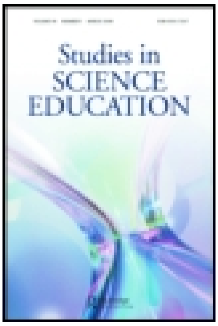

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Digital games and the US National Research Council's science proficiency goals

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Digital games and the US National Research Council's science proficiency goals

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This review synthesises research on digital games and science learning as it supports the goals for science proficiency outlined in the report by the US National Research Council on science education reform. The review is organised in terms of these research-based goals for science proficiency in light of their alignment with current science education standards and reform documents worldwide. Overall, the review suggests that digital games can support science learning across the four strands but also suggests that there are few strong quantitative studies examining some of the strands. Much of the research conducted to date has centred primarily on the potential of games to scaffold conceptual knowledge, engagement and participation. Less research has focused on epistemological understanding and science process skills. While much debate has asked whether digital games are 'good' or 'bad' for learning, the research across the strands highlights that the design of digital games, rather than their medium, ultimately determines their efficacy for learning.

Keywords: science education; digital games; literature review; games for learning; science proficiency

Introduction

What does research on digital games for science learning demonstrate in terms of their affordances? This review synthesises the findings of 56 research articles on games for science learning, organised through the framework provided by the four strands of science proficiency outlined in the US National Research Council's report *Taking Science to School: Learning and Teaching Science in Grades K-8* (National Research Council [NRC], 2007). This report lays out not only learning goals but also a broad framework for curriculum design that is generally applicable to science education as a whole, not just in the elementary grades. According to the authors of *Taking Science to School*, a student who is proficient in science is envisioned as one who is able to:

> (1) Know, use and interpret scientific explanations of the natural world; (2) Generate and evaluate scientific evidence and explanations; (3) Understand the nature and development of scientific knowledge; and (4) Participate productively in scientific processes and discourse. (NRC, 2007, p. 36)

We view these strands as proxies for defining research-based goals for science learning in light of their alignment with current science education standards and

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reform documents worldwide (e.g. Australian Department of Education, Employment and Workplace Relations, 2008; European Commission, 2007; National Research Council, 2012; Nuffield Foundation, 2008).

This paper uses the framework of *Taking Science to School* as a lens to assess the degree to which recent research on games for learning supports the overarching goals of science education. Our goal is not to provide a comprehensive review of the research literature on games for learning, but rather to explore this literature synthetically. Several excellent literature reviews on educational games have recently been published (e.g. Tobias & Fletcher, 2007; Young et al., 2012), and the examination of learning outcomes is a key element in these reviews; however, we feel that no literature review to date examines the degree to which the learning outcomes reported by educational game research align with the goals of science education. Assessing this alignment is urgent in light of changing sociocultural attitudes towards digital games and persistent questions about the role of digital games in classrooms.

It is very clear that digital games are an influential and ubiquitous presence in the lives of young learners. A 2008 study by the Pew Internet and American Life Project found that 97% of teens aged 12–17 play digital games, and 50% of them report daily or nearly daily play (Lenhart et al., 2008). With increasing access to computers, consoles and cell phones, young people encounter opportunities for gaming everywhere. Educational researchers are increasingly interested in the affordances of digital games as a medium for learning. Investigation into the use of games for learning has grown from a small niche area to a major focus of research over the past decade (e.g. Dieterle, 2010; Gee, 2003/2007). Support for research on gaming for learning has simultaneously increased. In 2006, the Federation of American Scientists issued a report stating their belief that games offer a powerful new tool to support education and encouraging governmental and private organisational support to expand funded research into the application of complex gaming environments for learning (Federation of American Scientists [FAS], 2006). In 2009, a special issue of *Science* (Hines, Jasny, & Mervis, 2009) echoed and expanded this call. The stakes and potential are high if games can be successfully engineered to support science learning given the extensive reach and saturation of game playing in modern youth culture (Mayo, 2009).

Definition of digital games, explanation of learning outcomes and organisation of review

Digital games for learning are remarkably diverse as a medium; they are designed with vastly different affordances and constraints, they target a wide range of age groups and content areas, they are deployed in a variety of educational settings, and they lend themselves to a range of quantitative and qualitative research methodologies. One challenge in viewing this literature synthetically is determining whether or not any two given studies of game-based science learning can be profitably compared to each other in spite of their manifold differences. A further complication is that game-based learning researchers subscribe to a considerable range of definitions of what a *digital game* is, and these definitions are not always mutually interoperable. Often when reviewing the papers gathered from our initial search, we found ourselves arguing less over the characteristics of the study that might help us position it within the synthetic framework, and more over whether or not the software being used in that study was actually a game at all and therefore ought to be excluded. Thus, we found invaluable to our work to *a priori* decide what constitutes a game and how to distinguish it from a simulation, a learning environment, or any other technology-based activity for science learning that might have similar interactivity and structure.

For the purposes of this review, we define a *digital game* as an activity structured by rules and mediated by digital technology in which the participants seek desirable outcomes that are defined in terms of the participants' performance (cf. Klopfer, Osterweil, & Salen, 2009; Salen & Zimmerman, 2003). Furthermore, we make a distinction between digital games and computer simulations. Most digital games designed for science education contain embedded simulations that focus the player on manipulating the core interactive models, but not all simulations are games. The most useful way to draw this distinction is to think of digital games as subsets of simulations with three additional characteristics. First, games are designed specifically to engender certain levels of play, engagement and enjoyment as core characteristics (which are not requisite characteristics of simulations). Second, games more explicitly specify rules and goals for the player. Third, games provide more explicit scoring or reward systems to track players' progress toward those goals. Digital games, for the purposes of this review, thus share many similarities with simulations, and include some form of simulation at their core, but they place more emphasis on explicit rules, goals and systems to track progress toward those goals.

These definitions and distinctions were central in helping us form a useful critical lens, i.e. one that would allow us to detect repeating themes in the literature and to assemble these themes into a more coherent framework. The central axis for organising the literature was provided by the four strands of science proficiency outlined in *Taking Science to School*. We classified the studies into one of the four strands according to their principal research questions and reported outcomes. Several articles we reviewed could potentially be included into more than one strand, e.g. students participated in a study showed gains in both conceptual understanding and self-efficacy; in those cases, we decided on a study's classification based on which of the two possible strands was more strongly featured in the study's data. In a few outlying cases, where a single study reported similarly strong findings related to more than one strand, we classified that study under the less populated strand. We feel this scheme does more justice to the unique contributions of each study.

We planned to use the four strands of goals outlined in *Taking Science to School* as the principal classification scheme; however, as we populated the categories, we detected some topical clusters in the studies within that category. So, we created several subheadings within these strands where the body of research suggests that such a sub-classification is appropriate. These subheadings also allow us to trace distinct patterns in the findings and outcomes present in the literature. A broad outline for each of these topical clusters, as well as our rationale for its inclusion, will be provided under the corresponding subheading.

Selection criteria

This review includes all studies identified through an EBSCHOLAR database search meeting the following criteria:

(a) Journal articles published between 2000 and the first quarter of 2012.
(b) The title or abstract included the terms ‘game’ or ‘games’.
(c) The studies included an explicit focus on digital environments or digitally augmented environments that met the definition of games outlined in the previous section.
(d) The authors of the research article explicitly defined the environment as a game.
(e) The research article reported qualitative and/or quantitative data on learning outcomes related to the learning of science, engineering, or programming proficiency in line with the strands of science proficiency defined in the NRC report on goals for science proficiency *Taking Science to School* (NRC, 2007).

This review further supplements the database search with additional studies identified through a hand-based search of other journal articles that meet our definition of games and criteria c, d and e.

Classifying the learning outcomes

The question of whether or not digital games support the four goals of science proficiency outlined in *Taking Science to School* demands that we systematically examine the learning outcomes reported in the literature. Each individual study, once classified into one of the four strands, has something to say about how well digital games support this particular strand. The nature of this support hinges largely on the learning outcomes of a particular study in relation to the rest of the studies classified under each strand. Do the learning outcomes of the studies under each strand paint a coherent picture of how exactly each strand is supported? Are certain outcomes specifically linked to one strand or can they be seen as broadly supportive of science learning as a whole?

Our next challenge then became how to examine the learning outcomes systematically. Since our intention was not to produce a meta-analysis, we chose not to perform any statistical analysis on the learning outcomes. Rather, we needed a classification scheme that would allow us to view at a finer grain the empirical support that digital games may provide for each learning strand. However, studies of digital games are nearly as methodologically diverse as the featured games themselves, so rather than creating a taxonomy of possible learning outcomes *a priori*, we chose to allow the literature itself to suggest a classification scheme. Our approach most resonates with the principle behind *grounded theory*: that theory can be discovered by examining data in such a way that the generated theory supports a perspective stance and provides clear, verifiable categories (cf. Glaser & Strauss, 1967).

We started by summarising each study so that the research question, the nature of the game used, the age of the participants, the nature of the study, the research methodology used and the outcome measure(s) were clearly described. For age group, we distinguished between learners aged 11 or younger (i.e. primary school, where science is generally not taught as a separate topic); 12–18 years olds (who most often have separate science classes, often focusing on one domain per course, e.g. physics, chemistry and biology); and baccalaureate or post-baccalaureate students or teachers, whom we classify together as ‘adult learners’. Research methods were described according to the classification of research styles given in Cohen, Manion and Morrison (2007), i.e. as ‘experiments’, ‘case studies’, ‘design-based research', 'testing and assessments', 'ethnographies', or 'surveys'. Then, each summary was tagged by a single coder with one or more descriptive nouns. During initial tagging, the descriptors were reused for more than one paper only when the studies being tagged were nearly identical with regards to the nature of their findings, e.g. when two studies reported students playing a game and then showing improvement on a pen-and-paper test, the tag 'transfer' was used for both. Each study received as many tags as the distinct outcomes being reported; most had only one, and about a third had two or more. The initial round of tagging produced around 30 unique descriptors. During subsequent rounds, the tags were collapsed using the following criteria: given any two papers A and B, does A's tag describe the nature of the findings of B better than B's tag describes the outcome of A? If the answer was yes, then B's tag was changed to A's. If not, then the tags of both papers were preserved. This process continued iteratively over four rounds, when the tags became distinct enough that in no instance could a study's tags reasonably apply to any other study that did not already have them. This analysis converged on a list of 11 descriptors, indicating 11 fundamental types of findings reported in the selected literature. These descriptors, along with their definitions and frequencies, appear in Table 1.

