Games in science education: Discussion of the potential and pitfalls of games-based science education

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Abstract: This paper discusses the hypothesis "games are good for learning", presented by Gee (2011) in relation to game-based science learning. Using game learning theory as its starting point, the discussion draws on examples from our research on designing and studying science games based on five categories: 1) training games, which are designed to develop individual skills for solving isolated problems; 2) inquiry games, which are structured around players conducting an inquiry; 3) professional simulation games, where players simulate being part of a professional context; 4) embodied system games, where players explore scientific phenomena by manipulating simulations or models of them; and 5) research collaboration games, where players generate data for scientific research by manipulating simulations of the research object, such as protein structures or atoms in quantum computers.

Based on our design-based research in games and learning the paper discusses the learning theories or models these game formats are based on or specifically support. Examples are presented on how training games can be based on behaviouristic learning theories and on how socio-cultural theories are central for designing and studying inquiry games and professional simulation games. There are also examples on how constructionist learning theories are essential in designing embodied system games and research collaboration games, in addition to a presentation of how these types of games can support intuitive learning of abstract and theoretical phenomena. Finally, we discuss what is central in games and learning for the games to be good for science learning. Elements such as authenticity, intrinsic learning, game goals and designing the context of the game are key aspects of good games in science education. The aim of this paper is to initiate a discussion on the specific potential of science games from a theoretical learning and game research perspective, but further studies will need to be conducted to substantiate its conclusions.

Keywords: Science games, science education

1. Introduction

Games have been claimed to be well suited for creating narrative frameworks or simulations that allow students to gain first-hand experience on scientific contexts or phenomena they would otherwise be unable to experience directly in school science class (Magnussen et al., 2012). This can occur through game-based simulations, where students have the opportunity to manipulate scientific phenomena in environments impossible to create in the classroom by using a computer or computer-assisted role-playing games that provide the opportunity to work as professional technical or scientific experts in simulated universes with fictional problems (Shaffer, 2006).

Despite extensive interest in game studies, the evidence for or against games as learning tools is not substantial. Consequently, this relatively young field involving games and learning needs more robust game and learning research studies that take learning design, pedagogical content, game genres and design into account (Gee, 2011; Tobias et al., 2011).

For over a decade, research groups all over the world, including our team at ResearchLab: ICT and Design for Learning, Aalborg University, Copenhagen, have conducted studies on games for science learning in and outside educational settings. During that time, the learning game field has matured beyond initial experiments involving the integration of games into science education. New learning games with learning styles more suitable to previous generations are nonetheless still being produced in an educational field with a sparse understanding of game mechanics, genres and game-learning approaches. A continuous focus on improving methods for designing and studying games and for learning is thus needed to be able to more substantially document what games can contribute to different types of learning contexts. This focus, however, should not primarily be on how games can more effectively teach students skills already currently being taught in schools. It is instead essential to spotlight the development of a greater understanding of how games can contribute to changing learning approaches and content in schools to overcome some of the comprehensive challenges schools face in their efforts to educate students for the future knowledge society (Sawyer, 2006).

This paper discuss the hypothesis, "games are good for learning", with reference to Gee's reflections on how games are good for learning (2011) and with specific focus on science learning. Gee notes the lack of substantial studies documenting learning in games and advocates a strengthening of empirical studies on learning in games. He presents a model with a strong emphasis on designing studies solidly based on what 'games', 'good' and 'learning' are within the specific context for which the learning game is designed.

The aim of this paper is not to prove that games are good for science learning, but to discuss how the concepts of 'games' learning and 'good' can be understood in the context of science game research. The discussion draws on both learning game theory and examples from our years of research on game-based science learning in order to identify aims for future science games studies.

2. Science games

In the attempt to define what games are in a science learning context, we describe a broad range of formats. Teaching science with the use of digital games and simulations dates back to the 1970s and early 1980s, where the potential of games and simulations were discussed extensively as a new teaching tool (Ellington et al., 1981). In the early 1990s, the first games based on information and communication technology for exploring science and technical subjects were developed (Egenfeldt-Nielsen, 2005). After the turn of the millennium, awareness concerning the potential of using commercial computer games in science education has grown, as is also the case for developing serious games for scientific subjects such as chemistry, physics and biology (Magnussen, 2007; Shaffer, 2006; Squire and Klopfer, 2007). Some of these newer formats, based on learning theory and game design methods, have been developed in collaboration between research and education institutions and game developers.

