allows them to verify or reject their hypotheses, and implement this plan within the simulation or microworld (de Jong & van Joolingen, 1998). On the basis of the learning environment’s response, the learners can analyze results and relate their findings to the explanation of the phenomena originally observed. In many cases, this results in the creation of new sets of questions and hypotheses, and a new cycle of inquiry (Lehrer & Schauble, 2006; Windschitl et al., 2008). In a few cases, researchers had concerns about the amount of time students took to learn how to use the simulation or game rather than learning about the subject (Leutner, 1993; Roth et al., 1996). However, the fact that active exploratory learning can be more effective than direct instruction challenges the broad assumption that all constructivist learning has failed (Kirschner, Sweller, & Clark, 2006).

**Affect in learning from simulations and microworlds.** Results from research on simulations and microworlds have included measures of affect as well as content or process learning. Studies showed, for example, that learners’ experienced emotions had an impact on cognition and learning outcomes (Plass et al., 2014; Um et al., 2012) and that learning from simulations can increase self-efficacy (Plass et al., 2009a; Tapia et al., 2007), interpersonal social-behavioral competence (Young & Upitis, 1999), and interest and motivation (Rutten et al., 2012). These findings provide evidence for the importance of considering the impact of affect, as well as affective outcomes, on multimedia learning and support the development of a cognitive-affective theory of learning with media (Moreno & Mayer, 2007; Plass et al., 2014).

**Social processes in learning from simulations and microworlds.** Social processes have emerged from research as another important component of learning with simulations and microworlds. In particular, more recent extensions of these environments, including gamelike features, affinity groups, and participatory aspects, make the consideration of social processes of collaboration and competition an increasingly relevant part of understanding how these environments enhance learning outcomes and how learners construct knowledge within them (Barab et al., 2005; Klopfer et al., 2004). In addition, research has highlighted the importance of distributed mentorship in affinity groups related to gaming, where players move fluently between the roles of mentor and mentee (Klopfer, 2008; National Research Council, 2011; Squire, 2006; Stevens, Satwicz, & McCarthy, 2008). Future models of multimedia learning, therefore, will need to include social processes in addition to cognitive processes.
Extending Cognitive Theory to Include Social and Affective Aspects of Learning

The results described in the preceding sections show that theoretical models of learning from simulations and microworlds must consider not only cognitive processes, but affective and social components as well. The INTERACT model (Domagk et al., 2010) emphasizes that interactivity in any multimedia environment is a dynamic process involving behavioral, cognitive/metacognitive, and affective factors. The expanded version pictured in Figure 30.3 additionally highlights socio-emotional activity. Because these components can be systematically varied and examined, INTERACT provides a useful framework for structuring systematic explorations of these factors (Domagk et al., 2010). In particular, the INTERACT model suggests that the effects of various components are iterative: not only does social and emotional activity affect cognitive processes, but cognitive processes, in turn, affect further social and emotional behavior.

Learning from Simulations and Microworlds: Limitations of Cognitive Load Theory

Results of research on simulations and microworlds highlight several limitations of the application of cognitive load theory (CLT), in its current conceptualization, for describing learning in exploratory environments. These limitations concern the goal-free approach and the redundancy principle, and they suggest that the broad critique of constructivist approaches to learning based on CLT (Kirschner et al., 2006) may be a result of conceptual limitations of the theory.
The goal-free approach of CLT is challenged by results such as those of a study involving a microworld on electrical fields, which showed that specific goals resulted in better learning than did general goals (Miller et al., 1999). This is in contrast to claims supported by CLT that goal-free scenarios introduce the least amount of extraneous cognitive load and therefore result in the best learning outcomes (Sweller, 1994).

Research on learning from simulations also showed that the integration of multiple representations, which CLT would describe as redundant, can lead to improved learning (van der Meij & de Jong, 2006) and that the frequency of gaze transitions between multiple representations is linked to increased comprehension and transfer (O’Keefe et al., 2012). Rather than being redundant, as CLT would suggest, information from multiple representations serves different, complementary functions in the learning process (Ainsworth & van Labeke, 2004).