We use these descriptors in all subsequent tables to describe the learning outcomes. These descriptors have a consistent meaning regardless of which strand they are organised under. It is important to note that even when some descriptors may indicate a close alignment to a particular strand, not all of the studies that report a certain finding fall under a particular strand. So, for example, not all studies that report improvement in inquiry skills fall under strand 2. This is an effect of how findings are reported in the literature, i.e. what evidence the researchers make more salient in their papers, and how that evidence is marshalled to support their research question. Far from being a weakness of our analysis, we interpret these cross-cutting types of findings as reflective of the interwoven nature of the strands of science proficiency, as well as an accurate portrayal of the rich texture of game-based research as a whole.

Research overview: games for science learning and the strands of science proficiency

In the following sections, we describe each strand of science proficiency as represented in the literature, and provide a summative overview of the studies that researched questions relevant to that strand. Because *Taking Science to School* is directed specifically to grades K-8, in some cases, the core definitions of each strand were expanded slightly to accommodate the paradigms of secondary- and tertiary-level science education, and to allow for a cleaner classification of studies so that each one fell under a single strand.

Research related to conceptual understanding

The first strand of goals for science proficiency outlined in *Taking Science to School* focuses on the degree to which students 'know, use, and interpret scientific explanations of the natural world' (NRC, 2007, p. 37).

Table 1. Types of findings present in the literature on digital games for science learning.

Type of finding	Definition	*N*
Transfer	Students demonstrate improved content knowledge after playing the game, e.g. through a test taken out of the game. Most commonly pre–post test experimental designs	21
Motivation and engagement	Students who played the game were shown to be more willing to engage with science concepts, to actively participate in the activity, and follow through with the assigned tasks. Also, students report the game-based learning experience as interesting, enjoyable and stimulating	16
Broad	Refers to one or more of a broad range of positive outcomes that are considered important for STEM learning by the researchers, but are not directly connected to a particular content. E.g., improved problem-solving skills, scientific habits of mind, systems thinking	9
Inquiry skills	Students show an increased ability to investigate the causal nature of scientific phenomena, form testable theories and models, and design experiments to evaluate these theories	6
Engineering skills	Participants in these studies developed skills that were analogous to professional engineering (i.e. designing or programming their own games)	4
Collaboration	Students more readily worked together and were accountable to each other when pursuing a science-like goal in the game. E.g. gathering data, researching information online	2
Self-efficacy	Students demonstrate a more expansive vision of their own capabilities as scientists, researchers and engineers than they had before playing the game	2
STEM practices	Students participating in the game-based activity showed one or more of a range of behaviours researchers associate with epistemological practices most associated with the STEM disciplines	1
Argumentation skills	Students who played the game were more likely to engage in fact-based argumentation that follows the structure of scientific reasoning. E.g. supporting claims with facts	1
Improved attitudes towards science	Students who played the game reported a greater appreciation and/or understanding of STEM	1
Null	Researchers reported no effect from playing the game	6

> This strand includes acquiring facts and the conceptual structures that incorporate those facts and using these ideas productively to understand many phenomena in the natural world. This includes using those ideas to construct and refine explanations, arguments, or models of particular phenomena. (NRC, 2007, p. 37)

We refer to this first strand of science proficiency as 'conceptual understanding' for brevity, but through this descriptor, we intend the expanded meaning described above. Conceptual understanding has been a central goal of science classrooms historically, but the emphasis has often centred more heavily on isolated facts than on well-structured conceptual systems, a goal for which digital games would seem well-suited.

Of the 56 studies we reviewed, 33 reported findings that related to this strand. Of these 33, the majority (20) use experimental methodologies, 11 were case studies and two used methods of design research. We classified the studies that support this strand into four subheadings to highlight in more detail the different nature of the research questions being asked. Thus, within these studies, we found investigations on immersive worlds, casual games, programming games to learn and designing for learning outcomes. The definitions and frequencies related to these subheadings appear in Table 2.

Immersive worlds and conceptual learning

Many studies on digital games and science learning have centred on immersive 3D virtual worlds where students take on the roles of scientific investigators in those worlds. Barab et al. (2009), for example, studied the impact of the *Taiga* ecological sciences curriculum in *Quest Atlantis*. Barab et al. compared learning outcomes among 51 undergraduate participants in four conditions. They found that learners in the virtual world-based conditions significantly outperformed learners in the electronic book group, and outperformed book and 'simple-framing' groups on a transfer test.

In another *Taiga* study, Hickey, Ingram-Goble, and Jameson (2009) demonstrated gains in individual understanding of science content and socio-scientific inquiry with a performance assessment that presented related problems in a related context. The first study involved a sixth-grade teacher using the curriculum with two classes and obtaining significant gains in understanding and achievement compared to two of his other classes that used expository text on the same concepts and skills. After two new types of virtual formative feedback were developed for the in-game quest submissions, the same teacher used the *Taiga* curriculum in all four of his classes the subsequent year, resulting in significantly larger gains in understanding and achievement.

Another game in which students are asked to take on the role of a scientist, *Message in a Fossil*, was studied by Henderson, Klemes, and Eshet (2000). In this game, student participants take on the role of a palaeontologist excavating fossils. Both pre- and post-test data were collected for a class of 27 second graders and three pairs were selected for further in-depth data collection. There was a 24% increase in the number of correct responses on the post-tests after the completion of the unit. Students' skills improved in the areas of identification, logical sequencing and logical classification.

In addition to improving science learning outcomes in broad terms, virtual environments created for science learning have been shown to increase students' motivation to participate in activities of science learning, as well as increasing their engagement with specific learning tasks. Miller, Chang, Wang, Beier, and Klisch (2011) studied the effectiveness of a game as a tool to both teach content and improve students' dispositions toward science careers in their study with a sample of over 700 secondary schools students. In this game, students are asked to take on the role of scientific investigator in the online forensic science game known as *CSI: The Experience*. They found that students gained content knowledge with the assistance of the game, as evident through the significant gains from the pre-test to the delayed post-test. Post-intervention surveys for this study also supported the idea that satisfaction with science games can motivate students to consider STEM careers.

Casual games and conceptual learning

In addition to research on immersive worlds, research has also been conducted in more casual games where the targeted science learning is integrated more deeply

Table 2. Summary report of research on digital games for science learning – conceptual learning strand.

			By type of finding*		By age group		
Subheading	Overarching research question	*N*	Outcome	*N*	K-6	7–12	Adult
		33		41			
Immersive worlds	Do fully realised virtual worlds support understanding of science concepts?	4					
			Transfer	4	2	1	1
			Broad	1	1		
			Motivation & engagement	1		1	
Casual games	Do simple games with low barriers to entry help gamers of all ability levels learn concepts of science?	9					
			Transfer	5		3	3
			Motivation & engagement	3		1	2
			Broad	2	2	1	
Programming games to learn	Can designing and programming games support learning of applied concepts of STEM?	10					
			Engineering skills	4		3	1
			Motivation & engagement	2	1		1
			Transfer	2	2		
			Broad	4	2	2	
			null	1		1	
Designing for learning outcomes	Does the presence or absence of certain game features improve students' understanding of scientific ideas?	11					
			Transfer	7	1	1	5
			null	4		2	2
			Motivation & engagement	1			1

Note: Differences in row/column totals reflect studies that examined more than one age group, or reported more than one finding.
*See Table 1 for details on each class of finding.

into the core mechanics of the game itself than is typically seen in immersive world-based science games. The relative simplicity of design and metaphor that is the hallmark of casual games allows for designers to integrate scientific concepts and relationships more directly into the game as rules that players must interact with. This design practice may be contrasted to embedding science activities into expansive, immersive virtual worlds. The first design practice leads to conceptually integrated games, while the latter results in games that are conceptually embedded; in prior work, we have proposed that these design patterns may provide significantly different affordances for learning (Clark & Martinez-Garza, 2012).

This theme of tighter integration between game rules and educational content is an emergent trend in research into digital games for science learning. In one such study, Holbert and Wilensky (2012) examined the ability of third- to eighth-grade students to construct speed vs. time graphs before and after playing a racing game (*FormulaT*). Holbert and Wilensky offer *FormulaT* as an example of a 'representationally congruent game' in which students meaningfully construct with primitives that are conceptually integrated in order to create representations relevant to expert use of the domain. After playing the game, students were able to express a more qualitatively correct understanding of the velocity–time relationship and an improved use graphs to represent that relationship. The authors argue that representationally congruent games encourage players to see their in-game experiences and constructions as relevant in settings outside of the game.

Casual games require a smaller time investment, are less complex in their rules and presentation, and require less prior digital gaming experience by students; these traits combined make them easier to include as a classroom activity or as part of a more conventional curriculum unit. A significant portion of the research literature that shows digital games being used to further conceptual understanding has this structure, i.e. a combination of game play with traditional modes of instruction. As an example, MacDonald and Bean (2011) studied the *Quarked!*™ programme, which is an educational enrichment programme that combines a website with games and videos with a hands-on workshop experience. Through the games and other materials, students are able to learn advanced physics concepts, including particle theory and size and scale of our universe, at a young age. McDonald and Bean assessed 132 elementary and middle school students. When asked what they discovered through the programme, over 50% of the students responded with more than just a new scientific term; many, through their responses, showed a deeper understanding of the invisible world and how it relates to aspects of the observable world.

