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Computer Games in Education

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computer games, video games, educational games, serious games, computer-based learning, instructional design, cognitive skill training

Abstract

Visionaries offer strong claims for the educational benefits of computer games, but there is a need to test those claims with rigorous scientific research and ground them in evidence-based theories of how people learn. Three genres of game research are (*a*) value-added research, which compares the learning outcomes of groups that learn academic material from playing a base version of a game to the outcomes of those playing the same game with one feature added; (*b*) cognitive consequences research, which compares improvements in cognitive skills of groups that play an off-the-shelf game to the skill improvements of those who engage in a control activity; and (*c*) media comparison research, which compares the learning outcomes of groups that learn academic material in a game to the outcomes of those who learn with conventional media. Value-added research suggests five promising features to include in educational computer games: modality, personalization, pretraining, coaching, and self-explanation. Cognitive consequences research suggests two promising approaches to cognitive training with computer games: using first-person shooter games to train perceptual attention skills and using spatial puzzle games to train two-dimensional mental rotation skills. Media comparison research suggests three promising areas where games may be more effective than conventional media: science, mathematics, and second-language learning. Future research is needed to pinpoint the cognitive, motivational, affective, and social processes that underlie learning with educational computer games.

Contents

INTRODUCTION TO COMPUTER GAMES FOR EDUCATION

Objective and Rationale for Scientific Research on Computer Games for Education

Every day, in households across the world, parents tell their children that they can play their video games after they do their homework. However, imagine a world in which playing video games is the assigned homework, as first suggested by Celeste Pilegard (Pilegard & Mayer 2018). Researchers studying computer games for learning are busy investigating the feasibility of using educational computer games to improve student learning of academic material and relevant cognitive skills. This article reviews the current state of this effort to scientifically study how to use computer games for educational purposes. As such, it provides examples of the application of the science of learning to education (Mayer 2011a).

Visionaries make exuberant claims for the power of computer games to revolutionize education (Gee 2007, McGonical 2011, Prensky 2006). For example, Prensky (2006, p. 4) asserted: "Kids learn more positive, useful things for their future from video games than they learn in school." Gee (2007, p. 10) argued: "Good games are problem-solving spaces that create deep learning—learning that is better than what we often see in schools."

In contrast to this optimistic view of computer games for education, some game researchers take a more cautious approach by raising the issue of the need for evidence to test these claims (Blumberg 2014, Honey & Hilton 2011, O'Neil & Perez 2008, Tobias & Fletcher 2011, Wouters & van Oostendorp 2017). For example, in a consensus report from the National Research Council, Honey & Hilton (2011, p. 21) concluded: "There is relatively little research evidence on the effectiveness of simulations and games for learning." In another review, Mayer (2011b, p. 281) lamented: "Many strong claims are made for the educational value of computer games, but there is little strong evidence to back up those claims."

In opting to take an evidence-based approach in this article, I seek to lay out the requirements of scientific research methodologies that can address fundamental questions about game-based learning and to summarize and systematize the existing research base on game-based learning. In short, my approach to understanding computer games for education is to focus on evidence and evidence-based theory rather than claims and promises.

The history of educational technologies—ranging from motion pictures in the early 1900s, to radio in the 1930s, to educational television in the 1950s, to programmed instruction in the 1960s—is rife with cycles of extravagant claims followed by large-scale implementation in schools followed by disappointing results and abandonment of the technology (Cuban 1986, Saettler 2004). Time will tell whether computer games will also fit into this well-worn script for cutting-edge educational technologies; however, today, we come equipped with research methods, evidence, and learning theories that can help us avoid the patterns of the past. In this case, we are better situated to use the tools of science to guide how we use the latest educational technology. This is the ultimate goal of this article.

Specifically, this review examines three basic research questions concerning computer games for education:

1. Which game features produce learning?
2. Do people learn anything useful from playing a computer game?
3. Do people learn academic material better from computer games or from conventional media?

In taking an evidence-based approach, this review addresses these questions by systematically reviewing research evidence and evidence-based theories of how people learn.

Theoretical Framework for Learning with Computer Games for Education

Transfer involves being able to take what you have learned in one context and apply it to solve problems or learn in a new context (Mayer 2011a, Singley & Anderson 1989). Stimulating learning in ways that promote transfer is a fundamental mission of most educational enterprises (Pellegrino & Hilton 2012). In short, transfer is at the heart of learning and, as such, has a long history both in psychology and in education.

Consider what happens when someone is presented with an educational experience such as reading a textbook, viewing a slideshow lecture, interacting with a computer-based tutorial, or even playing an educational game. These are all examples of multimedia learning scenarios, because the presented instructional material involves both words (in printed or spoken form) and pictures (such as graphics, animations, or video). **Figure 1** provides a model of how learning works in these kinds of multimedia learning situations based on three basic principles from the science of learning (Mayer 2011a, 2014): (*a*) the dual channels principle, according to which people have separate channels for processing visual and verbal material; (*b*) the limited capacity principle, according to which people can process only a small amount of material in each channel at one time; and (*c*) the active processing principle, according to which deep learning occurs when people engage in

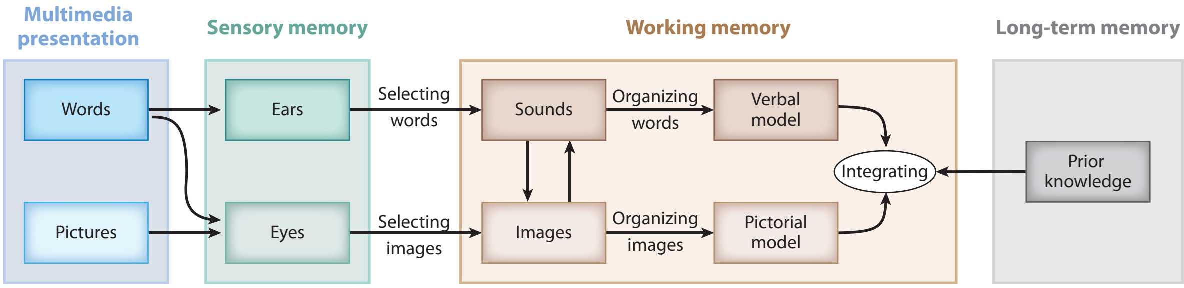

Figure 1

Cognitive model of multimedia learning. This model summarizes the cognitive processes and mental representations involved in multimedia learning.

active cognitive processing during learning. Examples of this active cognitive processing include attending to relevant incoming material (i.e., selecting), mentally organizing it into a coherent representation (i.e., organizing), and connecting the incoming material with relevant existing knowledge activated from long-term memory (i.e., integrating).