With these challenges in mind, and considering the importance of social and affective processes previously described, the broad-based criticism by some CLT researchers of any constructivist approaches to learning appears to be due in part to the focus of CLT on cognitive processes only. CLT in its current form may therefore be unable to adequately address the broad range of outcomes that can result from model-based inquiry in exploratory environments. An extension of the theory that considers social and emotional processes, as well as related outcomes, is needed (Plass, Moreno, & Brünken, 2010).

**Implications of the Research for Instructional Design**

Evidence indicates that simulations and microworlds have the potential to function as rich learning environments, offering possibilities for supporting learners in the acquisition, construction of subject matter knowledge and competencies as well as 21st-century skills such as communication, collaboration, and critical thinking. Though many areas of research demand more rigorous investigation, existing studies offer a number of principles and recommendations for the design of simulation environments. A smaller body of empirical evidence exists with respect to microworlds and games; nevertheless, these principles may offer some starting points for those environments as well. We begin with general recommendations based on the research and offer some specific principles for the design of simulations.

**The use of inquiry learning environments.** Despite the educational potential of simulations, microworlds, and games that are based on them, these environments may not be appropriate for all topics, learners, or settings. For procedural skills such as learning to solve long division problems, for example, discovery should not be the starting point (de Jong, 2006). Rather, this approach is most valuable when the learning domain is a complex system with
many interacting variables (Gredler, 2004) for which the process of exploration is an aspect of the learning objective. Simulations and microworlds can provide access to learning experiences that are otherwise invisible, impractical, or impossible (Linn et al., 2010) and can have a positive impact on students’ interest and motivation (National Research Council, 2011).

Setting clear goals for learning. Clear learning goals and objectives are essential for fostering learning through simulation environments (National Research Council, 2011). On the most basic level, the goals of an environment should determine how information is designed, what tasks will be required of learners, and how the context of the environment can reflect these goals (Miller et al., 1999). The structure mapping effect suggests that features of a graphic representation have a direct effect on a learner’s mental model (Rasch & Schnotz, 2009; Schnotz & Bannert, 2003; Schnotz & Kürschner, 2007); in simulations and microworlds the underlying model is critical, and structural representations within the model should be designed with care.

Several useful principles for information design, interaction design, and the design of instructional guidance in simulation and microworld environments can be derived from the research previously considered. Table 30.1 presents these principles and lists supporting studies for each.

Simulations, microworlds, and the learning environment. Though instructional guidance in a simulation or microworld environment is commonly conceptualized as embedded within the digital environment itself, the importance of the educational context should not be overlooked (Hegarty, 2004). Simulations have been shown to be more effective as a supplement rather than a replacement for traditional classroom instruction (Bayraktar, 2002; Rutten et al., 2012; Smetana & Bell, 2012), and research on the effectiveness of simulations used in an integrated classroom context reveals that the design of the digital resource itself is only the first step (Plass et al., 2012). The instructional design of simulations and microworlds must also take into consideration how to prepare teachers to support students in the use of these resources, both in the classroom and in the world at large, as newer instantiations of simulations and microworlds flourish in mobile devices, after-school programs, and a range of online environments (Kafai et al., 2010; Kwah et al., 2012).

Limitations of Current Research and Implications for Future Research

Research on simulations and microworlds has provided important insights into cognitive aspects of learning with interactive multimedia environments and has, in particular, contributed to instructional design considerations for such environments. However, there are several conceptual and methodological issues that limit the generalizability of the existing research.
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Conceptual Limitations

One of the most important conceptual limitations relates to the definition of simulations, microworlds, and games and the distinction – or lack thereof – between them. For the purpose of this review, for example, we considered only interactive environments that were based on an underlying model of the phenomena presented. However, the terms simulation and microworld are frequently used to describe other multimedia learning environments, which makes meta-analyses and other comparisons of research findings difficult.

Related to the lack of conceptual clarity of definitions for simulations and microworlds is the question of how users interact with environments through the user interface. New technologies such as the MS Kinect system allow for the use of embodied, gesture-based interactions that considerably expand affordances of input approaches and will likely influence learning (Antle, Droumeva, & Ha, 2009; Homer et al., in press). However, systematic investigations of these modes of interaction in the context of simulations and microworlds are rare in the research literature to date.