Our previous work on the *SURGE* computer game focused on helping students connect intuitive understandings about physics developed through game play with formal concepts and representations. *SURGE* integrates the targeted physics concepts directly into the fabric of the game itself. Work with more robust versions of *SURGE* (Clark et al., 2011) demonstrated high engagement and learning on measures based on the Force Concept Inventory (FCI), an assessment developed by physicists to measure conceptual understanding in university courses (Hestenes, Wells, & Swackhamer, 1992). These gains were achieved in *SURGE* in two class periods in contrast to the lengthier instructional frame intended for the FCI. This study also showed striking similarities in learning and engagement between students in Taiwan and the USA, suggesting that this genre of games may prove suitable for engaging students in active exploration of core science concepts across multiple countries.

Like *SURGE*, *Relativistic Asteroids* was also designed to help student make connections to formal physics concepts. Carr and Bossomaier (2011) designed *Relativistic Asteroids*, a game meant to scaffold the learning of the theory of special relativity. The game, which is based on the traditional video arcade game, *Asteroids*, allows the students to interact with principles of which they lack everyday experiences. After the game, both high school and undergraduate students were better able to correctly answer exam style questions on relativity. Game play led to significant learning results in groups of students both with and without prior knowledge of the topic. Klopfer, Scheintaub, Huang, Wendel, and Roque (2009) detail the findings of a pilot study involving a simulation-based game called *The Planet Game* with 47 middle school-aged students. A comparison of pre-tests and post-tests suggested that a number of the students addressed important misconceptions through the short activity.

A series of similar studies was also conducted with the *Supercharged* game (Jenkins, Squire, & Tan, 2004). *Supercharged* is a 3D game in which players utilise and explore the properties of charged particles and field lines to navigate a spaceship through the game world by taking advantage of charged particles in the game world. Anderson and Barnett (2011) continued the investigation of *Supercharged* with pre-service elementary teachers in the process of learning basic physics. The control group in their study learned through a series of guided inquiry methods while the experimental group played *Supercharged* during the lab sessions of the course. *Supercharged* pre-service teachers significantly outperformed the inquiry control pre-service teachers in terms of pre-post assessment gains, even though *Supercharged* group rated their own knowledge of the topic lower than the inquiry group.

Ebner and Holzinger (2007) studied students' use of *Internal Force Master* (*IFM*), a game developed for civil engineering master's-level students based on the theory of structures. One-hundred and twenty-one students were involved in this study. The post-test data showed that this game was just as effective as traditional teaching methods, but the game had an additional benefit of students rating their game play as very enjoyable. Also, motivation, which was a problem with the traditional methods, was maintained throughout game play. Researchers concluded that not only was *IFM* an effective educational tool that led to incidental learning, but students are also highly motivated to play it due to the fun and competition of the gameplay.

Clark and Smith (2004) investigated student satisfaction with the game *Outbreak!*, a game created to give students experience fulfilling the roles of different positions in the field of clinical microbiology. *Outbreak!* was designed as a supplement to microbiology courses. Clark and Smith collected data from 133 undergraduate students' questionnaires; over two-thirds of the comments were positive; and students stated that they enjoyed the game and learned new techniques.

The positive outcomes of game-based curricula are not limited to younger learners. Several of the studies we reviewed feature adult and/or professional students Greenfield, Camaioni, Ercolani, Weiss, and Lauber (1994) had university students play a video game for two and a half hours before taking a test to measure their ability to generalise and apply principles from a few demonstrated examples involving images of components in an electronic circuit. Video game performance was significantly correlated with increased scores on the electronic circuit test.

Teachers and students programming games to learn

A third interesting category of game-based conceptual learning studies focuses on allowing students and teachers flexibility in shaping or even programming games to learn science concepts. This idea builds on early research on students learning academic concepts in other content areas through programming (e.g. Kafai, 1995). This branch of research can be classified according to the main designer or programmer of the educational game, i.e. whether it is a teacher-led or a student-led creation. Related to teacher-centred studies, for example, Annetta, Mangrum, Holmes, Collazo and Cheng (2009) studied 74 fifth graders playing the game *Dr. Friction*, a teacher-created Multiplayer Educational Gaming Application, in the middle of a unit on simple machines. Using a pre/post-test design, students overall did significantly better on a post-test regarding simple machines, with a moderate-to-strong effect size. The study also looked at gender effects and found no significant difference. In a separate paper; however, Annetta, Minogue, Holmes and Cheng (2009) studied 66 students using a teacher-created game about genetics (as a review in class) and found no significant increase on a post-test when compared to 63 students not playing the game. All students had the same general instruction with the same teacher in four high school biology classes. Teachers also find value in creating science games for their own classrooms, as was demonstrated by Annetta, Murray, Laird, Bohr, and Park (2008). In their study, a group of in-service teachers enrolled in a graduate-level course are required to create a game within the course's Multi-user Virtual Environment (MUVE), *WolfDen*, on a topic of their own choice. Although after completing the course, teachers still had some questions regarding the implementation of MUVEs in their own classrooms; they felt that their students would benefit from the many positive aspects of the MUVE, including the increased engagement and challenge that the environment provides.

Research on students designing and creating games has focused on one of two purposes. One purpose, detailed further below, is computer science and programming education. The other purpose follows the pattern of games for learning research more generally, i.e. to cause a positive educational outcome through the use of digital games, except that in this case, the study involves the students much more centrally in the process of creating the game itself. For example, Klopfer, Scheintaub, et al. (2009) also describe a series of pilot studies conducted with eighth-grade students using *StarLogo TNG* to combine games, simulations, engineering and science for students. The pilot studies provide qualitative descriptions demonstrating student learning of content and programming skills during their development of their own simulations, and showed that high school students building games as part of their course work gained insight into the scientific method, as well as fostering problem-solving and creativity. A potentially important hypothesis of this branch of research is that the process of design of an educational game causes students to think about the science content that the game represents in a qualitatively different way. Students who design games for learning science must necessarily become familiar with the subject matter of their game as well as the relevant relationships, representations, and mathematical and phenomenological underpinnings. Several studies support this hypothesis, e.g. the study conducted by Khalili, Sheridan, Williams, and Stegman (2011) that investigated the connection between student game design and science learning. The high school students who participated created their own science games using the *Game Maker* software. None of the students had previously studied neurology, but in their games they were able to represent complex neurological processes. Creating the game allowed students to recognise the gaps in their own knowledge and find ways to fill in those gaps; through the process students were able to reach a level of complex modelling of scientific concepts of which they had no or limited prior knowledge. Likewise, Baytak and Land (2011) found that elementary age students were also able to create their own science games. They studied a group of fifth graders who designed their own environmental science game using *Scratch*, a programming language designed for ease of use. The students predictably expanded their own programming knowledge during the course of the study, but they also expanded their science concept knowledge. They were required to visually represent their scientific thinking and found it necessary to seek out further scientific knowledge and build their knowledge base to accurately complete their games. Li (2010) also studied a group of elementary students at an education summer camp who created games using *Scratch*. Students created their own games meant to teach Newton's Laws of Motion to others. Not only did students express positive emotions attached to the process, they also gained and deepened knowledge of scientific, mathematical and technological concepts. Furthermore, they were required by the very process of game creation to actively apply these concepts.

As previously noted, not only can game creation be used to teach the traditional sciences, it can also effectively be used to teach students computer science and programming. Denner and Werner (2007) studied 126 middle school girls involved in programming games in an after-school and summer programme. Each pair of students created their own narrative game using *Flash MX*. Students in this study learned the concepts of computer programming through actively problem-solving during the process of game design. In this way, they not only gained conceptual knowledge of computer programming, but also developed and implemented problem-solving techniques vital to the practice of computer science. Denner, Werner, and Ortiz (2012) studied 59 middle school girls who created games, using *Stagecast Creator*, as part of an after-school class. Each student designed multiple games, and through these projects they were able to learn computer science concepts. They found that game programming can be useful in engaging students in computer science learning; however, they concluded that in order for students to tackle more complex problems, the learning by discovery approach needs to be supported by a teacher's instruction.

Squire, DeVane and Durga (2008) and DeVane, Durga, and Squire (2010) built on this research on learning outside of games through design-based research studies of organising learning communities for disadvantaged students around the commercial game *Civilization*. These qualitative studies demonstrated that students in these after-school learning communities can learn to 'mod' (i.e. to use software tools to programme or create extensions or variants of the game) and design games themselves. Furthermore, the authors showed how the students in these communities developed important academic skills, socio-scientific understanding, systems thinking skills and problem-solving strategies.

Following these patterns at the undergraduate level, Cagiltay (2007) found that university students of software engineering also greatly benefit from designing games as part of their studies. Cagiltay analysed the data from 125 university students. The students had the option of taking a computer game development course; 39 students did so. Students who took the course scored significantly higher on their senior projects and they also reported improvements in their problem-solving skills and had high intrinsic motivation to study game development.

Importance of game design to learning outcomes

The fourth and final category of research on games and conceptual learning that we will discuss refers to the role of design in efficacy. This research mirrors the NRC's report on the effectiveness of labs for science learning (NRC, 2005) in the sense that the research on games for learning supports a consensus perspective about the importance of effective design and scaffolding in any tool or media that supports science learning.

