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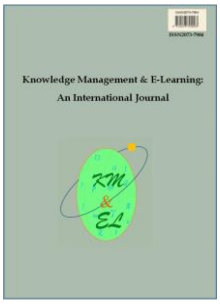

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Investigating the impact of an adventure-based 3D solar system game on primary school learning process

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Abstract: Teachers face many difficulties in the motivation, engagement, and improvement of learning outcomes for students in Science, Technology, Engineering, and Mathematics (STEM). In this paper, we present a research study on the learning experience of a new interactive educational 3D video game called Final Frontier, designed for primary school students. This game supports student knowledge acquisition on two Solar System planets Mercury and Venus, and a satellite - Moon through direct experience, interactive challenges and fun. This article compares the learning impact of the computer game-based learning approach with a classic teacher-based learning approach. User experience with the game and game usability are also evaluated. A case study that involved 53 children was conducted for the evaluation. Among the most important findings, include the facts that the experimental group that used the game in their learning activity have performed much better than the control group and the students had a great learning experience when using the Final Frontier game.

Keywords: Technology enhanced learning; STEM; Educational game; Primary education; Solar system

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1. Introduction

Technology Enhanced Learning (TEL) refers to the use of technologies to facilitate students' acquisition of skills or knowledge with the help of teachers or learning support tools (Aleven, Stahl, Schworm, Fischer, & Wallace, 2003). TEL is a large domain for research and practice, and includes e-learning, mobile learning, Learning Management Systems, and game-based learning.

The research work presented in this paper, focuses on game-based learning. Game-based learning involves the use of gaming technology for educative purposes where students explore relevant aspects of games in a learning context designed by teachers. Teachers and students collaborate in order to add depth and perspective to the experience of playing the game (Editorial Team, 2013).

In the game-based learning context, we are interested in STEM, which is an education set of disciplines, which includes Science, Technology, Engineering, and Mathematics. Note that many studies investigate curricular reform in order to improve STEM education for students (Goode & Margolis, 2011). The motivation behind this work is the disengagement of young people from STEM. Students need to be exposed to STEM subjects as early as in primary schools and have reinforced their basic STEM knowledge at secondary and vocational school levels. In addition, there is a need to improve STEM teaching quality and students' comprehension even at higher education levels. Regardless of the level targeted, a new 21st century STEM teaching and learning paradigm has to be employed for improved results. This paradigm needs to replace the old approach in which the educator is viewed as the only source of all the knowledge, everyone learns the same way, the class is the only place where knowledge disseminates and the course is the only way in which knowledge is transmitted. The new 21st century teaching and learning paradigm must be dynamic and student-centric. In addition, computer games have an important role in increasing student's motivation, engagement and self-efficiency. This is why we propose to develop a computer game-based learning to be employed in this field. In this game-based approach, the student acts as a performer that actively controls the flow and the amount of knowledge accessed according to their specific needs, and in this process the student is helped by technology, which supports this selection effort. We believe that the use of the game will create engaging classrooms in STEM subjects, demystify the preconceived idea among students that science and technologies are difficult subjects and improve learning outcome and increase student motivation and engagement.

Game-based learning (GBL) represents an educational approach that integrates video games with defined learning outcomes, also called serious games. The appeal of using video games in education can be partially explained by the need to reach today's digital learners that have continuous access to entertainment content through the Internet. At the same time, games provide highly engaging activities that are stimulating, generate strong emotions, require complex information processing, provide challenges and can support learning and skill acquisition (Boyle, Connolly, & Hainey, 2011). The learning experiences and outcomes of educational games can be classified into knowledge acquisition, practicing and processing (content understanding), knowledge application (skill acquisition), reflection (behaviour change) knowledge anticipation (motivation outcomes) (Jabbar & Felicia, 2015).

Previous research work has shown that game-based learning can have positive effects on important educational factors such as student motivation and engagement (Ghergulescu & Muntean, 2012), learning effectiveness (Erhel & Jamet, 2013), as well as learning attitude, achievement and self-efficacy (Sung & Hwang, 2013). Moreover, game-based learning has the potential to facilitate the acquisition of 21st century skills such as critical thinking, collaboration, creativity and communication (Qian & Clark, 2016). While there is much research evidence of GBL benefits, some studies failed to reproduce them or obtained contradictory findings. (Tobias, Fletcher, & Wind, 2014) argue that this may be due to lack of design processes that effectively integrate the motivational aspects of games with good instructional design to ensure learners acquire the expected knowledge and skills (Tobias et al., 2014). The authors also made recommendations for educational game design, such as to: provide guidance, use first person in dialogues, use animated agents in the interaction with players, use human rather than synthetic voices, maximize user involvement and motivation, reduce cognitive load, integrate games with instructional objectives and other instruction, use teams to develop instructional games (Tobias et al., 2014).