In **Figure 1**, the words and pictures in instructional material (such as a computer game delivered on the screen of a desktop computer, tablet, smartphone, or game console) enter the learner's visual sensory memory (through the eyes) and auditory sensory memory (thorough the ears), where they quickly fade. If the learner attends to this fleeting information, some of it is transferred to working memory for further processing (selecting). In working memory, the learner can mentally organize the incoming words into a verbal model and the incoming images into a pictorial model (organizing) and connect these verbal and pictorial representations with each other and with relevant prior knowledge activated from long-term memory (integrating). The resulting constructed knowledge is fit into long-term memory for storage.

When people play an educational computer game, they can allocate their limited processing capacity among three kinds of cognitive processing: (*a*) Extraneous processing is cognitive processing that does not serve the instructional objective and is caused by poor instructional design (such as when a game has many distracting features), (*b*) essential processing is cognitive processing needed to mentally represented the relevant material and is caused by the complexity of the to-be-learned content, and (*c*) generative processing is cognitive processing aimed at trying to make sense of the material and is caused by the player's motivation to exert effort. Computer games may be particularly helpful in fostering generative processing but are susceptible to creating extraneous processing. The goal of the instructional design of educational computer games is to minimize extraneous processing, guide essential processing, and foster generative processing.

To better understand game-based learning, two important additional elements need to be added to this cognitive model of multimedia learning: motivation and metacognition. First, motivation refers to the learner's willingness to exert effort to learn the material and is defined as an internal state that initiates and maintains goal-directed behavior (Mayer 2011a, 2014). In **Figure 1**, motivation is the force behind the activation of each of the arrows—that is, the force that initiates and maintains the processes of selecting, organizing, and integrating. An advantage of educational computer games is their supposed motivating power. An educational game is motivating to the extent that people opt to play it, persist in playing it, and exert effort to master it.

There are five classes of motivational theories that contribute to explaining the motivational power of games (Mayer 2014, Wentzel & Miele 2016):

1. Interest and value theories: People exert effort to learn when they are interested in and find personal importance in the learning task or material.
2. Self-efficacy and attribution theories: People exert effort to learn when they see themselves as competent for the task and believe that their efforts will lead to success.
3. Goal orientation theory: People exert effort to learn when their goal is to master the learning task or material.
4. Self-determination and intrinsic motivation theories: People exert effort to learn when they feel control over the learning task and when they experience internal rewards.
5. Social cue and embodiment theories: People exert effort when they experience a social partnership with the instructor and when they can use their whole body during learning.

Although progress is being made in incorporating motivational and affective processes into the cognitive theory of multimedia learning, as reflected in Moreno & Mayer's (2007) Cognitive Affective Model of Learning with Media (CAMLM), more work is needed to build an integrated model of game-based learning.

Second, metacognition refers to learners' awareness and control of their cognitive processing during learning (Mayer 2011a). Per **Figure 1**, metacognition refers to monitoring the cognitive processes of selecting, organizing, and integrating, as well as coordinating these processes and adjusting them as needed to achieve the learning goal. A suggested advantage for game-based learning is that players become self-regulated learners who take responsibility for monitoring and controlling their cognitive processing during game play. Research on game-based learning may be able to shed light on how to better incorporate metacognitive processes into cognitive theories of learning.

Three Genres of Scientific Research on Computer Games for Education

Given the need for evidence to test the claims about game-based learning, the field needs a solid evidence base gleaned from methodologically rigorous research on computer games for education. There is consensus that scientific research in education should "use methods that permit direct investigation of the question" (Shavelson & Towne 2002, p. 3). For research questions concerning instructional effectiveness—including the instructional effectiveness of playing computer games—the most appropriate research methodology is to conduct experiments (Phye et al. 2005). Therefore, in this review, I focus on experimental studies that meet the requirements of random assignment, experimental control, and appropriate measures (Mayer 2011a). In the case of game research, random assignment means that the participants are placed in the experimental and control groups based on a random procedure (e.g., rather than simply comparing pre-existing experts and novices in game play); experimental control means that the experimental and control groups are identical on all features except the one under investigation (e.g., rather than simply examining pretest-to-posttest gains for an experimental group with no comparable control group); and appropriate measures means that the groups are tested on measures of learning outcome or skill performance (e.g., rather than relying on self-report measures). Observational studies can add richness, and multiple methods are recognized as worthwhile (Shavelson & Towne 2002), but given the preliminary state of the field of game research, the present review focuses solely on experimental studies.

As is customary in research on instructional effectiveness, I focus on effect size as an important metric, with a special focus on treatments that cause an effect size of $d = 0.4$ or greater (Hattie 2009, Mayer 2011a). In the case of game research, Cohen's d (Cohen 1988) is computed by subtracting the mean score of the control group from the mean score of the experimental group (based on a measure of learning outcome or skill performance) and dividing by the pooled standard deviation, yielding a value of by how many standard deviations the experimental group differed from the control group.

Table 1 Three genres of scientific research on computer games for education

Type of research	Description	Research question
Value-added research	Compare the learning outcome of a group that plays the base version of a game (control group) to that of a group that plays the same game with one feature added (experimental group).	Does adding feature X to a game cause improvements in learning?
Cognitive consequences research	Compare the cognitive skill gain of a group that plays an off-the-shelf game for an extended time period (experimental group) to that of a group that engages in a control activity (control group).	Does playing game X cause improvements in skill Y?
Media comparison research	Compare the learning outcome of a group that receives academic content by playing a game (experimental group) to that of a group that receives the same academic content via conventional media (control group).	Do people learn academic material better with a game or with conventional media?

Table 1 lists three genres of experimental studies on the instructional effectiveness of computer games for education: value-added research, cognitive consequences research, and media comparison research. In value-added research, the primary research question concerns which game features cause improvements in student learning, that is, which features are the active ingredients responsible for fostering learning. To answer this research question, the control group plays a base version of an educational game, whereas the experimental group plays the same game with one feature added. We consider the added feature to be promising if the experimental group achieves a higher posttest score on the academic material provided in the game than the control group, with an effect size greater than or equal to 0.4. A looming challenge in value-added research is to control for time on task when one group may be primed to engage in more activities than another, thereby threatening the requirement of experimental control.

In cognitive consequences research, the primary research question concerns whether playing an off-the-shelf computer game (i.e., experimental group) causes improvements in a targeted cognitive skill relative to a control group that engages in a control activity such as playing a game that does not appear to require the targeted skill (active control group) or not playing any game (passive control group). We consider the game to be promising if the experimental group shows a greater pretest-to-posttest gain on a targeted cognitive skill than the control group, with an effect size greater than or equal to 0.4. A looming challenge in cognitive consequences research is to choose an appropriate control activity and thus respect the requirement of experimental control. Cross-sectional studies comparing expert and novice players violate the requirement of random assignment, making it difficult to make causal attributions about any differences in cognitive skill performance.