More specifically, significant research effort has been focused on determining which design traits must be included or highlighted in an educational game to produce the best possible learning outcomes. These studies typically concentrate on undergraduate students. The studies we summarise here are, broadly speaking, less concerned with supporting conceptual understanding in a specific domain area as they are in clarifying whether learning outcomes can be intentionally designed. An important goal of this research is to help scholars converge on a stable set of 'design principles' that, when reified into an educational game, can dependably and predictably lead to positive learning outcomes.

A series of studies by Moreno and Mayer (2000, 2002, 2004) investigated the impact of design principles applied to computer games on student retention of science content and on problem-solving transfer questions. In two of these studies, undergraduate university students played a computer game about environmental science (Lester's *Design-a-plant* game) that included personalised instructional content delivered as narrated speech by a pedagogical agent. Students who heard personalised content outperformed students who received neutral content on problem-solving transfer questions and post-implementation retention questions asking them to write down things they saw in the lesson. Moreno and Mayer (2002) further tested the effects of game design, specifically methods and media, using *Design-a-plant*. A group of 164 college students were given different variants of the game and they examined the most effective methods for science learning within the context of a virtual-reality environment (VRE). Moreno and Mayer found that the level to which the VRE was immersive did not affect students' learning. They discovered that the aspect most influential in the areas of retention and transfer was the method of communication, namely they were positively affected by verbal narration of prompts. In a follow-up study using the same game, but with personalised content delivered via text (not voice), they found similar results. Students who saw personalised content outperformed students who received neutral content on problem-solving transfer questions and, to a lesser degree, on post-implementation retention questions asking them to write down things they saw in the lesson. Moreno and Mayer (2004) continued these studies, once again with college students, and added a virtual-reality dimension that involved wearing a head-mounted display. They found that this version of head-mounted virtual-reality immersion did not impact learning.

In another follow-up study of *Design-a-plant*, Moreno and Mayer (2005) looked at the role of guidance (explaining the reasons for a correct answer) and reflection (having students explain their answer). The study consisted of 105 undergraduate students in four groups playing the game. Students were given retention, transfer and programme-rating tests. MANOVA analysis demonstrated significant differences on transfer measures between guidance and no-guidance groups, but no difference between reflection/no reflection groups. On other measures, there were marginal but non-significant differences between guidance/no-guidance groups. Similarly, Mayer, Mautone and Prothero (2002) in a study with 105 college students found that providing pre-training in the *Profile Game* (i.e. showing players pictures of possible geological features that would need to be identified) led to significantly better performance in identifying those geographical features in the game.

Also, Johnson and Mayer (2009) demonstrated that including 'self-explanation' in a game-like environment resulted in greater gains on learning measures. Twenty-three undergrads played a game in which they had to build electrical circuits; half the participants were asked to choose from a list of explanations for performing a given action after each action in the game. These students performed significantly better on an embedded transfer test. A follow-up study in which a third group constructed their own reasons failed to show improvement for that group, although significant improvement was seen for players who picked reasons from a list.

Along a similar theoretical trajectory, Erlandson, Nelson, and Savenye (2010) conducted a study with 78 undergraduate students in which they incorporated the modality design principle into a collaborative science inquiry game by replacing a text-based communication tool with a voice-based one. Student teams using the voice-based tool for collaborative inquiry tasks reported significantly lower levels of extraneous cognitive load related to communication, dealing with science content in the game world, and overall 'stress' than those using the text-based tool. Students using the voice-based collaboration tool in the game also reported 'feeling like a real scientist' at significantly higher rates. At the same time, however, the researchers found no significant differences in learning outcomes between the voice- and text-based collaboration players.

When performed on younger students, i.e. in a K-12 context, research into design principles tends to produce findings that are equally positive but somewhat more ambiguous. Miller, Moreno, Estrera, and Lane (2004) studied middle school students playing an episodic adventure game, *MedMyst*, where students take on challenges to combat diseases and microbes. Significant pre-test/post-test gain scores showed that students retained information from the game. The same game was used with high school students with smaller gains. Similarly, in research on *Savannah*, an augmented reality game where players use mobile technology oriented in real-world physical space to take on the roles of lions in a pride, Facer et al. (2004) describe their design choices and how the 11 and 12-year-old students were rewarded in the game for making decisions that fit with how the game designers wanted them to act. In some cases, the students did not act as they were intended to (for instance, they stuck with one strategy that worked instead of trying new things) due to a simplification of the design. While the students learned the rules of the game quickly, these rules were not always sufficient to help the students learn the science ideas at the appropriate level. 'The main challenge to designers is to develop sufficiently sophisticated games rules, and sufficiently focused challenges in order to encourage the children to attempt different strategies to overcome these problems' (Facer et al., 2004, p. 407).

It is one thing to create a fun and engaging game that students will want to play. It is another to create one that will also teach them the intended concepts and ideas. Thus, effective design and scaffolding for learning are critical. Simply building a digital game that includes interesting science concepts at its core is not enough. While commercial physics games may provide students with a strong intuitive 'feel' for physics concepts, for example, they do not appear to (and are not designed to) help students make the leap from tacit understanding to more formalised knowledge in isolation. For example, Masson, Bub, and Lalonde (2011) found that middle school students playing a commercially available physics-based game (*Enigmo*) 'improved their ability to generate realistic trajectories' (p. 1). However, the game did not help them learn more from a direct instruction 'tutorial' when compared to a control group. The tutorial centred explicitly on formalised concepts and 'explain [ing] the forces acting on moving objects and objects at rest', but the game itself gave the students an idea about what trajectories look like and some information about angles of incidence vs. reflection. Thus, while games typically support players in developing intuitive understandings of game mechanics and relationships that support success within a game, players typically do not connect this intuitive understanding to more explicit formal abstractions and concepts without well-designed scaffolding and game mechanics to support those connections. At one level, the challenge of digital games for science learning is to bridge the divide between scientific disciplinary forms and more intuitive, context-specific forms of understanding. This bridging may be a necessary condition for students to be able to transfer what they learn from digital games away from the game context. Barab, Sadler, Heiselt, Hickey, and Zuiker (2007) investigated how educators can best support transfer from a digital game to decontextualised experiences, such as tests. In two separate studies with fourth graders, Barab et al. found that students performed better on standards-based assessments that dealt the game's content when content–context relations were highlighted and students were scaffolded in developing multiple representations of scientific formalisms.

It should be noted that the online communities surrounding some commercial games sometimes explore the formal physics underlying the games, thus providing effective social scaffolding for more formal learning for active participants. *Portal* is one such game. In *Portal*, players create and utilise entry and exit portal holes on the walls, floors and ceilings of locked rooms to move about and escape the rooms. The portals incorporate realistic physics such that, for example, when a player exits a portal on the ceiling of a room, he/she will fall to the ground below. While playing *Portal* may help players develop some intuitive understandings about acceleration due to gravity, it is it intended to support formal understandings. Some online communities surrounding *Portal*, however, explore and discuss the formal concepts of momentum and gravity within the game (see *Portal* entry in Wikipedia.org for an example). These communities, however, include only a tiny percentage of players, making any learning seen in such communities is difficult to generalise to a broader population. However, lessons from such examples and careful planning might provide ways to make the scaffolding and thinking supported by these tiny communities more broadly available in a manner that engages larger percentages of players in and out of schools around learning games as well as recreational titles.

Conceptual understanding: summary

Studies such as these demonstrate that digital games can contribute to a learner's conceptual understanding of scientific concepts, systems, and phenomena in a number of areas. Many of the studies discussed in this section have shown that learners can learn and explain specific concepts related to Newtonian mechanics, epidemiology, genetics and inheritance, other topics central to science standards (e.g. AAAS, 1993; NRC, 1996, 2012), sometimes at an earlier age than via traditional curricula. Similarly, games, particularly immersive world-based games, have been shown to bolster learning about the complex systems underlying science areas such as disease transmission, traffic systems and genetics. These studies parallel findings about the potential of games to support substantial conceptual gains in other domains. Rosas et al. (2003) and Margolis, Nussbaum, Rodriguez, and Rosas (2006), for example, demonstrated that 1274 economically disadvantaged first- and second-grade students playing a hand-held math game for a few minutes per day outgained both internal and external control groups in a math achievement test and that using this hand-held game had more effect on these students' achievement than either ongoing teacher training or reducing classroom size.

While many of the studies conducted to date with regard to science learning have been 'proof-of-concept' or fairly simple 'media comparison' studies, more recent research has examined the design and curricular supports (such as learner self-explanation, reflections, group discussion and game personalisation) that most impact learning with these tools. These studies show that design and scaffolding are critical to digital games in order for students to make the connections between the environment and the more formalised knowledge required in a school-based context. These findings suggest, for example, that simply having players engage with physics-based games without well-designed scaffolding is not sufficient to help them learn formal physics. This result is not overly surprising; it would be akin to the suggestion that, for example, playing football without any additional scaffolding will teach people formal physics even when football is a physics-based game. As we described, *Enigmo* was developed as a commercial recreational game rather than as a learning experience, and thus unsurprisingly did not support formal physics learning. *Enigmo*, and other games, however, could potentially be re-envisioned or redesigned in a manner that would support explicit articulation and exploration of the core physics implicit in their game experience. These findings follow the findings of the NRC *America's Lab Report* (NRC, 2005), which highlights the importance of scaffolding students' connection of hands-on and digital experiences with core ideas and concepts.