The history of science game design and studies thus spans from games aimed at training individual skills, such as memorising chemical substances, to complex games designed to improve the ability of students to construct logical arguments. This paper draws on the understanding that the digital science game concept is not a uniform concept, but refers to different types of games designed to teach a variety of competences or skills 'Game' has been defined in multiple ways, including as an exercise of voluntary control systems (Avedon and Sutton-Smith, 1971), systems (Salen and Zimmerman, 2003) and as an art form (Costikyan, 2002). This paper defines game in accordance with Wittgenstein (1958), who argues that similarities between games, such as play, rules and competition, do not adequately define what games are, which is why they should be characterised as resemblances between members of the family games form. The understanding of science games represented in this paper is thus an understanding of a large family of different formats and the aim is to discuss specific learning potential based on examples from our research in science games, which is grouped into different categories in figure 1.

Science game category	Game learning goals and activities	Game research examples
1. Training games	Designed to train skills through repetition of an individual exercise, e.g. training basic math skills or the composition of chemical compounds	*MateMaTris*, (other game examples outside our research*: DragonBox*)
2. Inquiry games	Focus on scientific inquiry; can involve data collection processes, verifying hypotheses and generating theories or building scientific arguments	*Homicide* (*Quest Atlantis*)
3. Professional simulation/epistemic games	Gamers role play scientific or technical professions and conduct authentic practices, e.g. as forensic detectives or urban planers	Game-based innovation *Homicide* (*Urban Planer*)
4. Embodied system games	Focus on experience and manipulation of scientific phenomena; centre on, e.g. atomic models or electromagnetic forces	*Quantum Moves* (*Supercharged, NewtonWorld*)
5. Research collaboration games	Participation in real high-level scientific research and technical development, e.g. in scientific discovery games designed to help real-life scientists solve authentic scientific challenges	Game-based changing of unsafe urban spaces *Quantum Moves*

	(Foldit)

Figure 1: Categorisation of science games in research projects at the ILD Lab at Aalborg University. The games listed in parentheses were not covered by our research.

Each of the five categories listed in figure 1 has specific central elements, but they also share similar features. Professional simulation games elements overlap with that of inquiry games and research collaboration games often draw on elements from system games. The categorisation presented here is not based on the individual game's possible platform or on whether it contains a specific feature, but primarily on what the main goals are for players. The categories thus chiefly depend on what the goal of the game is, e.g. to solve a murder mystery, conduct scientific tests or inquiries, participate in authentic professional processes using the tools of the trade, manipulate simulations of scientific phenomena, or collaborate with researchers. The five game categories are described in more detail below.

2.1 Training games

The research and development we have been involved in regarding training games centres on players training a single skill or types of skill. Training games also belong to the wider category of problem games, which focus on solving a single problem or a class of problems (Gee, 2006). This can, for example be games where players train basic mathematics skills or memorise chemical substances in photosynthesis. An example of this type of games is *Matematris*, an educational math game we used to study player tests of (Magnussen and Misfeldt, 2004). The game was developed by a group of teachers in collaboration with a Danish software developer and the idea was to create a computer game to teach mathematical competencies and for it to be as fun as regular computer games. The result was an educational multiplayer game involving teams competing against each other. The game consists of two game levels. The first one is a 3D game universe where the players move around as avatars, initially in an underground base and later in a pyramid. The avatars wear combat attire but do not carry weapons. The sole purpose of the game is for players to find the entrance to the 2D sub-game *Matematris,* where players form teams to compete against each other in an educational math version of *Tetris*.

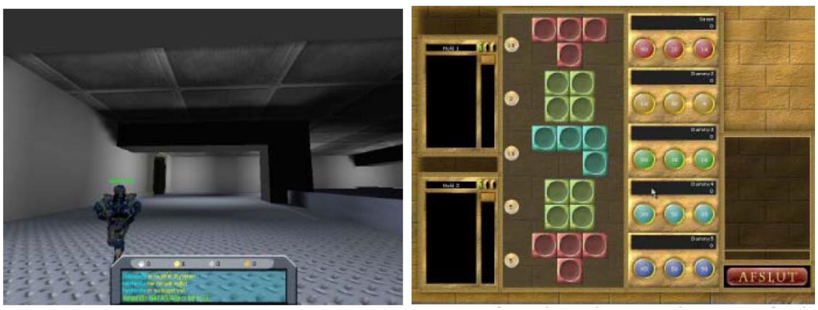

Figure 2: The two game levels in *Matematris,* from left to right: 3D exploration and 2D *Tetris* educational math