In media comparison research, the primary research question concerns whether people learn academic content better from playing games than from conventional media. To answer this question, we compare the learning outcomes of an experimental group, which plays a game that contains the targeted academic material, to those of a control group, which receives the same academic material via conventional media such as a textbook lesson, an online narrated animation, or a face-to-face slideshow presentation. We consider the game to be more effective than conventional instruction if the experimental group outperforms the control group on learning outcome measures, with an effect size greater than or equal to 0.4. However, even if the experimental and control groups produce equivalent learning outcome performance, this may be considered support for game-based learning in light of the proposal that students are more likely to initiate and persist with playing a game than viewing a conventional lesson. A looming challenge in media comparison research is to equate the experimental and control groups in terms of instructional content and instructional method, which reflects the requirement of experimental control (Clark 2001).

Figure 2

Screenshot from *Design-a-Plant*, an educational computer game aimed at teaching environmental science principles about plant growth in different environments.

For each genre of game research, it is worthwhile to examine the boundary conditions for the effects, such as whether the size of the effect differs for different kinds of learners, academic content, or learning contexts. The next three sections of this review examine the evidence generated by each of the three genres of educational computer game research.

VALUE-ADDED RESEARCH ON COMPUTER GAMES IN EDUCATION

Description and Example of Value-Added Research

Consider a desktop computer game in which you travel to a distant planet that has certain environmental conditions (such as frequent rain and wind), and you are asked to design a plant that will survive there by choosing appropriate roots, stem, and leaves. Then you watch an animation of what happens to your plant, as a local inhabitant, Herman-the-Bug, explains the mechanics of plant growth through onscreen captions. This is the kind of scenario encountered in the game *Design-a-Plant*, as shown in **Figure 2** (Moreno et al. 2001). What would happen if you changed from having Herman's words presented as onscreen text to having Herman's words presented as speech? This is a value-added question because we want to know whether changing from printed text (control group) to spoken text (experimental group) will affect learning. In this case, learning is assessed by showing the learner a plant with certain roots, leaves, and stem, and asking the learner to specify which kind of environmental conditions would be best for the plant's growth. In a series of nine experiments, students performed better on a learning outcome posttest if they played *Design-a-Plant* with spoken words rather than printed words, yielding an average effect size of $d =$ 1.4 (Moreno & Mayer 2002, Moreno et al. 2001). In this way, value-added methodology allows us to pinpoint an effective feature of the *Design-a-Plant* game—using spoken rather than printed text.

Objective of Value-Added Research

Value-added experiments are intended to answer the basic question: Which game features promote learning? Thus, the primary goal of value-added research is to pinpoint features that improve the instructional effectiveness of a computer game. Overall, value-added research has implications for the instructional design of computer games because it generates an evidence base that suggests promising features to include and unpromising features to avoid.

Table 2 Five promising features of computer games in education

Feature	Description	Experiments in which the effect is observed	Effect size
Modality	Use spoken text.	9 out of 9 experiments	1.4
Personalization	Use conversational language.	8 out of 8 experiments	1.5
Pretraining	Provide pregame information.	7 out of 7 experiments	0.8
Coaching	Provide in-game advice and feedback.	12 out of 15 experiments	0.7
Self-explanation	Prompt players to explain or reflect.	13 out of 16 experiments	0.5

Review of Value-Added Research

Although value-added research on educational games is in its initial stages, we can examine what the current state of the evidence tells us about promising features (i.e., features that boost learning outcome scores by at least an average of 0.4 standard deviations across at least five experiments). Based on a review by Mayer (2014), **Table 2** lists five promising features.

First, across nine out of nine experiments all conducted in the same lab with *Design-a-Plant* (Moreno & Mayer 2002, Moreno et al. 2001), students learned better in a computer game when words were spoken rather than printed on the screen, yielding an average effect size of 1.4.

Second, across eight out of eight experiments (Cordova & Lepper 1996; Moreno & Mayer 2000, 2004; Wang et al. 2008), students learned better in a computer game when words were presented in conversational style (e.g., using first- and second-person constructions involving terms like "I," "you," or "your") than formal style (e.g., using third-person constructions), yielding an average effect size of 1.5.

Third, across seven out of seven experiments (de Jong et al. 1999, Fiorella & Mayer 2012, Leutner 1993, Mayer et al. 2002, Swaak et al. 1998), providing students with pregame information such as the names and descriptions of the key concepts in the lesson resulted in better learning posttest scores, yielding an average effect size of 0.8.

Fourth, across 12 out of 15 experiments (Adams & Clark 2014, Cameron & Dwyer 2005, Goldberg & Cannon-Bowers 2015, Leutner 1993, Mayer & Johnson 2010, Moreno & Mayer 2005, Serge et al. 2013, ter Vrugte et al. 2015, Van Eck & Dempsey 2002, Vandercruysee et al. 2016), providing advice or explanative feedback during the game resulted in better learning posttest scores, yielding an average effect size of 0.7.

Fifth, across 13 of 16 experiments (Adams & Clark 2014, Clark et al. 2016, Fiorella & Mayer 2012, Hsu & Tsai 2013, Hsu et al. 2016, Johnson & Mayer 2010, Lee & Chen 2009, Mayer & Johnson 2010, Moreno & Mayer 2005, O'Neil et al. 2014, Pilegard & Mayer 2016, ter Vrugte et al. 2015), providing prompts for players to write or select explanations during the game resulted in better learning posttest scores, yielding an average effect size of 0.5. The effect was stronger for college students than for younger students, presumably because of the challenges of engaging in self-explanation.

We can also consider three unpromising features, i.e., features that do not boost learning outcome scores by at least an average of 0.4 standard deviations across at least five experiments. First, one game feature that has attracted research attention is the level of realism. In a review, Wouters & van Oostendorp (2017) reported a strong effect size greater than 1 favoring cartoon-like representations rather than photo-realistic representations based on 10 comparisons. Similarly, Mayer (2014) reported that, in five out of six comparisons, students learned better when games were rendered on a desktop computer screen than in immersive virtual reality, with a median effect size of −0.1. A straightforward conclusion is that realism added for its own sake is not a promising game feature when the goal is to improve learning outcomes.

Other game features that have attracted research attention include collaboration (i.e., playing in dyads or groups versus playing individually) and narrative theme (i.e., playing a game that has a strong story line versus playing one that does not). However, in a review, Wouters & van Oostendorp (2017) reported a negligible effect size of under $d = 0.2$ for collaboration based on 18 comparisons and for narrative theme based on 9 observations. A straightforward conclusion is that the research evidence base does not yet justify adding collaboration or narrative theme when the goal is to greatly improve learning, although these features do not appear to harm learning and may be helpful for certain kinds of learners.