Research related to science process skills

The second science proficiency strand in the NRC report focuses on students' ability to 'generate and evaluate scientific evidence and explanations' (NRC, 2007, p. 39). As the report explains:

> Generating and evaluating scientific evidence and explanations encompasses the knowledge and skills used for building and refining models and explanations (conceptual, computational, mechanistic), designing and analyzing empirical investigations and observations, and constructing and defending arguments with empirical evidence. This strand also incorporates the social practices (e.g., critiquing an argument) and tools (conceptual, mathematical, physical, and computational) fundamental to constructing and evaluating knowledge claims. Hence, it includes a wide range of practices involved in designing and carrying out a scientific investigation, including asking questions, deciding what to measure, developing measures, collecting data from the measures, structuring the data, interpreting and evaluating the data, and using the empirical results to develop and refine arguments, models, and theories. (NRC, 2007, p. 39)

We refer to this strand of science proficiency as 'process skills' for brevity, but as with the conceptual skills, we intend the broader meaning outlined above. Historically and currently, most science classrooms focus more on conceptual understanding but still include some discussion of process skills. That said, just as traditional instruction has concentrated more on isolated facts than on integrated conceptual structures, it has generally settled on weaker decontextualised abstractions of the 'scientific method' than on the range of ideas and practices described above.

Research on games for science learning has generally focused on their viability for supporting students in developing process skills through situated, contextualised investigations. Researchers argue that virtual worlds offer a uniquely suited environment for conducting science inquiry and practising 'real science' (Ketelhut & Nelson, 2010; Nelson & Ketelhut, 2007) by taking on realistic roles (Shaffer, 2006). The number of studies that address this question as their primary direction is somewhat limited, but the evidence indicates that digital games provide opportunities to develop science process skills across a range of grade levels, even in environments without an explicit connection to an in-school science context. Of the five studies we classified under this strand, two were experiments, two were case studies and one used a quasi-survey methodology. The number and reported outcomes of studies that support this strand appear in Table 3.

While there is no general measure of 'science process skills', researchers have found that students who play games for science learning show a greater inclination towards using science-like processes as part of their gaming experience. For example, Kafai, Quintero, and Feldon (2010) studied students during Whypox epidemics in *Whyville*. Part of their study converged on students' use of two tools that allowed players to run small-scale and fast simulations of the epidemics. The simulations allowed the players to make predictions and compare their predictions to the simulation results. During Whypox outbreaks, simulation usage peaked with more than 1400 simulations performed by 171 players in their sample. Kafai and colleagues found that 68% of the players conducted some form of systematic investigation by running the simulations three or more times, 49% of those players demonstrated significant improvements in the accuracy of their predictions, and 70% of players pursued engineering type goals in the process rather than scientific strategies as

Table 3. Summary report of research on digital games for science learning – science process skills.

			By type of finding*		By age group		
Strand addressed	Overarching research question	*N*	Outcome	*N*	K-6	7–12	Adult
Science process skills	Can students use digital games to gain an understanding of the key process of science	5			1	4	1
			STEM practices	1			1
			Inquiry skills	2	1	2	
			Transfer	1		1	
			Motivation & engagement	1		1	

Note: Differences in row/column totals are due to studies that examined more than one age group or reported more than one finding.
*See Table 1 for details on each class finding.

indicated by the relationship between the independent variables and the accuracy of users' predictions. A similar finding was reported by Nelson (2007), who conducted a *River City* study with middle school students in which he explored the impact of embedded guidance messages on student understanding of real-world science inquiry processes and knowledge, as measured by pre- and post-implementation survey questions. Students in *River City* work collaboratively to solve a simulated nineteenth-century city's problems with illness by interacting with each other, digital artefacts in the game world, computer agents in the game world and various data collection tools in the game world. The study found that increased viewing of guidance messages was associated with significantly higher score gains on questions related to scientific inquiry and disease transmission.

Other studies have examined the development of process skills in augmented reality games that cast players in an 'investigator' role. Augmented reality games use digital technology, often hand-held computers, to add information or context to physical, real-world environments to create games or simulations within those real-world environments. A case of successful application of this technology is Rosenbaum, Klopfer, and Perry (2006), who studied 21 urban high school students playing *Outbreak @ The Institute*. *Outbreak* is an augmented reality game where players take on the roles of doctors, technicians and public health experts trying to contain a disease outbreak. Players can interact with virtual characters and employ virtual diagnostic tests and medicines while they move across a university campus in real life with hand-held computers. Rosenbaum, Klopfer, and Perry found that surveys, video and interviews of the students showed that the students perceived the game as authentic, felt embodied in the game, engaged in the inquiry and understood the dynamic nature of the model embedded in the game.

Students also take on the role of an investigator in the game *Crystal Island,* a microbiology mystery game. Spires, Rowe, Mott, and Lester (2011) conducted a study where 137 eighth-grade students, who had not previously been exposed to microbiology curriculum, took on the role of a scientific investigator searching for the cause of an illness that has struck in *Crystal Island*'s game space. In order to successfully combat this infectious disease, students must investigate, hypothesise, test and suggest treatments. Not only does the game allow students to participate in a meaningful way in the process of scientific investigation, specifically focusing on the process of creating and testing hypotheses, students also demonstrated

Table 4. Summary report of research on digital games for science learning – epistemological understanding.

			By type of finding*		By age group		
Strand addressed	Overarching research question	*N*	Outcome	*N*	K-6	7–12	Adult
Epistemological understanding	Can students use digital games to improve their understanding of what constitutes scientific knowledge?	3			1	3	
			Broad	2		2	
			Argumentation skills	1	1	1	

Note: Differences in row/column totals are due to studies that examined more than one age group or reported more than one finding.
*See Table 1 for details on each class finding.

Table 5. Summary report of research on digital games for science learning – participation and attitudes strand.

Subheading	Overarching research question	*N*	By type of finding*		By age group		
			Outcome	*N*	K-6	7–12	Adult
Total		15		20			
Motivation and engagement	Under which conditions do	7					
	students find games for science		Motivation & engagement	6	1	3	2
	learning intrinsically motivating?		Transfer	2		2	
			Inquiry skills	1		1	
Self-efficacy and emotion	Can students use digital games	3					
	as a way to see themselves as		Self-efficacy	2		1	1
	effective participants in the		Improved attitudes towards science	1		1	
	practices of science?		Inquiry skills	1		1	
Engagement with	Can students use digital	5					
science processes	games for learning to gain a		Inquiry skills	2	2		
	useful sense of how to participate		Collaboration	2	1		1
	authentically in the process of science?		Motivation and engagement	2	1		1
			null	1			1

Note: Differences in row/column totals reflect studies that examined more than one age group, or reported more than one finding.
*See Table 1 for details on each class of finding.

significant learning gains on concepts of microbiology as demonstrated by pre- to post-game tests.

In addition to learning inside games, other studies have investigated the development of process skills in the communities surrounding games, and the deployment of scientific language and processes in a form that was distributed across the community. Steinkuehler and Duncan (2008) studied the scientific habits of mind demonstrated in the discussion forums surrounding the commercial massively multiplayer online role-playing game *World of Warcraft*. The game itself features fantasy themes, but Steinkuehler and Duncan analysed 1984 posts by users in 85 different discussion threads and found that 86% of the posts involved social knowledge construction, more than 50% of the posts evidenced systems-based reasoning, roughly 10% evidenced model-based reasoning and 65% displayed evaluative epistemologies supportive of argumentation as a means for knowledge construction. Steinkuehler and Duncan argue that this is evidence that even popular commercial titles without a direct connection to science can support scientific thinking processes for members actively participating in the surrounding communities.

Process skills: summary

Because most studies shedding light on gains in process skills do so as a secondary focus to conceptual understanding, very few studies are discussed in this section in comparison to the first. That said, studies on the use of games for learning quite often centre on the learning of science concepts through guided inquiry activities, with the aim of providing an integrated inquiry–content–concepts experience. Games have been shown to provide opportunities for learners to conduct realistic inquiry activities often embedded in contexts modelled on real-world situations and mechanics. Participatory games set in virtual worlds have proven particularly effective at supporting the practice of realistic individual and collaborative inquiry around disease transmission and epidemiology, water cycle mechanics, ecology and evolution. Through embedded curricula and digital tools in games, learners are able to conduct virtual versions of essentially all the processes of inquiry described in the NRC report. In addition to learning in games, learning about process skills in the context of communities surrounding games is a hypothesis also being explored (e.g. Steinkeuhler & Duncan, 2008).

Research related to epistemological understanding

The third strand of science proficiency goals refers to students' understanding of 'the nature and development of scientific knowledge' (NRC, 2007, p. 39). As the report explains:

> This strand focuses attention on students' understanding of science as a way of knowing: the nature of scientific knowledge, the nature of theory and evidence in science, and the sources for, justification of, and certainty of scientific knowledge. It also includes students' reflection on the status of their own knowledge. This strand includes developing a conception of 'doing science' that extends beyond experiment to include modelling, systematic observation, and historical reconstruction. It also includes an awareness that science entails the search for core explanatory constructs and connections between them. More specifically, students must recognise that there may be multiple interpretations of the same phenomena. They must understand that explanations

> are increasingly valuable as they account for the available evidence more completely, and as they generate new, productive research questions. Students should be able to step back from evidence or an explanation and consider whether another interpretation of a particular finding is plausible with respect to existing scientific evidence and other knowledge that they hold with confidence. (NRC, 2007, pp. 39–40)

Whereas science classrooms traditionally centre on conceptual understanding and process skills, albeit not in the deep manner discussed in the NRC report, they generally focus less on epistemological understanding. Digital games have been held forth as offering excellent opportunities to support increased epistemological understanding but less research has been conducted on epistemological understanding to date. This line of research suggests that students who play digital games for science learning make progress in developing perspectives central to the processes of science. But, as is the case with the preceding section, the variety of behaviours associated with this construct (and the range of possible measurements for these behaviours) greatly limits the number of studies that qualified for inclusion into this section. Our selection criteria allowed us to classify only three studies under this strand, of which two were case studies and one used a design research methodology.