One common criticism of game-based learning studies is that they lack foundation in established learning theories. A meta-analysis of 658 game-based learning research studies published over 4 decades, showed that the wide majority of studies failed to use a learning theory foundation (Wu, Hsiao, Wu, Lin, & Huang, 2012). Among the studies that had a pedagogical foundation, constructivism appears to be the most commonly used as indicated by multiple review papers (Li & Tsai, 2013; Qian & Clark, 2016; Wu et al., 2012). Other learning theories that were also implemented by different research studies include: cognitivism, humanism and behaviourism. Common learning principles employed by game-based learning studies include among others: experiential learning, situated learning, problem-based learning, direct instruction, activity theory, and discovery learning (Wu et al., 2012).

In order to deal with the lack of design processes that integrates motivational aspects of educational game, our research work proposes a game methodology, functionality design, and game architecture of an educational video game for primary school students. We evaluate our solution from the learning impact, the user experience, and the game usability perspectives. This research work is dedicated to TEL community and more specifically to pedagogical engineers, researchers, and teachers in primary schools who encounter difficulties in engaging students in STEM courses.

The paper is organized as follows. Section 2 proposes the theoretical background of the study and introduces existing games related to the Solar System and different game methodologies. Section 3 details our scientific positioning and defines our game methodology, our functionality design, our game architecture, and gives an overview of the Final Frontier game. Section 4 presents research methodology of the case study and its results. Section 5 summarizes the conclusion of this paper and presents its perspectives.

2. Related work

2.1. Educational games related to planets or the solar system

While there are a considerable number of games dedicated to Science (Li & Tsai, 2013), there are few games that focus on Geoscience in general and planets/Solar System in particular. In (Pringle, 2013), an environmental Geoscience e-game is introduced with the purpose to provide effective and stimulating learning for undergraduate students. The learning content associated to the game derived from a scientific paper. Tests performed with a limited number of students (i.e. 17 students divided in 2 groups) demonstrated that the students were engaged in the learning process, were task focused during the game as the scores show and that they enjoyed the game-based learning. Only the students from the second group were inquired about their experience with the game. Noteworthy are the facts that some students repeated the game in order to re-inforce learning and the game had a positive impact on the way the students related to scientific research papers.

“Blind Mouse on the Moon and Mars” game (Gede, Hargitai, & Simonné-Dombóvári, 2013) was designed mainly for primary and secondary school students. The aim of the game is to improve user’s topographic knowledge related to Moon and Mars. Two types of games are provided: one requires the user to find the right place on the map for ten described objects, while the other game is represented by a planetary quiz with ten random questions that requires user to use the planetary globe. Similar to the previous analyzed approach, the focus is on the technical features and implementation rather than on the evaluation of the efficiency/impact of the game on learning. One of the main drawbacks of this game is that relies on different APIs and this leads to the need of continuous upgrade (e.g. the game was so far twice upgraded because of this reason).

In (Brown-Simmons, Kuester, Knox, & Yamaoka, 2009) a game engine for Earth and Planetary System science is introduced. This game. uses unconventional interaction with the users and different visualization techniques in order to give users/players a deep understanding on the complexity of Earth and Planetary System, their beauty and the possible impact that humans might have on these (e.g. climate change). The solution is solely focused on technical and implementation aspects and does not present any kind of subject-based evaluation of the game. One of the main drawbacks of this game is that the methodology followed is not clear.

HelloPlanet is a game where the player can observe and interact with a planet that has a dynamic ecosystem, where the player can simulate organisms, non-organisms, terrains, and more (Sin, Ng, Shiu, & Chung, 2017). The game requires a VR environment and HTC VIVE to be played. The game evaluation results from 41 primary and secondary school children, showed a statistically significant learning gain for both girls and boys, and an effect on interest in STEM for girls, but not for boys. The Space Rift game enables students to explore the Solar System in a virtual reality environment (Peña & Tobias, 2014). However, the game evaluation involved only 5 students and was mostly focused on usability rather than educational aspects. The Ice Flows game aims to educate the users about the environmental controls such as temperature and snowfalls on the behaviour of the Antarctic ice sheet (Le Brocq, 2017). However, the game was either not evaluated or the results were not published yet.

A recent systematic review of game-based learning in primary education has indicated that games were used to teach a variety of subjects with the most popular being mathematics, science, language and social studies (Hainey, Connolly, Boyle, Wilson, & Razak, 2016). However, the authors also concluded that more research studies are needed to evaluate the pedagogical benefits of GBL at primary level.

