Chapter 3
Digital Games for Science Learning and Scientific Literacy

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Abstract In this chapter, we focus on the links between science learning and digital games. We review previous studies in the field, identify key findings and propose a conceptual model for further research. We view digital games not only as media through which players can explore and understand or be motivated to further study the learning content, but also as cultural and social practices within which gameplaying is situated. The main themes discussed in this chapter as factors relevant to the support of science learning and scientific thinking through game-based learning are (a) game design issues, (b) individual factors such as game preferences and motivations, game experience and literacy, and perceptions of games and (c) the social and cultural context of gameplaying (e.g. formal, non-formal and informal learning settings). Digital games can be effective instructional tools for science education but in this chapter we further examine how they can become tools for empowering the learners to meaningfully engage with science and how they can support the learners' scientific literacy and citizenship.

Keywords Science learning · Scientific literacy · Game-based learning · Digital games · Literature review

3.1 Introduction

Back in 1997, in his book "*The demon-haunted world: science as a candle in the dark*", Carl Sagan wrote about the importance of scientific thinking and the scientific method in our everyday lives, and how crucial critical and sceptical thinking against fallacious arguments and deception is. Over the past years, with the spread of disinformation and the role the media and their impact on people's behaviours, decisions and attitudes (Koltay 2011), the importance of critical and scientific thinking is still relevant. Skills for evaluating evidence-based claims such as news articles and advertisements and for identifying "*bogus claims*" are needed for everyone and

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particularly for children as future consumers, scientists and citizens (Halpern et al. 2012).

In this chapter, we focus on the links between science learning and digital games. We review previous studies in the field, identify key findings and propose a conceptual model for further research. We view digital games not only as media through which players can explore and understand or be motivated to further study the learning content, but also as cultural and social practices within which gameplaying is situated.

The main themes discussed in this chapter as factors relevant to the support of science learning and scientific thinking through game-based learning are (a) game design issues, (b) individual factors such as game preferences and motivations, game experience and literacy, and perceptions of games and (c) the context of gameplaying (e.g. formal learning settings, non-formal settings such as workshops on game-based learning, informal settings such as game exhibitions and contests).

3.1.1 Scientific Literacy

Scientific literacy involves a range of skills and concepts such as science identity, scientific reasoning, scientific enquiry and mastery with science-related content, activities and methods. These skills and concepts relate not only to content knowledge, but also to knowledge and understanding of scientific practices, as well as the global context science is situated in and its contribution to society (Fraser et al. 2014; OECD 2012; Wallon et al. 2018). Knowledge of the scientific practices and content knowledge seem to complement each other. Science content knowledge is related to scientific sense making and scientific literacy skills (Cannady et al. 2019). Students who engage with scientific practices can learn science content more effectively.

A number of different factors seem to have an impact on the scientific literacy of children. Archer et al. (2015) discussed the concept of *science capital* as a set of environmental factors affecting students' attitudes towards science, such as their family, friends and daily activities (e.g. visits to museums, after-school programmes, access to science-related resources). Similarly, Markus and Nurius (1986) discussed the concept of the *possible self* (i.e. expectations and hopes of what one can become in the future) and linked it with personal experience and the environment, e.g. cultural norms, friends, teachers, parents and the media. Beier et al. (2012) built upon the *possible self* construct and proposed a measure for the scientific *possible self* of students for examining the impact of a science-focused game on the possible selves of the students.

In a formal or informal learning environment, interesting and motivating experiences may have a positive effect on personal interest and engagement with science-related activities, as well as on individual attitudes and predispositions towards science. Studies have shown that instructional interventions and techniques triggering *situational interest*, such as hands-on activities, toys and science games in formal education settings can increase *individual interest* and further participation in science-related activities in informal settings, such as talking, thinking and reading about science (Hidi 1990).

It seems, therefore, that science literacy and attitudes towards science are influenced by the quality of the learning activities as well as the context these activities are situated in, and the social environment of the children.