Generally, the studies we reviewed find evidence of improved epistemological understanding mainly in adolescent and pre-adolescent students (4th–12th grades) in a broad range of game formats. An overarching theme of this research is that immersive virtual contexts of digital games, combined with the situated embodiment they engender, seem to support learners in better understanding the complex and sometimes messy nature and development of scientific knowledge in the real world. Multiplayer virtual environment-based games, such as *Quest Atlantis*, *River City* and *Whyville*, which enable students to learn and practice authentic inquiry skills collaboratively, also help them better understand the nature and development of scientific knowledge.

A second group of studies on virtual worlds for science learning is concerned with demonstrating gains along a broader range of behaviours, understandings and forms of participation. Neulight, Kafai, Kao, Foley, and Galas (2007) investigated two sixth-grade classes' (46 students in total) understanding of a virtual infectious disease from a participatory simulation (*Whypox*, a part of the *Whyville* game environment) in relation to their understanding of natural infectious diseases. Students are able to experience a disease outbreak in the virtual world in which the game takes place. Qualitative analysis of the sixth-grade student chat in *Whyville* and, in answers to surveys, showed improved accuracy in participants' understanding of the spread of infectious disease. Also, Neulight et al. found that there was a significant shift in students' responses pre- and post-intervention from pre-biological to biological explanations; twice as many students reasoned about natural infectious disease with biological reasoning by the end of the curriculum.

Similar broad findings were reported with augmented reality games by Squire (2010), presenting a case study that investigated one enactment by 55 seventh-grade students of an augmented reality game-based curriculum called *Sick at South Beach*. The case study found that (a) fictional elements of the augmented reality game situated the learning experience and encouraged academic practices, (b) student-created inscriptions influenced the students' emerging understandings, (c) the game-based curriculum's design enhanced students' conceptual understandings and (d) learning through a technology-enhanced curriculum encourages students' identities as independent problem-solvers.

Squire and Klopfer's (2007) case study on the augmented reality game *Environmental Detectives* documented similar general progress towards developing an epistemological viewpoint of science. Squire and Klopfer (2007) demonstrated how students can (a) be supported in negotiating complex problem spaces that demand the integration of multiple information data sources and (b) develop a narrative of science on which they can build deeper understandings of both the conceptual content and the socially situated nature of scientific practice in the future. Related to this work in terms of studying student's understanding of argumentation as part of the epistemic process of science, Squire and Jan (2007) presented a cross-case comparison of three case studies, involving students in fourth grade, middle school and high school, involving approximately 28 students who participated in the place-based augmented reality game *Mad City Mystery*, which focuses on environmental science. Squire and Jan demonstrated that *Mad City Mystery* engages students in meaningful scientific argumentation as they develop narrative accounts of scientific explanation.

Epistemological understanding: summary

There is some tentative evidence from games research that these platforms can positively impact learners' epistemological understanding of the nature of science and scientific thinking (Table 4). At the same time however, it is important to note that it is somewhat difficult to disentangle epistemological and conceptual understanding in these studies. In most cases, the studies were not centred directly on epistemological understanding, but the study authors make inferences linking demonstrated gains on content and concept measures with corresponding increases in students' knowledge of processes of scientific inquiry. Because most studies shedding light on gains in epistemological understanding do so as a secondary focus, very few studies are discussed in this section in comparison to the first. Most studies including findings related to epistemological understanding featured a primary focus on conceptual understanding, and thus are discussed in that section. More research on the affordances of games for science learning connected to epistemological learning is clearly needed. Work in adjacent fields of educational technology may inform our understanding of the impact of games and simulations on students' epistemological understanding and suggest directions for further scholarship. For example, research into Internet-enabled learning environments has investigated the link between students' epistemologies of science and their use of computerised learning environments (e.g. Tsai, 2001, 2004); similar work has not yet been done in the realm of games for science learning that establishes this link.

Research related to participation and attitudes

The fourth and final science proficiency strand focuses on students' ability to 'participate productively in scientific practices and discourse' (NRC, 2007, p. 40).

> To understand science, one must use science and do so in a manner that reflects the values of scientific practice. Participation is premised on a view that science and scientific knowledge are valuable and interesting, seeing oneself as an effective learner and

> participant in science, and the belief that steady effort in understanding science pays off. To participate fully in the scientific practices in the classroom, students need to develop a shared understanding of the norms of participation in science. This includes social norms for constructing and presenting a scientific argument and engaging in scientific debates. It also includes habits of mind, such as adopting a critical stance, a willingness to ask questions and seek help, and developing a sense of appropriate trust and skepticism. (NRC, 2007, p. 40)

This proficiency strand, which we refer to as 'participation and attitudes' for brevity, thus encompasses students' self-efficacy, identity and attitudes surrounding their interest and willingness to engage in inquiry and science. Whereas science classrooms have traditionally been satisfied with the goal of helping learners understand things from a third-party perspective, the NRC report describes goals of engaging students directly in the experiences and in having students come to view themselves as interested and able to engage in these processes. While this strand of science proficiency has not been a significant goal of traditional science instruction, it has been a goal of research on digital games for science learning.

Research into digital games for science learning is heavily motivated by perceived opportunities for increased engagement. In fact, it may be said that the prime mover behind much game-based learning research is the repeated finding that learners readily engage with digital games and persist at them, sometimes far more than they would with thematically similar but more traditional educational media. For example, Sanford, Ulicsak, Facer, and Rudd (2006) conducted a survey of what students and teachers think about commercial games. They found that (a) students love games and want to play them and (b) teachers do not play them but think that they might be useful for learning because they are motivating and engaging for students. As a specific example, Galloway (2006) found that integrating learning activities in the *Neverwinter Nights* game engine in a college course increased course completion and grades for specific skills ranging from 30% to 100% (as cited in de Freitas, 2006).

Whereas relatively few studies were discussed in the second and third sections because most studies that reported on process skills or process skills did so as a secondary finding to a primary focus on conceptual understanding (and thus were discussed in that section), a larger number of studies (15 of the 56 reviewed) are centred primarily on participation and attitudes (Table 5). Regarding the choice of methodology of these 15 studies, five used experimental methods, five were case studies, two were large-scale assessments, two could be described as design research and one was ethnographical. In consideration to the variety of methods and research questions represented in this subset, we organised the studies in this section into three groups according to the change in participation and attitudes that researchers observed. The first group of studies found increased interest and willingness by students to participate in the processes of science. In the second group, researchers observed that students displayed an increased sense of self-efficacy, i.e. they felt more capable and effective in engaging with science topics. Finally, we grouped together those studies in which a digital game was central in enabling students to feel as active, central participants in the enterprise of science. Naturally, there is some overlap between these categories (and with the two preceding sections), but the studies themselves encompass a cross-section of grade levels, experimental designs, research questions and outcomes. That students across all these studies improve their participation and their attitudes towards science suggests that digital games themselves have elements that scaffold engagement and self-efficacy.

Motivation and engagement

While digital environments are generally considered to be appealing to students, evidence from studies on game-based learning suggests that the addition of a convincing context and a layer of game-based interaction can enhance the motivation and willingness of students to productively engage with a simulated world and its science-based concepts. Some researchers have specifically investigated the features of games for science learning that students find most motivating and engaging. For example, Barab, Arici, and Jackson (2005) reported on their iterative design process in creating and modifying Q*uest Atlantis* to support engagement, finding (among other things) the need for a strong narrative backstory.

A significant portion of the research demonstrates that design is crucial to successfully engaging students, and that extends to providing a range of interfaces that are more immersive and accessible to students than the conventional computer desktop. Jones, Minogue, Tretter, Negishi, and Taylor (2006) investigated the impact of haptic (sense of touch) augmentation of a science inquiry simulation/game (*Mystery of the Sick Puppy*) on 36 middle school and high school students' learning about viruses and nanoscale science. They compared use of a sophisticated haptic desktop device, a haptic gaming joystick and a mouse (no haptic feedback). Results showed that the addition of haptic feedback from the haptic gaming joystick and the sophisticated haptic desktop device provided a more immersive learning environment that made the instruction significantly more engaging across engagement measures and significantly influenced the way in which the students constructed analogies in their understandings about the abstract science concepts across measures. Thus, providing the students with increasingly haptic feedback greatly increased the efficacy of the environment.

Not only is the design of the game important, the design of activities around the game is also important for learning. Lim, Tay, and Hedberg (2011) studied *Quest Atlantis* in two fifth-grade classrooms with the goal of finding ways to structure the classroom activities in order to effectively integrate the multiuser game virtual environment. They note multiple areas that can be developed in order to optimise the utility of a multiuser environment. Initially, the 3D environment and the navigation in the game proved to be rather distracting for the students, and as a result, they had low levels of engagement in the education quests, instead choosing to simply explore the environment. The authors suggested that scaffolding of the game is necessary to allow students to achieve high levels of engagement, and with the additional teacher coaching and whole class discussions, students reached higher levels of engagement in the educational tasks within the game.

Even without a specific design focus on engagement, it is clear from the research that learners of all ages find games for science learning more appealing than the science content by itself. For instance, Coller, Shernoff, and Strati (2011) presented the results of a multiyear study where the game *EduTorcs* was introduced into an undergraduate mechanical engineering course and, over the course of three years, student engagement and other factors were measured. *EduTorcs* asks students to write a control algorithm that will allow them to carefully drive and manoeuvre cars and bikes through the virtual environment of the game. Students in the course were significantly more engaged in year three of the study, in which they had the game, than in year one of the study, in which they did not have the game. In year three, 50% of the students reported that their coursework felt like both work and play, while only 15% of students made that claim in the first year. Students were also significantly more intrinsically motivated to complete coursework and reported significantly more positive affect. Similarly, Munz, Schumm, Wiesebrock, and Allgower (2007) found the motivational aspect of educational games as highly influential in helping undergraduate students bridge the gap between theory and practice of systems analysis. Two-thirds of 150 students in those courses found that playing a game helped them understand a difficult topic. The authors also report that 97.5% of students used the game unprompted.