In this context, our research contributes to the advancement of science by evaluating the Final Frontier game for teaching planet-related concepts to primary students. The need for the Final Frontier game is motivated by the fact that the existing games have some drawbacks (presented in Table 1) that cannot be easily overcome. Some games are employing prohibitively expensive equipment for a large-scale deployment in the primary schools (i.e. HelloPlanet, Space Rift) and some other games rely on the different APIs that get quickly outdated (i.e. Blind Mouse on the Moon and Mars). Some games are designed for a different audience – i.e. higher education students (Pringle, 2013), and others lack any evaluation or methodology (i.e. the remaining approaches presented).

2.2. Evaluation of educational games

The most common methodology employed by previous research studies to evaluate the benefits of game-based learning is the media comparison approach. This approach involves typically comparison between the outcomes of an experimental group playing the educational game and those of a control group exposed to traditional learning media. Another approach proposed by Mayer and colleagues is the value-added methodology, where the same instructional method (i.e., game-based learning), is used for both groups, but the control group plays a version of the game that lacks the feature being evaluated such as narrative (Adams, Mayer, MacNamara, Koenig, & Wainess, 2012).

The games presented do not follow any of these approaches. Moreover, as emphasized in the previous section, some of them do not perform or report any kind of evaluation that involves subjects/learners; instead, they are more focused on the technical implementation aspects of the game. In Table 1, it can be seen a summary of the evaluation details for each of the presented approaches. Noteworthy in this context is the fact that the aforementioned review on the game-based learning in primary education underlines as main finding the necessity of evaluating the game-based approaches following the media comparison approach.

Table 1
Summary of analyzed approaches

Approach	Evaluation method	Weak points
Pringle (2013)	2 study groups – group 1: 9 students, group 2: 8 students. The approach is evaluated partially quantitatively and qualitatively. The learning outcome is evaluated through the score obtained by the users during the game. However, this result cannot be really interpreted, as there is no comparison involved (no pre-test has been done, no control-group results either). The students from the second group were asked to fill a questionnaire evaluating their experience with the game. Also, impressions from the users were recorded and quoted in the paper.	Game designed for undergraduate students. Not very thorough evaluation.
Blind Mouse on Mars and on the Moon (Gede et al., 2013)	No subjects-based evaluation	Rely on different APIs that get outdated quickly No evaluation performed
Game Engine (Brown-Simmons et al., 2009)	No subjects-based evaluation	Unclear methodology No evaluation performed
HelloPlanet (Sin et al., 2017)	The evaluation included 41 students and it is based on pre-test and post-test and a comparison against the results obtained by the students in these 2 sittings. It also included feedback related to the learning experience and feedback from the teachers.	The game requires prohibitively expensive equipment for a large-scale deployment in primary schools
Space Rift (Peña & Tobias, 2014)	The evaluation included a very limited number of students only, namely 5. The evaluation was more focused on the user experience; however, there are few reported results in terms of learning outcome that are quite worrying: the students did not remember almost anything from the learning content.	The game requires prohibitively expensive equipment (i.e. Oculus Rift) for a large-scale deployment in primary schools
Ice Flows (Le Brocq, 2017)	No evaluation	Scarce information about the game; no evaluation performed

2.3. Existing pedagogical game methodologies

A number of previous research papers have proposed methodologies for game-based learning. (Moreno-Ger, Martínez-Ortiz, Sierra, & Fernández-Manjón, 2008) have proposed the <e-Adventure> development process model consisting of a storyboard-driven methodology for developing educational games. This model places game writers and instructors at the centre of the game development process, working collaboratively with the game developers. The process creates and updates a number of products, namely: the <e-Adventure> language based on XML, the <e-Adventure> document that provides an XML description of the game's storyboard, the game art assets such as images and character sprites, and the <e-Adventure> game engine that generates the final game based on the XML storyboard and art assets. One main characteristic of this model is that the language and engine is continuously updated based on the input of the writers to fit the needs of the game's storyboard. The <e-Adventure> game production process consists of several steps: conception and revision of the game storyboard; extension and customization of the language if this does not have sufficient expression power for the new storyboard; production of the artefacts for this game iteration (including customized engine, storyboard mark-up, and art assets) and production of the game executable. The game development can go through multiple iterations that may involve changes in the storyboard, language, engine, as well as user testing to get feedback on the early game versions.