3.2 Game-Based Learning

Extensive literature on game-based learning over the past 20 years shows that games can be used as instructional and learning tools; they can integrate various learning theories and pedagogical techniques; they can support a number of different learning outcomes such as content understanding and problem-solving skills and facilitate transfer of knowledge and understanding of processes and practices to other domains (Egenfeldt-Nielsen 2007; Kafai 2006; Ke 2009; O'Neil et al. 2005; Shaffer 2006).

As digital games can simulate complex systems and allow the players to explore and experiment with the role of each component and the relationships among the components, they have the potential to support scientific literacy objectives (e.g. content knowledge, systems thinking, social implications). In their report, Clark et al. (2009) review existing games and studies on science learning, and identify goals such as conceptual understanding and process skills, epistemological understanding, attitudes and identity, and design issues. Games can further be motivating learning experiences for the students, increasing the depth and duration of the students' engagement with the learning content (Cordova and Lepper 1996; Ryan et al. 2006). Considering this potential of games for science learning (National Research Council 2011, p. 2), and the need for further study of the factors involved (see also Li and Tsai 2013 for a meta-review on this topic), we reviewed latest literature in order to identify trends and factors in relation to the games' content, design and integration into learning settings for science literacy.

3.3 Science Learning and Digital Games

Although this chapter is not an extensive, empirical meta-review, we tried to get a better and unbiased understanding of the area by following a more standardised protocol for identifying representative trends in the area: we used Google Scholar as a publicly available index of scholarly literature with the keywords ("games" OR "game") AND ("science" OR "scientific"), so that the search can be easily reproduced. The search, on October 2019, returned approximately 994 results without including patents or citations. After (a) limiting the range to more recent studies, over the past decade following up on Li and Tsai's review (2013) and up to 2019, (b) excluding papers not written in English, (c) only including journal articles which had received at least 10 citations for ensuring the quality of the studies reviewed and

(d) excluding papers not relevant to digital games and science education or learning, the remaining set of 30 papers was more thoroughly examined. In the following sections, we describe main trends relevant to the learning goals, the games used, factors involved, research settings and methods.

3.3.1 Research Methods

Most of the studies reviewed used experimental or quasi-experimental conditions, collecting data from pre-post surveys measuring constructs such as flow experience, knowledge, attitudes about games and perceptions about self-efficacy in science or games. Observations and interviews have also been used for collecting data on the context of gameplay and for gaining more in-depth insights on the motivations, perceptions and interpretations of the participants. The participants' concept maps have also been used as data collection instruments for analysing their perceptions, mental schemata and prior knowledge [e.g. Waddington and Fennewald (2018)].

A large number of studies further examined the actual gameplay, in-game behaviours and performance of the participants, collecting and analysing data such as video recordings of gameplay, game metrics such as playtime and number of restarts, log files, eye-tracking and videos of facial expressions for studying attention allocation and emotion (Ault et al. 2015; Hou 2015; Muehrer et al. 2012; Taub et al. 2018).

In one case, where physical activity was also examined, heart rate monitors were used for data collection (Sun and Gao 2016). An ethnographic study was used, in another case, on public online fora, for studying motivations for participation in citizen science projects (Ponti et al. 2018).

3.3.2 Science Domains and Learning Objectives

Recent reports and meta-reviews of empirical studies on game-based learning for science learning indicate an emphasis on learning goals such as learning scientific content knowledge, conceptual understanding and knowledge, knowledge construction, problem-solving, engagement and participation, while aspects such as complex problem-solving, critical thinking, understanding of scientific processes, epistemological understanding, the potential of games to motivate interest in science, affective outcomes, and socio-contextual learning are less researched (Cheng et al. 2015a, b; Li and Tsai 2013; Martinez-Garza et al. 2013; National Research Council Report 2011, p. 2). It was also found that the games used in previous studies were mainly focused on physics and biology or they were interdisciplinary. With these limitations in mind, we sought to examine whether these trends persisted over the past decade and also identify any relevant factors as barriers or possibilities.

Most of the studies we reviewed focus on scientific fields such as Physics, Biology, Chemistry and Environmental Education, with very few examining game-based learning in Social Sciences. Additionally, there seems to be a shift to learning objectives such as understanding of scientific processes and practices, attitudes towards science and higher order thinking skills.