Limitations and Future Directions

The previous section demonstrates the potential of value-added research for identifying design features that can increase the instructional effectiveness of computer games in education. Work is needed to add to the research base, including with replication studies using different games and based on different instructional goals. Work is also needed to pinpoint the conditions under which each feature is most helpful, e.g., for which kinds of learners or instructional objectives. Finally, work is needed to help explain how the features work; that is, we need research on the cognitive and motivational processes underlying game-based learning. This line of research requires techniques for measuring cognitive and motivational processes during learning, including eye tracking, physiological measurements, and cognitive neuroscience measures such as electroencephalography or functional magnetic resonance imaging. In summary, continued value-added game research offers the potential to create a powerful research base, pinpoint boundary conditions for each promising feature, and help us understand how features affect the learning process.

COGNITIVE CONSEQUENCES RESEARCH ON COMPUTER GAMES FOR EDUCATION

Description of Cognitive Consequences Research

Portal is a computer game in which players must move through a succession of chambers by bouncing off of and traveling through portals that they create. For example, **Figure 3** shows a screenshot of chamber 13 in the game. *Portal* can be used to improve students' intuitions for physics principles about force and motion, as well as their spatial cognition skills. What happens when students play *Portal* for an hour? Across two experiments, Adams et al. (2016) found that students playing *Portal* did not demonstrate greater increases than a control group on tests of physics intuitions, spatial cognition skills, or even the ability to learn from a physics lesson. In short, there was no strong evidence that playing *Portal* for a short time has positive cognitive consequences.

Next, suppose you are playing a desktop computer game in which friendly space aliens are coming down from the top of the screen. The red ones are hungry, so you should shoot food up to them by aiming and pressing a food button, but the blue ones are thirsty, so you should shoot drinks up to them by aiming and pressing the drinks button. Throughout the game, the rules change, e.g., by reversing the rule or basing the rule on a new feature (e.g., aliens with one eye are hungry and aliens with two eyes are thirsty). The game has levels of increasing challenge in which you must rapidly change from one rule to another, as shown in **Figure 4**. This game is now called *All You Can ET*, and it is intended to teach the executive function skill of shifting—being able to shift attention from one task to another rapidly and effectively (Parong et al. 2018). Across two experiments, students who played *All You Can ET* for two hours across four sessions showed greater improvements on cognitive tests of shifting than did a control group that played a word search game, yielding effect sizes of $d = 1.4$ and $d = 0.8$.

Figure 3

Screenshot from *Portal*, a game that can be used to teach physics principles about force and motion.

These are examples of cognitive consequences research, the goal of which is to determine whether playing an off-the-shelf (or custom-designed) computer game can improve educationally relevant cognitive skills or competencies. In one case, game playing does not appear to produce positive effects, but in another it does, so in this section I investigate when game playing has positive consequences.

Objective of Cognitive Consequences Research

As you can see from the above examples, cognitive consequences experiments are intended to answer the basic research question of whether people learn anything useful from playing computer games. Thus, the primary goal of cognitive consequences research is to pinpoint which kinds of

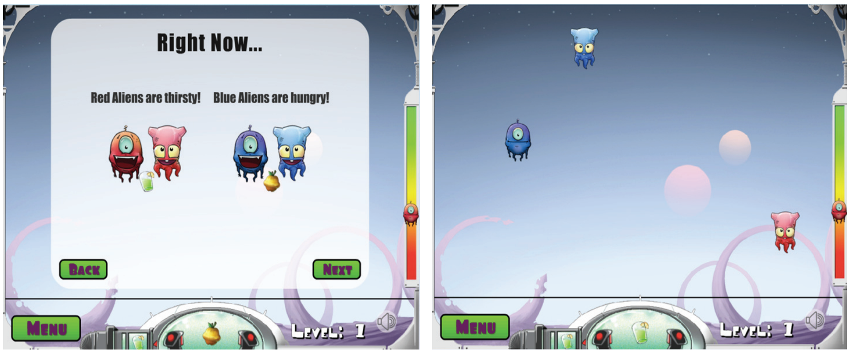

Figure 4

Screenshots from *All You Can ET*, an educational computer game aimed at improving students' executive function skill in switching between cognitive tasks.

Table 3 Two promising cognitive consequences of playing computer games

Type of game	Cognitive skill	Experiments in which the effect is observed	Effect size
First-person shooter	Perceptual attention	17 out of 18 experiments	1.2
Spatial puzzle	Two-dimensional mental rotation	6 out of 6 experiments	0.8

computer games affect which kinds of cognitive skills. Cognitive consequences research has implications for the choice of computer games that have positive impacts on educationally relevant skills performed outside the game environment. According to the theory of specific transfer of general skill, the best chance for positive cognitive consequences of game playing occurs when the cognitive test evaluated outside the game environment taps a skill that was repeatedly exercised within the game in a variety of contexts and at increasing levels of challenge (Anderson & Bavelier 2011, Mayer 2014, Sims & Mayer 2002, Singley & Anderson 1989). In short, in cognitive consequences research, we look for computer games that appear to require players to exercise an important cognitive skill.

Review of Cognitive Consequences Research

Although cognitive consequences research focuses on off-the-shelf games that were designed for entertainment rather than training of cognitive skills or learning outcomes, the research provides some examples of games that improve cognitive skill scores by at least an average of 0.4 standard deviations across at least five experiments. Based on a review by Mayer (2014), **Table 3** lists two promising cognitive consequences findings.

First, people who were assigned to play first-person shooter games (e.g., *Unreal Tournament* or *Medal of Honor*) for an extended period of time (e.g., 10 h or more) performed better on perceptual attention tasks (e.g., useful field of view) than people assigned to play a control game or no game in 17 of 18 comparisons, yielding a large average effect size greater than 1 (Boot et al. 2008; Feng et al. 2007; Green & Bavelier 2003, 2006a,b, 2007; Li et al. 2009; Nelson & Strachan 2009; Wu et al. 2012). Other recent reviews of the cognitive consequences of playing first-person shooter games also identified substantial effects on perceptual attention (Bediou et al. 2018, Powers & Brooks 2014, Wang et al. 2017). This is the single strongest and most consistent cognitive consequences finding in the research literature. Interestingly, playing first-person shooter games has not been shown to have consistently useful effects on some other cognitive measures. This is consistent with the theory of specific transfer of general cognitive skills, in which the skills that are repeatedly practiced in the game are the ones that are most likely to transfer to nongame contexts.