In *Matematris*, one team member played *Tetris* by twisting and turning falling pieces produced by a competing team to construct a solid pattern. The other team members produced pieces for the competing team to cope with. The goal was to produce a quantity of pieces so high that the opposing team's *Tetris* player would lose. The winning team earns a bonus and the teams can either battle again or choose another team to battle against. The production of the pieces comprises the educational aspect of the game as the players who produce the pieces have to fill in holes in the *Tetris* pieces with numbers that are a multiplier of or equal to the number connected to the *Tetris* piece (figure 2). A correctly filled in *Tetris* piece disappears from the production interface and appears as a falling piece on the opposing team's *Tetris* interface. That team's *Tetris* player now has to place the piece in the wall. If the production team incorrectly fills out a piece, the team loses points and the piece is given to their own player. The overall educational goal of the game is for children to learn alternative ways of handling numbers besides division and multiplication done with paper and pencil. The time factor forces children to invent and use their own strategies for handling numbers. The overall conclusion on *Matematris* is that the 3D explorative game was not fully integrated with the educational 2D game. The general idea was for the 3D universe to contribute to the game experience and for the 2D game to focus on practicing math skills. The lack of integration between the 3D first-person game universe and the interactive 2D educational math universe resulted in a game play that did not provide meaningful play for the students. Consequently, this led to a player transformation of the game, which we will come back to. The phenomenon of disintegration of the game and educational elements is well known, especially in early edutainment development, where game elements have largely been viewed as the sugar coating necessary for making the educational elements palatable (Egenfeldt, 2006). In games where the learning aspects and the game aspects are not fully integrated, students will often try to bypass the educational part to spend time on the fun part (Baker et. al., 2004). This was also observed in our study of *Matematris*, which will be described in the learning section below.

2.2 Inquiry games and profession simulation games

Inquiry games involve solving complex problems by conducting specific investigations that involve defined processes or process tools. Profession simulation games potentially include inquiries too, but the focus on authenticity is central to these games. Simulation of authentic professional values, tools and processes are thus key elements in profession simulation games. The profession simulation games that we have been involved in the design of and research on also include inquiries, which is why they are being described together in this section. An example of this is the game, *Homicide*, which we developed (Magnussen, 2007) for use in cross-disciplinary science education for students 13–16 years of age. In the game, players act as forensic experts and have to conduct an inquiry by collecting data from murder scenes as technical evidence to be tested. One of the main learning goals of *Homicide* involves supporting the ability of students to conduct a scientific inquiry and to construct scientific arguments by defining hypotheses, collecting data to support or reject these hypotheses and to reach a final theory supported by data from technical tests. Central to the game, however, is that the students gain insight into how to work with the professional values, tools and processes of forensic experts. The game can thus also be categorised as a profession simulation game, which are also known as epistemic games (Shaffer, 2006). This type of game is based on professional values, practices and tools and players solve simulated problems within a specific profession. The goal of this class of games is that students take on the role of experts and learn to operate using the knowledge, skills and tools of a profession to find innovative solutions to authentic professional problems. One example outside our research of these categories of games is *Quest Atlantis*, where the game of the goal is to save Atlantis, which is being run by misguided leaders (Barab et al., 2007). In this 3D game, players take social responsibility by conducting inquiries and building arguments.

Inquiry games and profession simulation games are part of the wider category of games that Gee (2011) defines as world games that simulate a wider world where players have to solve not just one type of problem, but many types of problems. Our research on game-based simulations of the professional inquiry environments in *Homicide*, where students play forensic experts, shows that students' inquiry practices and learning are influenced by new types of actors (Magnussen, 2009) comprising characters in the game, actors related to the simulated profession and actors in the school context. The influence of these new types of actors will be explored in the next section on learning.