In a study with slightly younger learners, Papastergiou (2009) found games to be both highly motivating and, consequently, effective learning tools. In the study, 88 high school students learned concepts of computer science through one of two computer-based methods. Two computer applications were created, the first, *LearnMem1*, was a game-based application and the second, *LearnMem2*, was non-game based application. The game-based learning approach correlated with higher student motivation and greater conceptual learning. Papastergiou suggests that this study provides even stronger support for game-based learning than previous studies on the topic due to the fact that the game-based learning was not compared with traditional learning techniques, but, instead, was compared to a web-based technique that students find appealing. In this way, it demonstrates that student motivation and learning are positively impacted by the game aspect, not simply by the novelty or appeal of the non-traditional method.

Many studies have researched the value of immersive game environments as platforms for situated curricula that can motivate and engage students to learn and apply science content and process skills. Some studies we have summarised in previous sections also note increased engagement and positive affective outcomes, in addition to whatever gains students may have shown on measures of conceptual or epistemological understanding. For instance, Ketelhut (2007) investigated sources of student engagement in *River City*, finding that middle school students reported the ability to conduct inquiry as a key motivating element, along with the ability to use virtual tools such as bug catchers and microscopes to aid in their inquiry. Similarly, in a study investigating a middle school classroom' use of a science inquiry curriculum embedded in the *Whypox* event in *Whyville*, Galas (2006) found that the curriculum was engaging for students and supported realistic opportunities to collaboratively conduct scientific inquiry.

Self-efficacy and emotion

Studies in this research strand focus on the repeated finding that people tend to work hard, persist and demonstrate enhanced performance when they expect to do well (Pintrich, 1999). A person's sense of self-efficacy represents a set of beliefs that are specifically restricted to beliefs about personal capabilities to learn and employ skills and knowledge (Schunk, 1991; Weiner, 2010). In the science classroom, these beliefs manifest themselves as a willingness by learners to engage in challenging open-ended tasks while retaining a sense of competence when obstacles arise, among other things. Since this descriptor might well be applied to the scientific enterprise as a whole, it is therefore crucial to support students in developing beliefs of self-efficacy and competence that orient them in such a way that they can see themselves not as passive recipients, but as doers of science.

Research into digital games for science learning that fall into this category investigate how students leverage the experience of playing a science-based game into personal narratives about being a scientist or participating in science authentically. For example, in a study based on the *River City* software, further work by Dieterle (2009) showed that a set of 574 students who completed the curriculum had statistically significant gains in measures of self-efficacy in science inquiry. Specifically, he found that (a) students who preferred creating and sharing artefacts through the Internet were well equipped for learning about disease transmission and scientific problem-solving skills in the curriculum and that (b) students who felt highly connected with the media, tools and people involved in their communication, expression and problem-solving within the curriculum were more likely to believe they could successfully complete the activities that a scientist might engage in. In addition, participants in these kinds of games report changes in their understanding of what science means and of how they view themselves in relation to science.

Research by McQuiggan, Mott, and Lester (2008) investigated how intelligent tutoring systems and games might assess student's sense of self-efficacy using a combination of questions, physiological measures and behaviours in the environment. McQuiggan and colleagues were able, in a study of adults, to correctly classify approximately 85% of instances with regard to student's sense of self-efficacy. To further complement this work, McQuiggan and Lester (2007) explored methods for modelling and evaluating the empathy displayed by embodied companion agents and the degree to which empathy might enhance the agents' efficacy in supporting learning.

Engaging students in authentic practices

A number of studies have also centred on issues relevant to the fourth science proficiency strand in terms of how game-based curricula in multiplayer virtual environments can support and promote authentic scientific practices and the use of science-centred discourse. For example, Barab and his colleagues have conducted a number of studies in this area around their Taiga curriculum in the *Quest Atlantis* virtual environment studying similar questions (e.g. Barab, Sadler, et al., 2007; Barab, Zuiker, et al., 2007; Barab et al., 2009). In one such study, they report on a mixed methods study into the power of the Taiga curriculum to support the kinds of productive inquiry practices and scientific discourse described in the NRC report (Barab, Sadler, et al., 2007). In the design experiment with 28 fourth-grade students in a gifted class, *Quest Atlantis* researchers found that all participants were actively engaged in discourse related to the inquiry tasks of the curriculum, and that they participated actively and productively in inquiry practices (data gathering, negotiation, data interpretation, etc.).

In her *Whyville* implementation, Galas (2006) found that the Whypox curriculum supported realistic opportunities to conduct collaborative scientific inquiry. Middle school students in the study worked together to track the spread of the disease. Study participants also visited *Whyville*'s 'Centre for Disease Control' to gather and share information about the disease outbreak, and used an embedded simulation that modelled the ways in which diseases spread through a population.

In addition to engaging students in authentic scientific inquiry, the use of computer games as empowering contexts where students can tackle complex engineering challenges is also an emerging theme. Mayer and van der Voort (2006) edited a special issue of *Journal of Design Research* featuring participation by students in collaborative design or engineering tasks set within game environments. In this issue, Bekebrede and Mayer (2006) contrasted attitudes and outcomes for professional and students engaged in a cooperative game, *SIM Maasvlakte 2*, featuring a complex design task. They found that, while both groups reacted very positively to the game, students found the game more enjoyable and relevant to their studies, while professionals found more value in the level of detail of the design task and its potential to promote cooperation. Bianconi, Saetta, and Tiacci (2006) used a web-based game to simulate a design project with many complex variables and interactions. Students played cooperatively for 72 hours and turned in their final design for evaluation. The authors found that, while students adopted professional strategies to organise themselves and solve the design task, the specific techniques that those strategies entail did not transfer as well, suggesting that the nature of the game promoted a more idiosyncratic approach. And finally, Johns and Shaw (2006) examined concept generation, collaboration and peer critique in a group of design students working together to produce designs in the context of a physics game. When compared to traditional design processes used in class, students were more likely to critique each other's work and negotiate design ideas as a team when using the game environment. These studies highlight the value of games that engage students with problems that are complex and multifaceted, while retaining opportunities for collaboration.

Participation and attitudes: summary

Research suggests that games can increase motivation and engagement, that they can engender positive affect and that they can engage students in practices that the students perceive as authentic (and which more closely resemble authentic practices than typical classroom practices). As with the other strands, the importance of design is highlighted for both games, although there is more emphasis on affective dimensions compared to the typical cognitive focus of research on design principles for learning.

Synthesis and implications

In summary, the research reviewed suggests that digital educational games can support science learning across the NRC's four strands of science proficiency. Our analysis indicates, however, that there are necessary caveats. We can more easily discuss overall patterns in the literature by summarising and categorising the studies we examined in terms of (a) the strand they support, (b) the type of finding they report and (c) the age group of the study participants.

Concerning the distributions, some disparity appears in the distribution of studies across focal age group. Table 6 includes a substantially higher frequency of studies focusing on middle school and high school populations (grades 7–12) compared to K-6 or college and older. One possible explanation is that games for science learning are heavily centred on student populations where science is a separate subject (i.e. often starting around grade 7 in many countries). These may also be the grades in which science learners might especially benefit not only from

Table 6. Summary report of research findings on digital games for science learning.

Strand addressed	Overarching research question	*N*	By type of finding* Outcome	*N*	By age group K-6	7–12	Adult
All strands		56					
Conceptual understanding	Can digital games help students learn science concepts?	33					
			Transfer	18	5	5	8
			Broad	7	5	3	
			Motivation & engagement	7	1	2	4
			Engineering skills	4		3	1
			null	5		3	2
Science process skills	Can students use digital games to gain an understanding of the key process of science	5					
			Inquiry skills	2	1	2	
			STEM practices	1			1
			Transfer	1		1	
			Motivation & engagement	1		1	
Epistemological understanding	Can students use digital games to improve their understanding of what constitutes scientific knowledge?	3					
			Broad	2		2	
			Argumentation skills	1	1	1	1
Participation and attitudes	Can students use digital games to gain a sense of participation in the enterprise of science and to see themselves as potential scientists and engineers?	15					
			Motivation and engagement	8	2	3	3
			Inquiry skills	4	3	2	
			Self-efficacy	2		1	1
			Transfer	2		2	
			Collaboration	2	1		1
			Improved attitudes towards science	1		1	
			null	1			1

Note: Differences in row/column totals are due to studies that examined more than one age group or reported more than one finding.
*See Table 1 for details on each class finding.

improved conceptual understanding but also from the motivational affordances that digital games can provide. Furthermore, many approaches to digital games for science learning have incorporated text, which in turn requires some degree of literacy, which might also explain some of the emphasis on middle school and high school in comparison to the elementary grades. The lower emphasis on college and adults may represent an artefact of research funding, which often focuses more heavily on the K-12 grades for science education.

Larger disparities appear in the distribution of studies across proficiency strands. The majority of the 56 reviewed studies are concerned mainly with either the conceptual understanding strand or the participation and attitudes strand, whereas the other two strands represent the primary focus of far fewer studies. Furthermore, the conceptual understanding strand includes more than twice as many studies as the participation and attitudes strand (and more studies than the other three strands combined).

There are several possible interpretations of this imbalance. Standards and policies in many countries emphasise standardised test performance, which in turn tend to focus on conceptual understanding. It is therefore not surprising that designers and researchers of educational games are mainly concerned with outcomes related to conceptual understanding. More specifically, science curriculum standards in many countries include large numbers of concepts that students must learn. Furthermore, many of these concepts inform and support each other, making it difficult for students with incomplete understanding of these concepts to advance to more complex ones. From this perspective, the potential pay-off in terms of student achievement is very appealing to educators and researchers, particularly when presented in a medium to which school-aged children generally respond positively.