Second, in six out of six comparisons, people who were assigned to play the spatial puzzle game *Tetris* for an extended period (e.g., 6 h or more) scored higher on mental rotation tests of two-dimensional shapes (including shapes like those in the game) than people who were assigned to not play *Tetris*, yielding an average effect size of 0.8 (Boot et al. 2008, Okagaki & Frensch 1994, Sims & Mayer 2002). Interestingly, playing *Tetris* does not have a similar effect on mental rotation of three-dimensional shapes, other kinds of spatial cognition tasks, perceptual attention, reasoning, or memory tasks (Boot et al. 2008, Pilegard & Mayer 2018, Sims & Mayer 2002). This is also consistent with the theory of specific transfer of general skills.

As you can see, there are not a lot of promising connections between game playing and cognitive skills. Mayer's (2014) review revealed several unpromising connections (i.e., games that do not boost learning outcome scores by at least an average of 0.4 standard deviations across at least five experiments): brain training games with perceptual attention, brain training games with spatial cognition, spatial puzzle games with perceptual attention, spatial puzzle games with spatial cognition, real-time strategy games with perceptual attention, and real-time strategy games with executive function.

Brain training games such as *Lumosity* and *CogMed* contain a suite of mini-games intended to improve performance on basic cognitive tests such as memory, attention, and spatial cognition. However, reviews conclude that there is no convincing evidence to show that these kinds of brain training games are successful (Bainbridge & Mayer 2018, Melby-Lervåg & Hulme 2012, Simons et al. 2016). One problem may be that these games involve a collection of different games aimed at different cognitive skills rather than promoting repeated practice on a single, focused skill.

In contrast, there are several initial studies showing that playing brain training games that are focused on specific executive function skills (such as switching from one task to another) can have strong and consistent effects (Anguera et al. 2013, Nouchi et al. 2012, Parong et al. 2018); this is an area that warrants further study. A potentially fruitful line of research involves examining the cognitive consequences of playing computer games that are focused on a single cognitive skill and that require repeated practice of that skill in varying contexts and at increasing levels of challenge.

Limitations and Future Directions

More than 30 years ago, when *Pac-Man* was the game of the day, Loftus & Loftus (1983, p. 121) wondered whether people learn anything useful from playing video games: "It would be comforting to know that the seemingly endless hours young people spend playing Defender and Pac-Man were teaching them something useful." Currently, cognitive consequences research is beginning to provide a somewhat disappointing answer. There is little evidence that game playing improves cognitive skills besides a couple of promising effects listed in **Table 3** (i.e., first-person shooter games improve perceptual attention skills and *Tetris* improves two-dimensional mental rotation skill), and a potentially important effect in which specially designed games that focus on a specific executive function skill may be effective. The next generation of cognitive consequences research should examine how to design focused games that look like commercial games but are designed based on cognitive principles of skill learning to train people on educationally worthwhile skills.

MEDIA COMPARISON RESEARCH ON COMPUTER GAMES FOR EDUCATION

Description of Media Comparison Research

Consider a sixth grader, Sam, who is learning about decimal arithmetic. We ask Sam to order the decimals from smallest to largest: 0.217, 0.7, 0.30. Sam responds: 0.7, 0.30, 0.217. This suggests that Sam has the misconception that longer decimals are larger, which is common in his cohort (McLaren et al. 2017). Suppose we ask Sam to play a computer game, *Decimal Point*, that has been designed to help students confront and correct common misconceptions. In *Decimal Point*, the player travels through an amusement park and stops to play at various attractions along the arcade. For example, in the Balloon Pop booth (shown in **Figure 5**), the player arranges balloons with decimals on them from smallest to largest and makes corrections by throwing darts at balloons that are out of order. Each arcade game in the amusement park helps the player learn about

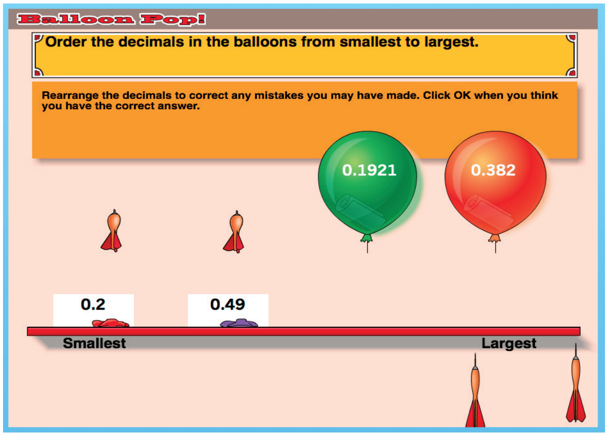

Figure 5

Screenshot from *Decimal Point*, an educational computer game aimed at teaching decimal fractions and decimal arithmetic.

how to overcome a different possible misconception. By the time players have made their way through Decimal Point Amusement Park, they have had a lot of practice in solving decimal problems.

McLaren et al. (2017) found that sixth graders who were asked to play *Decimal Point* showed significantly greater improvement on an immediate test ($d = 0.4$) and a delayed test ($d = 0.4$) than did a group that learned from a conventional computer-based tutorial lesson covering the same problems but in a different format than an arcade game. Importantly, students who played the game reported much higher levels of enjoyment ($d = 0.9$), suggesting that they might be more likely to initiate playing the game on their own and persist with it than students who received the conventional computer-based tutorial lesson. This is an example of media comparison research because we compare the learning outcomes of students who learn academic content from a game to those of students who learn the same content from conventional media.

Objective of Media Comparison Research

As you can see from the example in the previous section, media comparison experiments are intended to address the fundamental research question of whether people learn academic material better from computer games than from conventional media. Thus, the objective of media comparison research is to determine whether learning academic content with computer games is as effective as or even more effective than learning with conventional media, such as a computer-based lesson. In short, media comparison research attempts to answer questions about whether games can replace traditional education, as has been suggested by game proponents (Gee 2007, McGonigal 2011, Prensky 2006).

In media comparison research, a major challenge is to ensure that the game group and the conventional group receive the same content material and method of instruction, so that the only difference between the groups is the medium that is used to deliver the content (Clark 2001). Difficulties in achieving this level of experimental control have given media comparison research a somewhat unfavorable reputation throughout the history of educational technology (Clark 2001, Saettler 2004), so the goal is to review methodologically sound research in this section.

Table 4 Three disciplines in which playing games may be more effective than conventional instruction

Discipline	Experiments in which the effect is observed	Effect size
Science	12 out of 16 experiments	0.7
Mathematics	4 out of 6 experiments	0.5
Second language	4 out of 5 experiments	1.0

Review of Media Comparison Research

In conducting a review of published media comparison studies, we are interested in which disciplines produce findings showing that students learn better from playing games than from conventional media by at least an average of 0.4 standard deviations across at least five experiments. Based on a review by Mayer (2014), **Table 4** lists three promising media comparison findings.