Biology-related games (e.g. on neuroscience, virology, evolution), mainly single-player except Ketelhut et al. (2010) who used the multiplayer game *River City*, featured quite prominently among the studies on science learning, examining learning outcomes such as scientific argumentation, scientific inquiry (e.g. making hypotheses, gathering and analysing data, proposing predictions), conceptual understanding of scientific processes, transfer of knowledge, procedural knowledge and higher level of cognitive process, with generally positive results (Bergey et al. 2015; Cheng et al. 2014; Wallon et al. 2018). Israel et al. (2016) examined the relation between personal characteristics such as learning disability, gender and perceptions of games with the learning outcomes, situated their study in the context of scientific literacy, informed citizenship and interest in science-related careers and developed biology games (*Cell Command, Crazy Plant Shop, You Make Me Sick!*) aiming to address both content knowledge and problem-solving ("*thinking like a scientist*"). Although Marino et al. (2013) didn't focus on learning outcomes but rather on the correlations among factors such as gameplaying behaviours, reading ability, perceptions on scientific ability and disability status, they used the games *You Make Me Sick!* and *Prisoner of Echo* which focus on virology and physics, respectively, for examining students' attitudes about science and the work of scientists, and learning science through games. Even though Cheng et al. (2015a, b) mainly addressed content knowledge using the game *Virtual Age*, they recognised the need for further study of learning outcomes such as problem-solving and scientific reasoning. Results were not always positive, though, depending on certain conditions. Muehrer's et al. (2012) results, for instance, who used the game *Genomics Digital Lab*, showed that students improved their science vocabulary and not their understanding of abstract concepts. Also, Taub et al. (2018), using the game *Crystal Island*, found that efficiency at solving the game problems was significantly related to the gaming behaviours of the players (e.g. manipulation of the game items), concluding that appropriate scaffolding is required in game-based learning environments.

Physics (e.g. light and shadow, Newtonian mechanics, the solar system) was another prominent science domain for science learning through games. Similarly, higher order cognitive skills were addressed, such as scientific knowledge construction (Hsu et al. 2011), conceptual change—using the game *Space Challenge* (Koops and Hoevenaar 2013), scientific inquiry through experimentation and collaborative learning—with *Quantum Moves* (where students had to build a quantum computer) (Magnussen et al. 2014), content knowledge, problem-solving and scientific inquiry—with *Alien Rescue* (Liu et al. 2014), and also implicit science knowledge—with the *Carrot Land* (Chen et al. 2015) who also observed the emergence of collaboration and collaborative problem-solving in the collaborative play condition. Sun and Gao (2016) combined the physics game *Earth, Moon and Sun*, where students have to learn information about the solar system, with a stepper for students to control the game with, for examining science learning and motivation, in relation to physical activity. In both conditions, they found increased learning outcomes (science knowledge) and situational interest.

Similar learning objectives, such as science content, problem-solving, scientific inquiry meta-cognitive processes, scientific argumentation, motivation to engage in science and systems thinking, were studied in fields such as map reading (corresponding to STEM education-related objectives in the United States curriculum) using the game *Crystal Island* (Lester et al. 2014), chemistry with the game *Perfect PAPA II* in relation to the learners' flow experience and behavioural patterns (Hou 2015), STEM-related games (Schifter et al. 2012), the multidisciplinary game *Reason Raser* relevant to "earth and space, life, physical, and technology and engineering sciences" (Ault et al. 2015). Again the outcomes on students' performance, confidence and motivation to engage in science were positive, but under certain conditions. Waddington and Fennewald (2018), for example, used a climate change simulation game (*Fate of the World*). Their results were promising for the development of deeper and more robust systems thinking but learning outcomes and game interpretations by the players were limited due to the design and the mechanics of the game.