Huynh-Kim-Bang and Labat (2010) have proposed a taxonomy consisting of 35 design patterns for serious games grouped under 6 different categories. This taxonomy was proposed based on an analysis of 20 serious games and a literature review on design patterns writing. Each of the six categories contains patterns aimed at solving a general problem and can be related to the context (i.e., When do you need to combine entertainment with learning?), learning aspects (i.e., How to make interaction instructive? How to initiate the reflective process? And how to convey information without disturbing the game immersion?), or fun aspects (i.e., How to motivate users? and How to help users advance in the game?).

Kelle, Klemke, and Specht (2011) have also investigated the area of design patterns for educational games. Their main contribution consists of creating a mapping of learning functions to general design patterns for game development. The mapping interconnects the learning functions identified by (Shuell & Moran, 1994), with the general design patterns proposed by (Bjork & Holopainen, 2004), and representative learning taxonomies or frameworks such as Heinich pedagogical designs, Gagné's instructional events, Robinson's pedagogical goals, Kolb's learning activities, and Keller's ARCS model. The authors consider 22 learning and teaching functions grouped in six categories related to: preparation (e.g., motivation, attention), knowledge manipulation (e.g., comparison, repetition), higher order relationship (e.g., synthesis, analysing), learner regulation (e.g., feedback, evaluation), and productive actions (e.g., inferring, applying). The design patterns numbering over 200 are grouped into 11 categories related to: game elements; resources and resource management; information, communication and presentation, actions and events; narrative structures, predictability and immersion; social interaction; goals; goal structures; game sessions; game mastering and balancing; and meta games replayability and learning curves. The authors have also conducted an evaluation study with ten experts and a sample of 11 game design patterns, which showed that the mapping procedure is valid and reproducible.

Žavcer, Mayr, and Petta (2014) have proposed Design Pattern Canvas (DPC) that was inspired by the Business Model Canvas (BMC), and represents is a design template for developing new or documenting existing serious games. The DPC consists of the following 9 components: Purpose, Mechanics / Task / Gameplay / Rules, Scope / Users / Stakeholders, Media / Biofeedback / Channels, Desired Outcomes / Consequences, Using the Pattern / Related patterns, Key Data, Ethics, and Related research / References. However, the authors did not conduct an evaluation study to validate the proposed DPC.

Robertson and Nicholson (2007) proposed a theoretical model of the creative process involved in game design. The model was proposed as part of the Adventure Author project that investigated the domain and meta-cognitive skills that students can develop through designing games. The model consists of the following creative stages: exploration of the game design software and its capabilities; generating the game idea; designing the game by expanding on the idea and detailing the characters, gameplay forms, levels, and progression of the narrative; implementation of the game that combines technical and artistic skills; testing the game to identify and fix bugs; and evaluating the game with target users to identify any potential difficulties users may have and get feedback for improving the game.

McMahon (2009a) has proposed the Document-Oriented Design and Development for Experiential Learning (DODDEL) model for the design of serious games. The DODDEL model consists of four documentation stages each with various outcomes: situation analysis (i.e., aims and outcomes, learner and context, learning approach), design proposal (i.e., specific concepts, game approach, challenges and feedback), design documentation (structure concepts, gameplay, game treatment), and production documentation (i.e., scripts and storyboards, game logic and variables, global specs and templates). The model was evaluated with a group of 20 undergraduate students showing that it provides the flexibility, scalability and scaffolding required to design serious games (McMahon, 2009b).

Arnab et al. (2015) have proposed the Learning mechanics-Game Mechanics (LM-GM) model that includes various learning mechanics (e.g., participation, plan, ownership, incentive, modelling, analysis, etc.), and game mechanics (e.g., fun, story, feedback, realism, movement, etc.) to support serious games analysis and design. Moreover, (Arnab & Clarke, 2017) have proposed to combine multiple frameworks in order to create a trans-disciplinary methodology for game-based intervention development. This trans-disciplinary methodology combines the Intervention Mapping (IM) approach common to the health intervention field with the Four-Dimensional Framework of Learning (4DF) for game-based learning and the Mechanics Dynamics Aesthetics (MDA) model for digital entertainment games. Moreover, it uses the LM-GM model to add the pedagogical aspect.

3. The Final Frontier game

3.1. The NEWTON project

NEWTON is a large-scale EU Horizon 2020 project that aims to develop, integrate and disseminate innovative technology-enhanced learning (TEL) methods and tools, and create new or inter-connect existing state-of-the art teaching labs. Moreover, NEWTON aims to build a large pan-European learning platform that links all stakeholders in education, supports fast dissemination of STEM learning content to a wide audience in a ubiquitous manner, enables content reuse, supports generation of new content, increases content exchange in diverse forms, develops and disseminates new teaching scenarios, and encourages new innovative businesses (NEWTON, 2016).