First, the most-studied educational discipline is science, in which learning by playing games produced higher test scores than learning from conventional lessons in 12 out of 16 experiments, with an average effect size of 0.7 (Adams et al. 2012, Anderson & Barnett 2011, Barab et al. 2009, Brom et al. 2011, Evans et al. 2008, Hickey et al. 2009, Hwang et al. 2012, Moreno et al. 2001, Parchman et al. 2000, Ricci et al. 1996, Swaak et al. 2004, Wrzesien & Raya 2010). The conventional lessons included online tutorials, slideshow presentations, printed lessons, and face-to-face lectures. In each of the four instances in which a conventional medium was more effective than playing a game, the conventional medium involved computer-based instruction such as a hypertext, a computer-based slideshow, or a computer-based tutorial. This suggests that caution is necessary in assuming that computer games are always the most effective form of computer-based science learning.

Second, in reviewing mathematics studies, games resulted in better learning than conventional media in four out of six experiments, with an average effect size of 0.5 (Chang et al. 2012, Din & Calao 2001, McLaren et al. 2017, Papastergiou 2009, Sindre et al. 2009, Van Eck & Dempsey 2002). The control groups received classroom instruction, computer-based lessons, or paper-based worksheets. The effects tended to be greater for children than for college students.

Third, in four out of five experiments involving learning a second language, students learned better from games than from traditional media, yielding an average effect size of 1.0 (Liu & Chu 2008, Neri et al. 2008, Segers & Verhoeven 2003, Suh et al. 2010, Yip & Kwan 2006). However, the control group in each study involved classroom instruction, which may be hard to equate to game-based learning in terms of content and method.

Insufficient numbers of experiments are available in social studies and English language arts, although the existing evidence favors games in both disciplines (Mayer 2014).

Limitations and Future Directions

Overall, media comparison research must be interpreted in light of the difficulty in establishing adequate control groups and the potential for publication bias favoring significant media effects. The available evidence provides no reason to conclude that games are generally inferior to traditional instruction and some reason to suspect that games can be as effective or more effective than traditional instruction for certain instructional domains and objectives. Future research is needed in which the control group receives the same material as the game group; this can best be accomplished with computer-based tutorials and presentations rather than normal classroom activity. In addition, it is worthwhile to determine whether games also afford greater motivational outcomes, which manifest in students being more likely to initiate game play and persist with the

Table 5 An agenda for research on game-based learning

Item	Description
Replicate	Conduct methodologically sound replication studies with different games to create an adequate research base.
Analyze	Determine whether effects are stronger for certain types of learners, types of content, types of learning objectives, and learning contexts.
Contextualize	Determine how best to integrate games within existing formal and informal educational settings.
Explain	Determine how game playing affects learning, including effects on cognitive and motivational processing during learning, as measured with eye tracking, physiological measures, and brain-based measures.
Integrate	Determine how cognitive and motivational factors interrelate in game-based learning.

activity than they are with conventional media. Finally, research is needed to determine how to incorporate games most effectively into the regular classroom context.

AN AGENDA FOR SCIENTIFIC RESEARCH ON COMPUTER GAMES FOR EDUCATION

Research and theory on game-based learning are in their early stages, but this review demonstrates how the research methods and evidence-based theories of psychology can contribute to them. This review shows the value of the three game research paradigms of value-added research, cognitive consequences research, and media comparison research, as well as the value of following rigorous experimental methodologies to address fundamental research questions about game-based learning.

Table 5 offers a modest research agenda that includes conducting replication studies to increase the research base; conducting factorial experiments and analyses that allow us to establish boundary conditions for key effects; conducting research in actual formal and informal learning contexts, including measures of cognitive and motivational processes during learning, to understand the theoretical mechanisms underlying game-based learning; and figuring out how to integrate cognitive and motivational factors into the design of game-based learning.

CONCLUSION

In conclusion, this review provides examples of the benefits of applying the science of learning to education. This review demonstrates the progress being made by value-added research, which addresses the question of which game features promote learning; cognitive consequences research, which addresses the question of what is learned by playing games; and media comparison research, which addresses the question of whether people learn better from games than from conventional media. The benefit to practice is that psychology can offer education ways to improve the instructional effectiveness of educational games (Mayer 2016). The benefit to theory is that education can prompt psychology to enrich cognitive theories of learning to explain a broader set of learning situations and to incorporate motivational processes (Mayer 2014). I will consider this review a success to the extent that it stimulates research on game-based learning that is methodologically sound, theoretically grounded, and educationally relevant.

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LITERATURE CITED

Adams DM, Clark DB. 2014. Integrating self-explanation functionality into a complex game environment: keeping the gaming in motion. *Comput. Educ.* 73:149–59

Adams DM, Mayer RE, MacNamara A, Koening A, Wainess R. 2012. Narrative games for learning: testing the discovery and narrative hypotheses. *J. Educ. Psychol.* 104:235–49

Adams DM, Pilegard C, Mayer RE. 2016. Evaluating the cognitive consequences of playing *Portal* for a short duration. *J. Educ. Comput. Res.* 54:173–95

Anderson AF, Bavelier D. 2011. Action game play as a tool to enhance perception, attention, and cognition. In *Computer Games and Instruction*, ed. S Tobias, JD Fletcher, pp. 307–33. Charlotte, NC: Inf. Age Publ.

Anderson J, Barnett M. 2011. Using video games to support pre-service elementary teachers learning of basic physics principles. *J. Sci. Educ. Technol.* 20:347–62

Anguera JA, Boccanfuso J, Rintoul JL, Al-Hashimi O, Faraji F, et al. 2013. Video game training enhances cognitive control in older adults. *Nature* 501(7465):97–101

Bainbridge K, Mayer RE. 2018. Shining the light of research on Lumosity. *J. Cogn. Enhanc.* 2:43–62

Barab SA, Scott B, Siyahhan S, Goldstone R, Ingram-Goble A, et al. 2009. Transformational play as a curricular scaffold: using videogames to support science education. *J. Sci. Educ. Technol.* 18:305–20

Bediou B, Adams DM, Mayer RE, Tipton E, Green CS, Bavelier D. 2018. Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychol. Bull.* 144(1):77–110

Blumberg FC, ed. 2014. *Learning by Playing*. Oxford, UK: Oxford Univ. Press

Boot WR, Kramer AF, Simons DJ, Fabian M, Gratton G. 2008. The effects of video game playing on attention, memory, and executive control. *Acta Psychol.* 129:387–98

Brom C, Preuss M, Klement D. 2011. Are educational computer micro-games engaging and effective for knowledge acquisition at high schools? A quasi-experimental study. *Comput. Educ.* 57:1971–88

Cameron B, Dwyer F. 2005. The effect of online gaming, cognition and feedback type in facilitating delayed achievement of different learning objectives. *J. Interact. Learn. Res.* 16:243–58

Chang K-E, Wu L-J, Weng S-E, Sung Y-T. 2012. Embedding game-based problem-solving phase into problem-posing system for mathematics learning. *Comput. Educ.* 58:775–86

Clark DB, Virk SS, Barnes J, Adams DM. 2016. Self-explanation and digital games: adaptively increasing abstraction. *Comput. Educ.* 103:28–43

Clark RE. 2001. *Learning from Media*. Charlotte, NC: Inf. Age Publ.