There were fewer studies focusing on Social Sciences. The study of Sáez-López et al. (2015), for example, examined games for teaching Social Sciences in the classroom and identified a number of games of an "*economic, social, geographical, artistic and historic nature*", while Lee and Probert (2010) examined the game *Civilization III* for Social Studies teaching (History) to high school students, and highlighted the decision-making and problem-solving processes the students engaged in during gameplay, as well as the content knowledge they acquired. In their review (VanFossen et al. 2009) discussed the potential of Massively Multiplayer Online Role-Playing Games (MMORPGs) as learning tools for citizenship education in the social studies classroom; students potentially experience teamwork, understanding and tolerance of others, practice decision-making skills, and they can be encouraged to reflect on and discuss issues such as governance, rights and economic principles.

Games seem to have the potential to link the game experiences with a wider social and global context by strengthening the students' scientific identities and awareness of real-world problems. For instance, Marino and Hayes (2012) argued in favour of the potential of appropriately designed games to enhance science education, civic scientific literacy and participation of students in scientific discourse, referencing relevant empirical studies and games such as *River City*, *Quest Atlantis* and *Whyville.* Gaydos and Squire (2012) studied the game *Citizen Science* in school settings in relation to the students' identities as citizen scientists. The goal of the games was to "*encourage democratic participation in society by providing students with the perspective that they are capable of acting as legitimate sources of science-driven community activism.*" The scientific identity of 13–14-year-old students was also strengthened in Chee and Tan's (2012) study. The game used (*Legends of Alkhimia*) was an educational game about chemistry and through its inquiry-based design it helped students not only develop their understanding of chemistry but also engage in scientific processes such as critical thinking and experimentation, and positively enhance their perceptions for their scientific identities and their dispositions towards

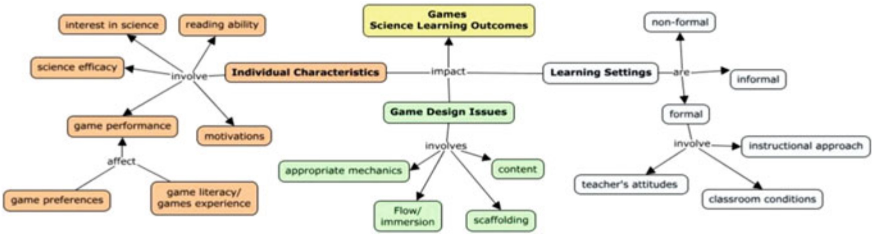

Fig. 3.1 Conceptual model of factors found to be relevant to science learning outcomes through digital games

science. Beier et al. (2012) examined the impact of a science-focused game on the scientific *possible selves* of middle-school students; their findings suggested that the game had a positive impact on students' acquisition of science content, science process skills and also their motivations for careers in science. In a wider social context, Chee and Tan (2012) and Dippel and Fizek (2019) discussed the role of playful technologies and games, situated in a context of collaboration and an external purpose, as tools for engaging in citizen science. Indeed, scientific ideals and also fun were the main motivations of people for participating in citizen science games (*Foldit*, *Galazy Zoo*) as identified in Ponti et al. (2018) ethnographic study of the public forums of the two games and also by Curtis (2015) who identified contribution, interest in science, interactions with others and challenge as the main motivations for participation in the online citizen science game *Foldit.*

Very few of the studies and games adopted a more multidisciplinary approach integrating multiple domains, even though games are appropriate environments for such approaches. Only in one case, the study addressed critical thinking, scientific reasoning and transfer of knowledge, across different domains of knowledge (psychology, biology and chemistry) using the game *Operation ARA (Acquiring Research Acumen)* (Halpern et al. 2012). This could be attributed either to research design goals (e.g. study-specific learning outcomes) or to the fact that a game used in school settings will have to comply with specific curriculum goals and final tests requirements such as explicit learning outcomes, for justifying its role and for being easier accepted by the teachers (Magnussen et al. 2014).

As previously implied, the efficiency of science literacy learning through games is related to certain factors. These factors are relevant to learner characteristics, game design and settings of the gameplay sessions and will be discussed in the following sections (see also conceptual model in Fig. 3.1).

3.3.3 Individual Characteristics

In their study, Fraser et al. (2014) examined the associations amongst youths' science identity, science understanding and gaming preferences, and identified personal game preferences as an important factor for the effectiveness of games in science learning. Different types of games and different game features may attract different types of learners. Social gamers, for instance, may be attracted by in-game social and instrumental interactions with others and seek support from others. Lower motivation, immersion and flow experience in the game may lead to fewer learning behaviours (Hou 2015). Science literacy games failing to consider the preferences of the learners may, therefore, produce lower learning outcomes, at least for the learners who are not attracted by the type of the game.