The relatively heavy emphasis on participation and attitudes is also not surprising given the perceived affordances of digital games for engagement and with regard to allowing students to explore various roles and identities. A common, although often untested, assumption is that increasing engagement will increase interest in not only STEM topics but also STEM learning. A related explanation is that playing games that cast students as scientists contributes to their self-efficacy as learners and participants in the scientific enterprise. This is an important consideration when games for learning are paired with notions of equity. Students who feel isolated from the pursuit of science or who do not have access to rich science learning experiences might not consider themselves as capable of science learning or future careers in STEM. The broad appeal of digital games, which cuts across ethnic, cultural and socio-economic boundaries, could be leveraged to increase the self-efficacy of all science learners and, in the long term, direct more of them towards careers in science and technology. That said, our sample contains only three studies that investigated self-efficacy of science learners as the primary focus and only two that report increases in self-efficacy, mainly as secondary findings. However, given the connections between self-efficacy and motivation (cf. Schunk, 1991), and the fact that our reviewed literature provides ample evidence for increased motivation, digital games appear likely to help improve the self-efficacy of science learners as part of games' broader affordances for motivation. That said, further research in this area is clearly warranted and needed.

Finally, current models of assessment likely contribute to the uneven distribution across strands. Research into games that concentrate on the conceptual understanding and participation and attitudes strand benefit from the relatively straightforward argument that can be made between improved outcomes within these strands and gains in the most commonly used educational measurements. Furthermore, the conceptual understanding strand tends to align most closely with existing assessment instruments, while measures of self-efficacy, interest and engagement are also widely available. Process skills and epistemological understanding, however, factor less directly into existing models of assessments of science learning (particularly those concerned with standardised testing). The lack of emphasis on these topics at the assessment level likely contributes both to lower buy-in from teachers and administrators as well as problematic issues in terms of research methodologies.

Methodologies represented in the literature

While the goal of our review is to present the various ways in which digital games have been found to support science learning, we have aimed to do so in a way that fairly portrays the rich texture and variety of the educational games literature. We argue that this variety reflects (a) the broad range of activities that could be called 'digital games'; (b) the many potential outcomes of these activities and (c) the efforts of researchers in this field to understand these outcomes causally, without oversimplifying or misrepresenting the nature of the activities. We have thus far constructed an overarching narrative for this body of research mainly in function of its goals and outcomes, not on its methods. However, our survey would be incomplete without commenting on the frequency and distribution of certain research methodologies, and their implications.

As shown in Table 7, the majority of the studies in our sampled literature can be described as either experiments or case studies. Understandably, research aimed at conceptual understanding outcomes tend heavily toward using experimental methods, as this method is best suited for detecting pre–post intervention differences along some measure of learning. Outside of this strand, case studies are more prevalent; we interpret this trend as an effort by researchers to situate the learning effect of digital games in the broader framework of science education, specifically in classrooms. This research would necessarily be more context-bound and have more unique features across games, grade levels and curriculum topics. Also, some research questions almost require certain methodologies, and the frequency of appearance of the latter is directly related to the extent of efforts into the former. For example, the hypothesis that games can improve the self-efficacy of science learners has mainly been investigated through ethnographies and design-based research (e.g. Eseryel, Guo, & Law, 2012; Pelletier, 2005; Squire et al., 2007) and theoretical arguments (e.g. Barab et al., 2010; Gee, 2003/2007) and, as we have seen, has not yet been thoroughly reported.

Implications for research

Researchers have recognised the need for synthetic work that helps guide the next wave of research. Several works have recently been published to that end (e.g. Young et al., 2012). In addition to the general issues of distribution discussed above, we make the following recommendations from what we feel are three important gaps in the literature based on the literature we have reviewed.

First, in light of the fact that 50% of teens play video games daily (Lenhart et al., 2008), it makes sense that the majority of findings were reported with high school and college students. This bias is strongest where transfer findings are concerned; only 5 of the 23 studies that reported transfer of knowledge from the gaming context involve learners in K-6. While this may simply reflect the aforementioned focus of research on grades 7–12, it may also suggest that the affor-

Table 7. Research styles represented in the literature on digital games for science learning.

			By strand			
Type of finding	Definition	*N*	Conceptual understanding	Science process skills	Epistemological understanding	Participation and attitudes
Experiment	Comparison under controlled conditions, with the intention of producing generalised knowledge	27	20	2		5
Case study	Portrayal, analysis, and/or interpretation of situated actions by individuals in unique instances	20	12	2	1	5
Design research	Implementation of a design intended to improve a specific outcome or problem of practice; analysis of a design in terms of its outcomes	5	2		1	2
Testing and assessment	Measurement of achievement or performance under specific circumstances	2				1
Ethnography	Portrayal of events in the participants' own terms	1				1
survey	Large-scale gathering of context-free data	1		1		

Note: Research styles, and their definitions, adapted from Cohen et al. (2007).

dances of digital games as a medium with regard to the learning processes of younger students remain a bit of a mystery. This possibility seems more salient when we consider that, as a whole, the state of the art of commercial game design (and thus the design expertise that educational researchers have primarily leveraged) is geared almost exclusively toward adult gamers. Creating an engaging game that is accessible to adolescents is challenging enough even when no attention is placed on learning outcomes; to build a game that engages young children and promotes learning of specific content is likely a far more complex task involving research on development, cognitive processes and more.

Second, while the reviewed studies most frequently focus on broadly defined cognitive skills, there is high variability in terms of the goals, methods and standards of evidence within this grouping. Many of the papers that we categorised as centred mainly on 'broad' cognitive outcomes feature constructs such as 'understanding', 'metacognition', 'reasoning' and 'problem solving'. While these constructs are undoubtedly critical for science literacy, it may be more difficult to make generalised claims for the educational affordances of digital games based on improvements of broad thinking skills because of differences in how educational researchers and classroom practitioners may categorise and prioritise these skills. In order for future findings into cognitive skills to satisfy both groups, it may be more effective to increase the specificity of the research questions and to demonstrate how cognitive skills developed through gaming impact science learning. This, in turn, will place a greater premium on sophisticated research methodologies, particularly where assessment is concerned. However, educational researchers need not reinvent the wheel in this regard. There is, in fact, a rich and growing body of research from the field of psychology and neuroscience that focuses on digital games as learning tools. Researchers interested in cognitive skills might find it productive to build partnerships with psychologists and neuroscientists who may be asking parallel questions.

Finally, of the 56 studies we reviewed, only six reported null findings. The absence of null findings complicates the task of clarifying design principles for leveraging affordances of the medium. The importance of advancing the state of the art of educational game design cannot be overstated. While design is key for all learning activities, as highlighted in the NRC's report on the efficacy of laboratory activities (NRC, 2005), attention to issues of design is key to digital games for learning for two reasons. First, the design space of educational games is very large. Educational games require an extensive, and expensive, design phase. Efforts during this phase are ideally informed by exemplars of successful design present in the literature. However, without sufficient examples of *un*-successful designs, there is no real way of knowing which design traits to emulate, refine or discard altogether. Furthermore, there are many variations within the medium concerning characteristics such as genre, platform, intended age group, topic and allocation of class time. Individual research groups cannot investigate this space exhaustively on their own. Both 'what works' and 'what doesn't work' need to be equally reported and disseminated given the complexity and scope of the design and development process for educational games. Research into games for learning would thus benefit greatly from increased publishing of null findings, as well as broader dissemination of ideas across research communities to minimise redundant efforts across programmes of research, particularly efforts on known underproductive approaches.

Final thoughts and next steps

History is littered with technological tools for learning that ultimately had little impact on learning but that enjoyed levels of enthusiasm and research interest similar to that now afforded games (Cuban, 2001). Thomas Edison famously predicted that motion pictures would completely revolutionise education, replacing textbooks and traditional classroom instruction. But, when studies were conducted on the impact of film on learning, results were mixed (Oppenheimer, 2003). In a similar sense, it would be foolish to claim that games are superior to other forms of instruction for all applications. Every tool has specific affordances. In this paper, we have tried to identify evidence pertaining to specific examples of the affordances of science games along several dimensions.

Overall, the research suggests that games can support science learning across the NRC's four strands of science proficiency with the greatest emphasis on conceptual understanding and engagement and participation. The key for all learning activities, as highlighted in the NRC's report on the efficacy of laboratory activities (NRC, 2005), is design. It is therefore the time to move beyond simplistic questions about whether games are 'good' or 'bad' for science learning. Similarly, asking whether games as a medium are better or worse than other media is not productive. Clearly, there are more and less effective designs for books, labs, movies, simulations and games depending on goals and audience. The important questions focus on what affordances are offered within a medium, which design approaches are productive, and for whom (cf. Underwood, Banyard, & Davies, 2007).

Furthermore, researchers of games for learning have based their questions and inquiry on a multitude of theoretical viewpoints including behaviourism, cognitive science, constructionism, constructivism, situated cognition, socio-constructivism and more. Theoretical views driving the design and implementation of games for STEM learning have evolved, and will continue to evolve as surely, if not as rapidly, as the technology of the tools themselves. One lesson to take from this diversity of views and approaches is to strive for open-minded yet critical agnosticism in developing games for science learning. We can apply and adapt the theories and design principles to the tasks, recognising the theoretical framework from which a given tool, learning perspective, or analytical methodology has sprung while carefully adapting them to new goals and settings. Likewise, researchers should take a pragmatic approach in applying findings from research done in the past and/or conducted under a different theoretical banner from their own situations, audiences and settings. Our own organisational framework, examining past and current research as it can be applied to the goals defined in the NRC report, is an example of this kind of pragmatic approach. The report's goals reflect the current thinking on what it means to 'know science'. The work described in this paper was conducted under a variety of assumptions, but this diverse inclusion provides guidance for current and future work under prevailing views of learning.

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