Cohen J. 1988. *Statistical Power Analysis for the Behavioral Sciences*. Mahwah, NJ: Lawrence Erlbaum. 2nd ed.

Cordova DI, Lepper MR. 1996. Intrinsic motivation and the process of learning: beneficial effects of contextualization, personalization, and choice. *J. Educ. Psychol.* 88:715–30

Cuban L. 1986. *Teaching and Machines: The Classroom Use of Technology since 1920*. New York: Teach. Coll. Press

de Jong T, Martin E, Zamarro J, Esquembre F, Swaak J, van Joolingen WR. 1999. The integration of computer simulation and learning support: an example from the physics domain of collisions. *J. Res. Sci. Teach.* 36:597–615

Din FS, Calao J. 2001. The effects of playing educational video games on kindergarten achievement. *Child Study J.* 31:95–102

Evans KL, Yaron D, Leinhardt G. 2008. Learning stoichiometry: a comparison of text and multimedia formats. *Chem. Educ. Res. Pract.* 9:208–18

Feng J, Spence I, Pratt J. 2007. Playing an action video game reduces gender differences in spatial cognition. *Psychol. Sci.* 18(10):850–55

Fiorella L, Mayer RE. 2012. Paper-based aids for learning with a computer-based game. *J. Educ. Psychol.* 104:1074–82

Gee JP. 2007. *Good Video Games and Good Learning*. New York: Peter Lang

Goldberg B, Cannon-Bowers J. 2015. Feedback source modality effects on training outcomes in a serious game: pedagogical agents make a difference. *Comput. Hum. Behav.* 52:1–11

Green CS, Bavelier D. 2003. Action video game modifies visual selective attention. *Nature* 423:534–38

Green CS, Bavelier D. 2006a. Effects of action video game playing on the spatial distribution of visuospatial attention. *J. Exp. Psychol. Hum. Percept. Perform.* 32:1465–78

Green CS, Bavelier D. 2006b. Enumeration versus multiple object tracking: the case of action video game players. *Cognition* 101:217–45

Green CS, Bavelier D. 2007. Action-video-game experience alters the spatial resolution of vision. *Psychol. Sci.* 18:88–94

Hattie J. 2009. *Visible Learning*. Abingdon, UK: Routledge

Hickey DT, Ingram-Goble AA, Jameson EM. 2009. Designing assessments and assessing designs in virtual educational environments. *J. Sci. Educ. Technol.* 18:187–208

Honey MA, Hilton ML, eds. 2011. *Learning Science through Computer Games and Simulations*. Washington, DC: Natl. Acad. Press

Hsu CY, Tsai CC. 2013. Examining the effects of combining self-explanation principles with an educational game on learning science concepts. *Interact. Learn. Environ.* 21(2):104–15

Hsu CY, Tsai CC, Wang HY. 2016. Exploring the effects of integrating self-explanation into a multi-user game on the acquisition of scientific concepts. *Interact. Learn. Environ.* 24(4):844–58

Hwang G-C, Wu P-H, Chen C-C. 2012. An online game approach for improving students' learning performance in web-based problem-solving activities. *Comput. Educ*. 59:1246–56

Johnson CI, Mayer RE. 2010. Adding the self-explanation principle to multimedia learning in a computer-based game-like environment. *Comput. Hum. Behav.* 26:1246–52

Lee C, Chen M. 2009. A computer game as a context for non-routine mathematical problem solving: the effects of type of question prompt and level of prior knowledge. *Comput. Educ.* 52:530–42

Leutner D. 1993. Guided discovery learning with computer-based simulation games: effects of adaptive and non-adaptive instructional support. *Learn. Instr.* 3:113–32

Li R, Polat U, Makous W, Bavelier D. 2009. Enhancing the contrast sensitivity function through action video game training. *Nat. Neurosci.* 12(5):549–51

Liu T, Chu Y. 2008. Using ubiquitous games in an English listening and speaking course: impact on learning outcomes and motivation. *Comput. Educ.* 55:630–43

Loftus GR, Loftus EF. 1983. *Mind at Play: The Psychology of Video Games*. New York: Basic Books

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

Mayer RE. 2011b. Multimedia learning and games. In *Computer Games and Instruction*, ed. S Tobias, JD Fletcher, pp. 281–306. Charlotte, NC: Inf. Age Publ.

Mayer RE. 2014. *Computer Games for Learning: An Evidence-Based Approach*. Cambridge, MA: MIT Press

Mayer RE. 2016. What should be the role of computer games in education? *Policy Insights Behav. Brain Sci.* 3(1):20–26

Mayer RE, Johnson CI. 2010. Adding instructional features that promote learning in a game-like environment. *J. Educ. Comput. Res.* 42:241–65

Mayer RE, Mautone PD, Prothero W. 2002. Pictorial aids for learning by doing in a multimedia geology simulation game. *J. Educ. Psychol.* 94:171–85

McGonigal J. 2011. *Reality Is Broken: Why Games Make Us Better and How They Can Change the World*. New York: Penguin Press

McLaren BM, Adams D, Mayer R, Forlizzi J. 2017. Decimal point: an educational game that benefits mathematics learning more than a conventional approach. *Int. J. Game-Based Learn.* 7(1):36–56

Melby-Lervåg M, Hulme C. 2012. Is working memory training effective? A meta-analytic review. *Dev. Psychol.* 49(2):270–91

Moreno R, Mayer RE. 2000. Engaging students in active learning: the case for personalized multimedia messages. *J. Educ. Psychol.* 92:724–33

Moreno R, Mayer RE. 2004. Personalized messages that promote science learning in virtual environments. *J. Educ. Psychol.* 96:165–73

Moreno R, Mayer RE. 2005. Role of guidance, reflection, and interactivity in an agent-based multimedia game. *J. Educ. Psychol.* 97:117–28

Moreno R, Mayer RE. 2007. Interactive multimodal learning environments. *Educ. Psychol. Rev.* 19:309–26

Moreno R, Mayer RE, Spires HA, Lester J. 2001. The case for social agency in computer-based teaching: Do students learn more deeply when they interact with animated pedagogical agents? *Cogn. Instr.* 19:177–213

Moreno RE, Mayer RE. 2002. Learning science in virtual reality environments: role of methods and media. *J. Educ. Psychol.* 94:598–610