Previous game experience was one of the mediating factors for the learning outcomes, in the studies reviewed. Game literacy and understanding of the game conventions lead to better content understanding and learning performance as observed by Gaydos and Squire (2012). Computer game self-efficacy, on the other hand, does not seem to significantly predict performance (Bergey et al. 2015). In Waddington and Fennewald (2018), previous game experience was a prerequisite for participation and even so, players found it difficult to navigate the affordances of the simulation game. On the other hand, based on findings in Bergey et al. (2015), game self-efficacy may not significantly predict performance in the game, and performance did not significantly predict changes in game self-efficacy. Succeeding in the game may not necessarily mean that the students achieved a better conceptual understanding (Muehrer et al. 2012). The students may focus on the game mechanics and discuss how to win the game, without necessarily gaining a deeper understanding of the content. And, in addition, players may develop their own meanings and interpretations of the game, sometimes entirely different from those intended or anticipated by the game developers (Waddington and Fennewald 2018). Game literacy, therefore, is an important factor for the learning effectiveness of the game but does not guarantee it.

Previous interest in science and the academic performance in science-related subjects of the learners may also impact the gaming performance and the learning outcomes of a science game. Factors such as reading ability, prior knowledge on the topic, perceptions about science knowledgeability and initial scientific inquiry self-efficacy influence the gaming performance and achievement, and the changes in scientific inquiry self-efficacy (Bergey et al. 2015; Israel et al. 2016). In addition, games involving science learning are more likely to be preferred by students with already high academic performance and science literacy, and students with a higher science literacy level may already spend more time in playing science games out-of-school (Fraser et al. 2014). In Taub et al. (2018), students who recognised and manipulated the in-game items that were more relevant to the problem managed to solve the problem more efficiently, which may be related to the familiarity of the learners with the game content. The science content of the game may also affect learning effects of video games on science learning (Israel et al. 2016). It seems, thus, that science-related games, at least those tested in the studies reviewed, may attract and benefit students with an already high level and interest in science-related topics, while excluding the students who actually need them more.

Gender does not significantly predict game performance and learning outcomes. In Bergey et al. (2015), although girls had lower scores in game self-efficacy, this did not seem to affect their game performance. Girls had also lower scores in attitudes about learning from games, but they had no other significant differences with boys on science achievement perceptions and interest in careers in science (Israel et al. 2016).

3.3.4 Design Issues

Drawing from studies indicating the importance of personal preferences in games and the importance of flow and immersion for the learning outcomes, it seems critical that the game design addresses these aspects; games adapted or adapting to the learner or player type, scaffolding participants based on in-game behaviours, increasing immersion and flow state of the players through elements such as clear goals and immediate feedback, have been proposed as design guidelines for effective science learning games (Cheng et al. 2015a, b; Hou 2015; Taub et al. 2018).

Certainly, designing immersive, engaging and adapted to the target group's requirements is not enough for science learning; the design of the learning content is equally critical. Clark et al. (2015) discussed the importance of designing games where learners can interact with models and systems accurately conveying the science content, phenomenon, system, model and relationships involved, allowing them to further engage in relevant epistemic practices. Science literacy is not only about content knowledge, as previously discussed, but also about understanding of and engagement in scientific practices. Science game designers have to consider not only the content but also the mechanics of the game; the mechanics will have to convey the science concepts, relations and processes modelled by the game with respect to the learning content and objectives.

3.3.5 Context and Settings

Most of the studies reviewed were conducted in formal education settings (classrooms), mainly in elementary, middle and high school, with very few exceptions focusing on preschoolers [e.g. Hsu et al. (2011)], higher education students (Hou 2015) or informal settings (playing at home) [e.g. Waddington and Fennewald (2018)]. In most cases though, the gameplay interventions in the classrooms were not part of the conventional school programme but rather an external intervention. The researchers cooperated with the teachers and examined the games and outcomes through experimental or semi-experimental conditions. In a number of cases, the researchers worked closely with education stakeholders such as teachers and school districts to develop games and curricula adapted to national curriculum objectives, and school needs and requirements (Ketelhut and Nelson 2010; Wallon et al. 2018). This is particularly important since learning outcomes seem to be affected by more than individual factors or the design of the game.