The NEWTON platform integrates and deploys many novel and emerging mechanisms and TEL methodologies including: inter-connected fabrication labs and virtual labs, multimedia and multi-sensorial media distribution, augmented reality, gamification, game-based learning, and self-directed learning pedagogies (e.g., flipped classroom, online problem-based learning, and e-practice testing).

Additionally, the NEWTON platform performs personalization and adaptation of content delivery and presentation to address the individual learner needs including their physical disabilities, to improve the learning process, and to increase the learning outcomes and learner quality of experience.

The new Final Frontier 3D interactive computer game (El Mawas et al., 2018) presented in this paper will be deployed on the NEWTON platform and tested in different European primary schools. Case studies that will investigate the benefits of the educational game in different European schools (El Mawas, Truchly, Podhradskỳ, & Muntean, 2019) will be organized and an analysis of the results across countries will be performed.

3.2. Game methodology

Our methodology for designing the Final Frontier game is based on (Marfisi-Schottman, George, & Tarpin-Bernard, 2010). However, we added two steps: general and detailed descriptions of the learning puzzle, respectively because we believe that recall is a very important step in the learning process. Moreover, we also took into account the recommendations for efficient game design made in (Tobias et al., 2014).

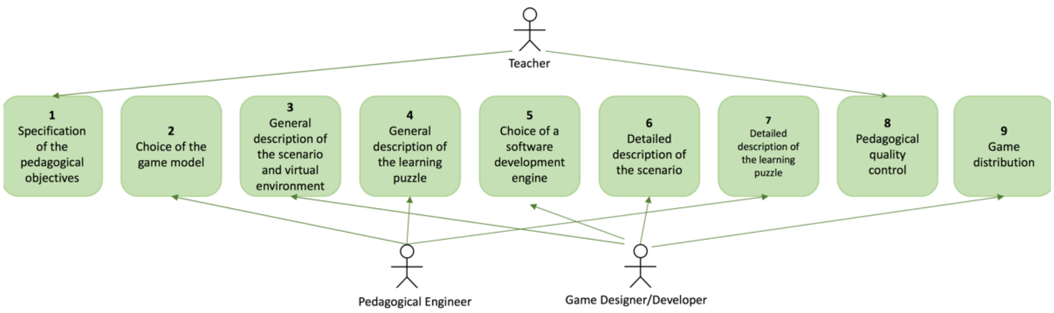

Fig. 1. Game methodology

Our game methodology is composed of the following nine steps, as displayed in Fig. 1: specification of the pedagogical objectives, choice of the game model, general description of the scenario and virtual environment, general description of the learning puzzle, choice of a software development engine, detailed description of the scenario, detailed description of the learning puzzle, pedagogical quality control, and game distribution.

Specification of the pedagogical objectives**:** our computer game-based learning will be used to teach Solar planet concepts in primary schools. These concepts can be decomposed into knowledge levels. The first step of the conception phase consists of defining these concepts that must be learned by the students. For this reason, we worked with teachers (Lunn et al., 2016) from European primary schools that teach the Geography subject to be sure that the game covers the required topics specified in the curriculum and we defined the complete pedagogical objectives of the game (see Table 2).

Choice of the game model: after defining the pedagogical objectives, we chose the adventure game as the game model for the Final Frontier. This game model is one of the most popular genre of video games among children. The children get more immersed and motivated when they play adventure games in comparison with other game types. In addition, in an adventure game, we can easily have a linear story (i.e. traveling across three planets in our case).

General description of the scenario and virtual environment**:** the aim of this part is to structure the pedagogical scenario and match it up with a fun based scenario. Our main focus was to make the game familiar to the students. The characters are simple human characters so the player can easily interact with. The story of the game is that the player is on a field trip, and he visits the planets. The player has a task to do on each the planet and learn implicitly topics about the planet.

Table 2
LOs of the Final Frontier game

Planet	LOs
Mercury	- Closest planet to the Sun (LO1)
	- Planet with the most craters (LO2)
	- Smallest planet (LO3)
Venus	- Hottest planet due to the greenhouse effect (LO1)
	- Spins opposite direction to Earth (LO2)
	- High Gravity; visitor cannot jump very high (LO3)
Moon	- Solar Eclipse (LO1)
	- Gravity differences (LO2)
	- First person on the Moon (LO3)

General description of the learning puzzle: When the player completed his task, he is brought back to the spaceship to do a puzzle to be able to progress to the next level. The puzzle learning was added because we believe that active recall is a principle of efficient learning. It claims the need to actively stimulate memory during the learning process. Many studies demonstrate the role of active recall in consolidating long-term memory (Spitz, 1973).