Nelson RA, Strachan I. 2009. Action and puzzle video games prime different speed/accuracy tradeoffs. *Perception* 38(11):1678–87

Neri A, Mich O, Gerosa M, Giuliani D. 2008. The effectiveness of computer assisted training for foreign language learning by children. *Comput. Assist. Lang. Learn.* 21:393–408

Nouchi R, Yasuyuki T, Takeuchi H, Hashizume H, Akitsuki Y, et al. 2012. Brain training game improves executive functions and processing speed in the elderly: a randomized controlled trial. *PLOS ONE* 7(1):e29676

Okagaki L, Frensch PA. 1994. Effects of video game playing on measures of spatial performance: gender effects in late adolescence. *J. Appl. Dev. Psychol.* 15:33–58

O'Neil HF, Chung G, Kerr D, Vendlinski T, Bushchang R, Mayer RE. 2014. Adding self-explanation prompts to an educational game. *Comput. Hum. Behav.* 30:23–28

O'Neil HF, Perez RS, eds. 2008. *Computer Games and Team and Individual Learning*. Amsterdam: Elsevier

Papastergiou M. 2009. Digital game-based learning in high school computer science education: impact on educational effectiveness and student motivation. *Comput. Educ.* 52:1–12

Parchman SW, Ellis JA, Christinaz D, Vogel M. 2000. An evaluation of three computer-based instructional strategies in basic electricity and electronics training. *Mil. Psychol.* 12:73–87

Parong J, Mayer RE, Fiorella L, MacNamara A, Homer BD, Plass JL. 2018. Learning executive function skills by playing focused video games. *Contemp. Educ. Psychol.* 51:141–51

Pellegrino JW, Hilton ML. 2012. *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century*. Washington, DC: Natl. Acad. Press

Phye GD, Robinson DH, Levin J, eds. 2005. *Empirical Methods for Evaluating Educational Interventions*. Amsterdam: Elsevier

Pilegard C, Mayer RE. 2016. Improving academic learning from computer-based narrative games. *Contemp. Educ. Psychol.* 44:12–20

Pilegard C, Mayer RE. 2018. Game over for Tetris as a platform for cognitive skill training. *Contemp. Educ. Psychol.* 54:29–41

Powers KL, Brooks PJ. 2014. Evaluating the specificity effects of video game training. In *Learning by Playing: Frontiers of Video Gaming in Education*, ed. F Blumberg, pp. 302–29. Oxford, UK: Oxford Univ. Press

Prensky M. 2006. *Don't Bother Me Mom—I'm Learning*. St. Paul, MN: Paragon House

Ricci KE, Salas E, Cannon-Bowers JA. 1996. Do computer-based games facilitate knowledge acquisition and retention? *Mil. Psychol.* 8:295–307

Saettler P. 2004. *The Evolution of American Educational Technology*. Charlotte, NC: Inf. Age Publ.

Segers E, Verhoeven L. 2003. Effects of vocabulary training by computer in kindergarten. *J. Comput. Assist. Learn.* 19:557–66.

Serge SR, Priest HA, Durlach PJ, Johnson CI. 2013. The effects of static and adaptive performance feedback in game-based training. *Comput. Hum. Behav.* 29(3):1150–58

Shavelson RJ, Towne L, eds. 2002. *Scientific Research in Education*. Washington, DC: Natl. Acad. Press

Simons DJ, Boot WR, Charness N, Gathercole SE, Chabris CF, et al. 2016. Do brain training programs work? *Psychol. Sci. Public Interest* 17(3):103–86

Sims VK, Mayer RE. 2002. Domain specificity of spatial expertise: the case of video game players. *Appl. Cogn. Psychol.* 16:97–115

Sindre G, Natvig L, Jahre M. 2009. Experimental validation of the learning effect for a pedagogical game on computer fundamentals. *IEEE Trans. Educ.* 52:10–18

Singley MK, Anderson JR. 1989. *The Transfer of Cognitive Skill*. Cambridge, MA: Harvard Univ. Press

Suh S, Kim SW, Kim NJ. 2010. Effectiveness of MMORPG-based instruction in elementary English education in Korea. *J. Comput. Assist. Learn.* 26:370–78

Swaak J, de Jong T, van Joolingen WR. 2004. The effects of discovery learning and expository instruction on the acquisition of definitional and intuitive knowledge. *J. Comput. Assist. Learn.* 20:225–34

Swaak J, van Joolingen WR, de Jong T. 1998. Supporting simulation-based learning: the effects of model progression and assignments on definitional and intuitive knowledge. *Learn. Instr.* 8:235–52

ter Vrugte J, de Jong T, Wouters P, Vandercruysse S, Elen J, van Oostendorp H. 2015. When a game supports prevocational math education but integrated reflection does not. *J. Comput. Assist. Learn.* 31(5):462–80

Tobias S, Fletcher JD, eds. 2011. *Computer Games and Instruction*. Charlotte, NC: Inf. Age Publ.

Van Eck R, Dempsey J. 2002. The effect of competition and contextualized advisement on the transfer of mathematics skills in a computer-based instructional simulation game. *Educ. Technol. Res. Dev.* 50:23–41

Vandercruysse S, ter Vrugte J, de Jong T, Wouters P, van Oostendorp H, et al. 2016. The effectiveness of a math game: the impact of integrating conceptual clarification as support. *Comput. Hum. Behav.* 64:21–33

Wang N, Johnson WL, Mayer RE, Rizzo P, Shaw E, Collins H. 2008. The politeness effect: pedagogical agents and learning outcomes. *Int. J. Hum. Comput. Stud.* 66:96–12

Wang P, Liu HH, Zhu XT, Meng T, Li HJ, Zuo XN. 2017. Action video game training for healthy adults: a meta-analytic study. *Front. Psychol.* 7:907

Wentzel KR, Miele DB, eds. 2016. *Handbook of Motivation at School*. Abingdon, UK: Routledge. 2nd ed.

Wouters P, van Oostendorp H. 2017. Overview of instructional techniques to facilitate learning and motivation of serious games. In *Instructional Techniques to Facilitate Learning and Motivation of Serious Games*, ed. P Wouters, H van Oostendorp, pp. 1–16. Berlin: Springer

Wrzesien M, Raya MA. 2010. Learning in serious virtual worlds: evaluation of learning effectiveness and appeal to students in the E-Junior project. *Comput. Educ.* 55:178–87

Wu S, Cheng CK, Feng J, D'Angelo L, Alain C, Spence I. 2012. Playing a first-person shooter video game induces neuroplastic change. *J. Cogn. Neurosci.* 24(6):1286–93

Yip FWM, Kwan ACM. 2006. Online vocabulary games as a tool for teaching and learning English vocabulary. *Educ. Media Int.* 43:233–49

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