2.3 Embodied system games and research collaboration games

The final two categories, embodied system games and research collaboration games, can potentially share gaming elements but have distinctively different goals. The former are quite distinctively science games as players manipulate natural phenomena that are often physically impossible to manipulate in the real world, for instance, due to their size (atoms, solar systems). Ochs, Gonzales and Jacoby's (1996) article, "When I come down I'm in a domain state", describes how physicists use 'I' and 'you' when discussing physical phenomena as being an embodied part of the complex systems they study. Gee (2007) compares this to how players talk about participation in game systems and asks whether games can encourage the same embodied enactment of participation. The category of embodied system games presented here is a class of games that potentially allows for this embodied enactment by making the first-hand manipulation of scientific phenomena possible. Manipulation of and experimentation with models of scientific phenomena are also central in research collaboration games, which are also known as scientific discovery games. Central in these types of games, however, is the research participation that these games facilitate. One example of a research collaboration game is *Quantum Moves*, where players collaborate with quantum physicists to generate data for research on quantum computers (Magnussen et al., 2012). Our studies on *Quantum Moves* show that a significant number of players are mainly motivated by the opportunity to collaborate with real researchers. The primary goal for players in this type of game thus partly seems to be extrinsic to the game. Results from studies of the game in four high school classes also indicate that elements central to the embodied system games are central in *Quantum Moves*. The teachers who taught the various classes said that the opportunity for tangible manipulation of atomic models allowed an intuitive approach to the otherwise highly theoretical subject of quantum physics (Magnussen et al., 2014). Other examples of embodied system games and research collaboration games are *Supercharged*, which is designed to strengthen students' intuitive understanding of electromagnetic forces (Squire et al., 2004) and the first scientific discovery game *Foldit*, where players fold amino acid chains to generate new types of protein structures (Cooper et al., 2010). Our results on learning in these types of games are discussed in the section below.

3. Learning in science games

Gee (2011) states that the claim "games are good for learning" is meaningless unless we theoretically define what learning is and any researcher testing games must define what theory of learning they are testing. This also has implications for the game, as clarifying that the game is designed based on a specific theoretical approach is essential to being able to use the game for testing the specific learning theory. Some game developers may claim that their particular learning game was not based on any particular learning theory. I argue, however, that learning games are always based on learning theories, regardless of whether this was done consciously or not as the development work is based on a behaviouristic response-reward system or a system designed for complex social interaction. I also argue that when developing new learning game practices and conducting solid game studies, defining what type of learning the various science game categories support is essential. Egenfeldt (2006) describes how games can be behaviouristic, cognitivist, constructionist or socio-culturally defined by the models of learning, motivation and problem solving upon which they are based. Our research on learning in science games shows that there are specific approaches to modelling learning in relation to the various categories of science games presented in this paper.

Training games are, designed, as described earlier, to develop problem-solving skills related to an individual problem or type of problem. These types of games often draw on behaviouristic learning models as they are based on laws that strengthen a specific response through rewards and stimuli (Egenfeldt, 2006). Testing done during our research shows that training games are in danger of being based on rewards extrinsic to the learning situation, which means players are given points or medals based on the game narrative but have little connection to the intrinsic qualities of mastering a skill. This weak connection between learning goals and game goals can demotivate students.

Results stemming from our study of *Matematris* show, as described in section 2.1, that the lack of integration of game and educational goals creates a lack of meaning for the students playing the game (Magnussen and Misfeldt, 2004). In studies of the game, it became clear that pupils transformed the game to accommodate more social interaction. With these transformed ways of playing the game, they managed to get to the top of the high score list while avoiding the educational parts of the game. Transformative play (Salen and Zimmerman, 2003) and transformation of educational software is well known (Baker et al., 2004). Rigid structures in the software lead to students 'gaming' the system by using the system's structure to get as far as possible without spending time on the educational content. There are several possible explanations for this, but one hypothesis posits that the introduction of a quantitative goal (advancing in the system) that competes with a more qualitative learning goal leads to a tendency among some students to concentrate exclusively on the quantitative goal. Players transforming educational games to escape learning elements can obviously be a problem when these games are used for formal education. In the *Matematris* case study, however, it can be argued that player transformation of educational games can form the basis of exciting, unconventional learning concerning valuable skills, such as how to transform information technology to better accommodate social interaction (Magnussen and Misfeldt, 2004).

Inquiry games and profession simulation games can potentially be based on cognitivist models of learning and motivation as the players' mental model of the inquiry process can be a central aspect of these games. Socio-cultural theories can potentially be visible in the foundation of these two types games, including the understanding that learning is situated in the specific context in which the skills are practiced and that a focus of the games is to simulate this environment. Future studies, however, need to verify this conclusion. As described above, our studies on the inquiry profession simulation game *Homicide* show that networks of actors related to the game, the profession and the school context influence student learning practices in the game world (Magnussen 2009). Results from studies on these games also show that students develop new types of inquiry competences and inquiry tools in the network of the various actors related to the game-based professional school context. An example of this was the different formats of inquiry representations that the students constructed and transformed in the process of scientific inquiry. The formats and construction of process tools was highly influenced by their conceptual understanding of the forensic profession as well as game and school elements such as the characters and teachers. These actors influenced formats and processes in the inquiry representations as well as the development of representational inquiry competences (Magnussen, 2009).