Choice of a software development engine: concerning the game development engine, Unreal Engine 4 or Unity are the two most popular game development engines that can be used. We decided to choose the Unreal Engine 4 because of its graphic potential, especially as we wanted to give the player the most realistic environment of the planets.

Detailed description of the scenario: In this part, we illustrated each scene with all the details and interactions we want to integrate into the game (see Table 3).

Table 3
Implementation of LOs in the game

Planet	LOs	How LOs are implemented in the game?
Mercury	LO1	- The Sun was much bigger on this level
		- An information screen saying it is the closest planet to the Sun.
		- One of the Non-Player Characters (NPC) also mentions this when you went up to talk to her
	LO2	- An Information screen at the start of the level explains it is the most cratered planet.
		- The player must go into to craters to get the meteors and they can see there are many craters
	LO3	- An information screen at the start of the level explains it is the smallest planet.
Venus	LO1	- The cooldown bar in the game shows that the planet is hot. As they go across the planet the cooldown bar drops, they must go inside to recharge it.
		- In one of the “space igloos” clouds.

	LO2	- In the first “space igloo” it shows the player a 3D model of Earth and Venus spinning in opposite directions. - It also has text beside the two models explaining that Earth and Venus have opposite rotations
	LO3	- When the player presses the jump key, he cannot jump very high
Moon	LO1	- The player sees a text pop up on the Moon level that explains what a Solar eclipse is - The player sees a small 3D version of the Moon go across a small version of the Earth and cast a shadow on it.
	LO2	- The player can jump higher on the Moon
	LO3	- The player can see a footprint on the ground of Moon level - A text pop up comes up and explains that the first person on the Moon was Neil Armstrong

Detailed description of the learning puzzle: the game presents three puzzles (see Table 4). The puzzle 1 is dedicated to Mercury. If the puzzle is answered correctly, the player is allowed to go to planet Venus. The puzzle 2 is dedicated to Venus and allows progression to the Moon. The puzzle 3 is dedicated to the Moon.

Table 4
The learning puzzles in the game

Puzzle	Which LO(s) was/were assessed?	How? (the question(s) + different choices)
1	Which planet is closest to the Sun?	The player must go to the 3D Mercury or Venus spheres. They will attach to the player and then the player will walk towards the Sun with the planet in hand. If the player gives Mercury, a congratulations message will pop up and a key will spawn.
2	Which planet is the hottest?	The player walks towards Venus orb, The player walks towards Venus orb or Mercury orb. If correct, a message pops saying congratulations and the key spawns. If incorrect, it says oops try again.
3	Which person was the first person on the Moon?	The player walks towards which person was the first on the Moon. If correct, a congratulation message pops up and the key spawns If incorrect, it says oops and try again.

Pedagogical quality control: the developed game was shown to the teacher to confirm and approve the pedagogical quality of the game.

Game distribution: Once the teacher was satisfied and the game was approved, the game was ready to be distributed on to the students in the class.

3.3. Functionality design

The game was designed with three people in mind (see Fig. 2). The “Game Designer”, the “Teacher” and the “Player”. Before initial building of the game, the Game Designer discussed with a teacher the topics and questions that the puzzle should cover in the game. After this discussion, the Game Designer created the puzzle and the questions. The Game Designer also created the levels in which the player exists. Each level contains several entities with which the player can interact. For instance, the player can collect objects, use the jetpack, and interact with the Game Menus. There is also a Non-Player Character (NPC) in the game that can discuss with the player.

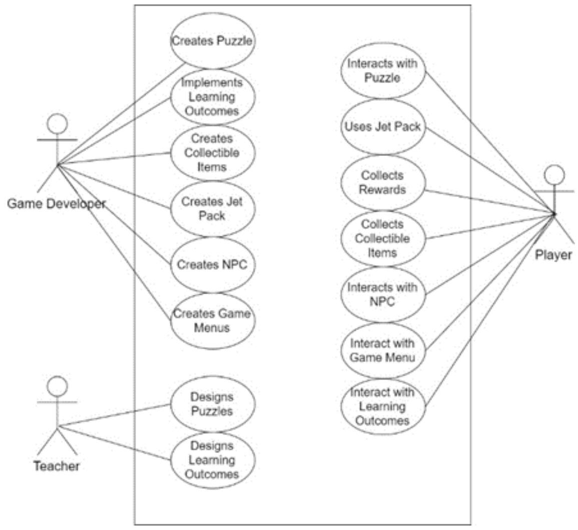

Fig. 2. Use case diagram of the game

3.4. Game architecture

The technical architecture (Fig. 3) is composed of four components: the game specific subsystems, the front-end, the back-end, and the gameplay foundations.