Considering issues of empowerment, equality and inclusion in science-related fields, the integration of science games in formal education classrooms seems to be particularly important. Repenning et al. (2015) described a critical issue when discussing the design of a middle-school curriculum for computer science education: self-selected student programmes such as after-school classes usually attract students already interested in the topic (i.e. computer science). Systemic integration of science-related games in schools would increase students' access to traditionally under-represented minority students and girls, similar to findings in (Voulgari and Yannakakis 2019). Only one study was found, though, to explicitly address learners with disabilities and appropriate game design: Marino et al. (2013) described and tested a game incorporating guidelines from the *Universal Design for Learning* (UDL) framework.

Students' interpretations of the game may vary beyond the game designers' intentions or expectations. The role of instruction and of the teacher is at that point important (Waddington and Fennewald 2018); the teachers, through reflection and discussions, can identify misconceptions and guide the students to view the game critically and consider alternative perspectives. Inversely, teachers' negative attitudes towards the game may also affect students' attitudes (Muehrer et al. 2012). Furthermore, students supported by material external to the game performed better in terms of the quality of their scientific argumentation (Wallon et al. 2018). In authentic classroom settings, other external factors such as slow internet connections, technical specifications of the computers and the conditions of the classroom (e.g. crowded, heat) can have an impact on the students' gameplay (Muehrer et al. 2012). The teachers, the quality of instruction and the surrounding conditions were, therefore, also found to factor in the learning outcomes.

3.4 Conclusions

In this chapter, we reviewed studies involving digital games and science learning. Our goal was to address not only the games as instructional tools, but also view them in a broader context involving cultural and societal practices. We observed a shift to higher order thinking skills and scientific practices such as inquiry, problem-solving and scientific reasoning, which is encouraging considering that such skills are important for the students to develop a critical and sceptical attitude in their lives. Even so, though, there is still great potential for research focused on the development of science literacy through social science-related games.

Although previous studies have described digital games as media that can trigger the interest for science and technology (Biles 2012; Bricker and Bell 2012; Mayo 2009), research and game development on this area is still limited. Further studies, for instance, could focus on the relation between the *science capital* of the students and their game preferences and propose game elements that can engage students with lower science capital scores.

Similarly, game studies and development could further consider the limited participation of girls in STEM-related fields (Dasgupta and Stout 2014) and the limited focus on games for children with intellectual, learning, sensory or motor disabilities (Beeston et al. 2018; Brown et al. 2010), and address these populations' requirements as well.

One of the main strengths of games is their potential as affective environments for science learning (Li and Tsai 2013). Fun, engagement, immersion and motivation in the studies reviewed have mainly been measured via surveys and self-reports. Research on the affective aspects of games based on biometric data and psychophysiological measures would provide more objective and valid data on the emotions and experience of the learners (Yannakakis and Martínez 2015).

Most of the studies reviewed focus on formal education settings. Games, though, are widely used in informal or non-formal learning settings, such as after-school programmes, science-fairs, FabLabs, Game Jams, or at home, supporting informal learning and the emergence of communities of practice spontaneously formed by even younger children and having a great educational potential (Arya et al. 2013; Squire and Patterson 2009; Williamson and Facer 2004). It seems that further research in informal and non-formal learning settings would yield valuable insights into the processes and factors involved. Research, though, in such settings presents challenges such as the lack of uniformity in learning objectives, and the varying attitudes and diversity of the participants (Honey and Hilton 2011, p. 78; Tisza et al. 2019).

Although this was not an extensive, empirical review of the literature, it did allow us to identify potential areas of interest for further research and design of digital games for science learning and scientific literacy. We tried to view the topic through a wider lens involving the game design, individual factors, as well as the social and cultural context considering the importance of media and digital literacy skills for children's education.

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