In both embodied system games and research collaboration games learning through experimentation, exploration and construction are central elements of the game. In both types of games, the game play is based on manipulating natural phenomena and potentially constructing new structures. As described above, results from studies on these games show that teachers see the intuitive approach of the games to a highly abstract subject, such as quantum physics, as one of their central strengths (Magnussen et al., 2013). Supporting intuitive forms of learning can be a key strength in these two types of games, as has also been documented regarding the embodied system game *Supercharged* (Squire et al., 2004). This can be challenged, however, by the students' understanding of 'learning science'. Results concerning students' perceived learning in tests of early versions of *Quantum Moves* showed that the majority of students in one of the participating high school classes felt they learned either nothing or very little form playing the game. According to an interview with their teacher, one potential reason for this could be their experience with what 'learning physics' was as quantum physics was generally taught on a highly theoretical level (Magnussen et al., 2013).

4. Discussion and conclusion: What is a good science learning in games?

Gee (2011) argues that for researchers to be able to test if a game is good for learning, understanding what type of game it is is key, as well as what qualifies it as a good game in the context in question. He suggests that whether games are good or not depends on general games elements such as motivation, the challenge, interesting problems, good stories and good game mechanics, but also on what gamers the game is good for. Different types of gamers like different types of games and not just all games, just as people learn in various ways and though assorted activities situated in diverse contexts. This paper also argues that 'good' in a science game context also depends on the category of science games and the learning context. Research and development on science games should be based on issues concerning what game narratives, goals, rules, processes, the structure, missions and other game elements are relevant. In science games, learning goals, processes, the structure and missions should be parallel. Games are interactive structures of endogenous meaning that require players to struggle toward a goal (Costikyan, 2002) and if learning goals are extrinsic and not closely related to the endogenous meaning of the games – as some training game formats demonstrate – the learning activities become meaningless in the game context (Magnussen and Misfeldt, 2004). In order to develop and study science games, we need to understand what game elements and learning processes are central in the different categories as well as their interplay in the context in which the learning game is being played. This concerns not just design and research on the digital game alone, but also on the social system of which the game is a part. These two approaches for understanding games are defined by Gee as the "little 'g' game" and the "big 'G' game":

> …it is important to distinguish between the game as software (let's call this the "little 'g' game") and the whole social system of interactions that players engage in inside (for multiplayer games) and around the game (this is sometimes called the "meta-game"). We can call the combination of the game (software) and the meta-game (social interactional system) the "big" 'G' game (2011, p. 226).

The main part of the games presented in this paper are designed as big 'G' games – Games – for educational contexts, online communities or as part of professional contexts. Inquiry games and profession simulation games, such as *Homicide*, are designed for teachers to play the role of investigators and for students to conduct tests in the physical school laboratories using fingerprint kits and other professional tools (Magnussen, 2007). In this type of game, it is central that learning activities lead to fulfilling the goals of the game. In the forensic investigation game *Homicide*, the learning goal is for students to conduct a scientific inquiry by building hypotheses and theories and to test these by doing technical tests. The game goal is to solve a series of complex murder cases that is only possible by collecting evidence. The teacher's role is to guide the investigation by communicating the values and practices of the profession the game simulates. Another central element in professional simulation games is the element of authenticity. As the game's claim to being a simulation is based on the authentic social system of a profession, it is essential that they are based on authentic tools, values and practices of the profession. This interplay of authentic actors can extend the social system the game enacts to include actors from outside the school context (Magnussen, 2009). This inclusion of professional actors in the Game is also visible in the category of research collaboration games. Our studies on the quantum physics research collaboration game *Quantum Moves* show that collaborating with researchers was a major motivational factor for the players (Magnussen et al., 2014). This indicates that the professional collaboration elements of the Game, rather than the interaction with the digital game, motivate players to play this type of game.

This paper presents five science game categories, some of which, for example inquiry games, can also fall into the general category of learning game, whereas others, such as embodied system games, are specific to the science games genre. The aim of this paper has been to discuss the potential and pitfalls of designing and studying science learning games. The categorisation and discussion presented in this paper are based on our results from a decade of research into science games, but whether the categories apply to science games in general needs to be verified further.

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