Notably absent from research are investigations of the impact of the essential play activity in such environments. In the context of games we refer to learning mechanics (Plass et al., 2013c), which have been shown to affect learners’ motivational and learning outcomes (Plass et al., 2012). Instead of treating learning mechanics as a given, researchers need to make this topic a subject of investigation, for example, by studying interaction design features, such as types of controls and types and modes of system feedback, and other elements of the INTERACT model.

Methodological Limitations

The generalizability and applicability of the available research on simulations and microworlds is hampered by several methodological limitations of related studies. Even though investigations date back at least to the 1980s, many of these limitations echo those usually observed in an emerging new area of research, with a predominance of media comparison and exploratory studies. As the field matures, this exploratory work needs to be backed up by more systematic investigations that make possible generalizations for policy makers, educators, and learning designers.

One useful avenue for continued investigation is research on the cognitive, affective, and social impact of learning with simulations and microworlds (Mayer, 2011; O’Neil, Wainess, & Baker, 2005). This approach uses existing environments and explores their effectiveness in promoting human development and learning. Another type of investigation that should be expanded is research on design features of simulations and microworlds. Appropriate information design, interaction design, and instructional guidance design are all critical for the efficacy of such learning environments, and effectiveness
research is not very fruitful unless related empirically based design guidance is available to developers (Jacobson & Wilensky, 2006; Plass et al., 2009b). These studies will need to consider the subject matter, the characteristics of the target audience, and the setting of the intended use and will have to include cognitive, affective, and social variables as predictors or mediators of the intended learning outcomes. Moreover, learning analytics, based on the log files produced by these environments, can be used in more systematic ways to provide detailed accounts of the learning process and learners’ state and trait variables (Plass et al., 2013c), using simulations and microworlds as assessments of learning and related outcomes (Kröner, Plass, & Leutner, 2005; O’Neil et al., 2005).

Finally, although we have argued for the importance of the curricular integration of simulations and microworlds, research studies must be designed in such a way that they allow the attribution of learning gains to a simulation or microworld itself, rather than the combination of a simulation or microworld and the curriculum in which it is embedded (National Research Council, 2011).

**Conclusion**

In this chapter we have reviewed research on simulations and microworlds conducted over the past several decades. Although progress has been made and the research base is expanding, we concur with earlier reviews suggesting that much work remains to be done (National Research Council, 2011). Only a solid base of well-developed theory and empirical research will allow us to fulfill the vision of interactive, dynamic, and visual environments in which learners can individually and jointly construct knowledge and acquire skills in situated, meaningful interactions.

**Glossary**

*Agent-based microworld*: A microworld environment that uses simple, individual-level rules to create complex collective behaviors (Blikstein & Wilensky, 2009).

*Design pattern*: A general solution to a design problem that can be adapted and applied to many situations.

*Emotional design*: A method of using information design elements such as color and shape to influence emotion and, in turn, facilitate learning.

*Gamelike elements*: Features such as clear goals expressed as win states, feedback, reward systems, levels, leaderboards, and message boards, which are typical of games but can also be incorporated into other environments to enhance learning and motivation.
**Icon:** A representation (sign) that bears a perceptual similarity to the object it represents.

**Information design:** How information is presented, including choices such as visual versus verbal presentations, the selection of specific types of graphics, and the combination of text and visual elements.

**Interaction design:** The activities, or types of engagement, available to the learner in a multimedia environment.

**Microworld:** An interactive digital environment that enables users to explore and build or modify a runnable system and provides dynamic responses based on an underlying computational model.

**MMO:** A massively multi-player online game, an online virtual environment that allows simultaneous use by multiple participants.

**Model-based inquiry:** A multi-step interrogation of the model of a system, including observation of a phenomenon, generation of hypotheses explaining the phenomenon, an inquiry based on the hypotheses, and an analysis of data collected to inform understanding of the model.

**Simulation:** In multimedia studies, an interactive digital environment that allows users to manipulate specific variables or parameters and provides dynamic responses based on an underlying computational model.

**Symbol:** A representation (sign) in which the relationship with the object represented is arbitrary or defined by cultural convention rather than by perceptual similarity.

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