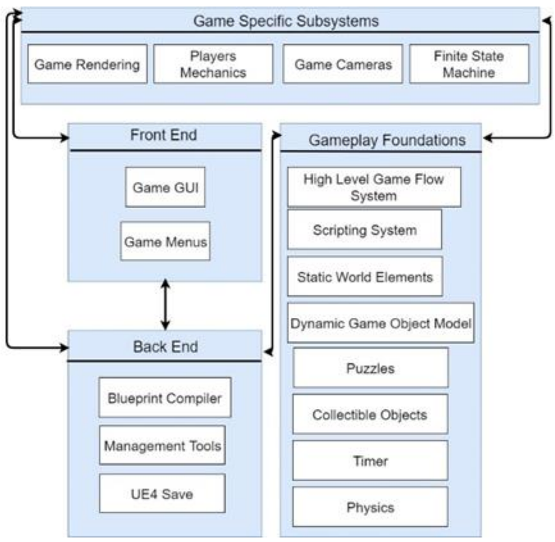

Fig. 3. The Final Frontier game architecture

The game-specific subsystems are a self-contained system within a larger system. The larger game system contains *the game rendering, player mechanics, game cameras, and finite state machine*. *The game rendering* is the system that displays the graphics on the computer screen. This would be the player character, game level's environment, objects in the game level, graphical user interface of the game such as the Head Up Display (HUD) and game menus. It is linked to the front-end game and game menus. *The player mechanics* refer to a set of rules allowing the player to move and interact within the game environment. These rules define how the player can move around the level, what objects s/he is allowed to pick up, what items s/he can use and in which context. For example, in the *Final Frontier* game, the player can walk around the environment controlling their character, can collect items, and can use a jetpack on one of the levels. The player's interaction with objects is linked to the gameplay foundations to ensure that the player can interact with that object, and if so, the scripting system kicks to run the code to allow the interaction. Certain interactions are only available when the player has done a certain previous task, which is checked through the high-level game flow system in the game foundations. *The game cameras* allow the player to see the game environment from different perspectives. For example, in our game we have a "third-person perspective" and this means that the camera is behind the character that the player is controlling at shoulder view. *The finite-state machine* is a model used to represent the control and the execution flow. Only a single state can be active at the same time, so the machine must pass from one state to another to perform different actions. His role is to control the flow of the game and to give the restriction rules to the High-level game flow system. This ensures the player cannot skip and jump into different levels that they are not meant to be able to get to.

The front-end is the "presentation layer" and it is what the user sees when they play the game. This includes menus and game's HUD. The front-end includes the game Graphical User Interface (GUI) and game menus. The Game GUI is linked with the game rendering, the game rendering renders all the graphical information, but the Game GUI places what should be where in accordance to where the player is and what the player is doing. The game menus give the players options to do different things, in our case this is to start the game, continue the game, change resolution of the screen, and during the game they can access a 'pause menu' and they can save the game or quit the game.

The back-end in this case refers to all the code and systems of the game engine. It essentially keeps the game ticking. It contains *the blueprint compiler, management tools and the Unreal Engine 4 (UE4) save File. The blueprint compiler* is the compiler of the script engine that UE4 uses (known as blueprints). The game Final Frontier was coded using its built-in "visual coding" called blueprints. Blueprints-based visual coding generates C++ code in the backend for the engine to understand what to do. *The management tools* communicate with various objects in the game such as physics, graphics and any plug-ins that are added. *UE4 save file* saves the game information as variables. In the case of our game, we are saving variables of the players' progress such as the time they spent on each level, and the number of stars they have collected. This is generated in an encrypted file which can only be read during gameplay by the scripting system, which then reads in the data from the save file and communicates with the High-level flow system to see the players progress in the game.

Gameplay foundations are what the game has at its core. The Gameplay foundations has several components such as *high-level game flow system, scripting system, static world elements, dynamic game object model, puzzles, object pickups, timer and physics. High-level game flow system* is the flow of the gameplay; it communicates with the finite state machine to see where the player is during the gameplay and keep track of the progress that gets saved in the UE4 save file. It also ensures that the player must complete all the objectives in the order that they are meant to be. *Scripting system* works with the blueprint compiler in the back-end. As already mentioned, the scripting system in UE4 is called Blueprints and generates C++ in the background. Blueprints uses a node-based interface to create different gameplay elements, from the editor you insert all the nodes to create the gameplay. This includes features such as arrays, variables, branches, loops, just like other object-orientated languages. This also includes features that are only related to gameplay such as OnTriggerEnter, OnTriggerLeave, etc. These features are linked to trigger boxes in the game environment, and are controlled by the game rendering. *Static world elements* are 3D objects in the world that the player cannot move or interact with. This would range from the landscape of the levels, walls floors to chairs, etc. These are necessary to give a level outline and definition. *Dynamic game object model* defines the contents of the game world, and defines the initial properties of game objects, also associates game objects with behaviours. Therefore, in Final Frontier, we have dynamic 3D models of the planets that the player uses for the puzzles, they can pick up the objects and it attaches to the player. We also have a jetpack that reacts when the player presses the right mouse button and fire comes out of the jetpack. *Puzzles* in the game are a mechanic that we use to evaluate the players progress through the game. Once the player does the puzzle, a collecTable key appears in the game to allow the player to progress through the game. *Object pickups* are several objects in the game that the player can pick up, such as keys (which link to the puzzles), Stars (which the player can collect throughout the levels), and Meteors (in the first level the player must collect 5 meteors from the craters to progress through as well). These are accomplished by using the scripting system and are saved in the UE4 Save File. *Timer* is used to see how long the player takes on the level this is done by using the scripting system and is stored in the save file. *The physics* in the game effect how the player can jump within the environments of the levels. An Example of this is the on the Moon the player can jump higher than normal whereas on the Venus level the players jump is limited.

3.5. Overview of the game

Final Frontier is an interactive 3D educational video game for children about space. The game supports knowledge acquisition on Solar system planets such as Mercury and Venus, and Moon – The Earth's satellite through direct experience, diverse challenges and fun. The topics coved by the game are part of the geography curriculum, section "Planet Earth and Space", defined for the primary school.

The player enters the spaceship and needs to go to the first planet that is Mercury. On Mercury, the player must collect 5 meteors using the jetpack to get in and out of the craters, and once they collect 5 meteors they are brought back to the Spaceship. The player now must complete a puzzle about Mercury and if they get it right, they gain access to the next planet Venus. On Venus, the player must go across the environment within the coolant time. Once they get to the last building, they are teleported back to the spaceship and they must complete a puzzle about Venus to unlock the next level that is the Moon. On the Moon, they must collect 10 stars jumping on the platforms. Once they collect 10 Stars, they are teleported back to the Spaceship where they must complete a puzzle about the Moon. They then gain access to the next and final level Mars. On Mars, they must go through the Maze and find the liquid water. They get teleported back to the Spaceship where they must complete a quiz and then the game ends. After each level, a section on the spaceship opens for the player to go to view the information they learned about the planets and when they finish the game, they can gain access to more information on the Gas Giant planets in the information hub.

The game is a 3D environment with different levels, each level contains different models and landscapes. The levels are designed to give a relatively accurate view of the planets in a cartoon style form. On the screen, there is a game HUD that displays information to the player such as, star counter, meteorite counter, coolant time, and game objective. It also displays the text box of what the avatar is saying. The game is composed of four activities:

- Activity 1: The player will see a pop-up text box appear on the screen, which will explain what the player must do. After this, the player can see on the HUD the display of the mission objective as well as the number of meteors they must collect and the number of stars they have collected. When doing the puzzle, it will ask the player a question and they drag the correct answer onto the question mark and then click the submit button.
- Activity 2: The player will see a pop-up text box appear on the screen, which will explain what the player must do. After this, the player can see on the HUD the display of the mission objective as well as the number of stars they have collected and the coolant bar. When doing the puzzle, it will ask the player a question and they drag the correct answer onto the question mark and then click the submit button.
- Activity 3: The player will see a pop-up text box appear on the screen, which will explain what the player must do. After this, the player can see on the HUD the display of the mission objective as well as the number of stars they have collected. When doing the puzzle, it will ask the player a question and they drag the correct answer onto the moon and then click the submit button.
- Activity 4: The player will see a pop-up text box appear on the screen, which will explain what the player must do. After this, the player can see on the HUD the display of the mission objective as well as the number of stars they have collected. When doing the puzzle, it will ask the player a question and they drag the correct answer onto the question mark and then click the submit button.

4. Game study

The goal of the research study was to investigate the effectiveness of the Final Frontier game when teaching scientific knowledge of the planets from the solar system to primary school students.

This section presents the evaluation methodology applied, case study set-up and the results analysis for of the collected data.

4.1. Evaluation methodology

4.1.1. Overview

The evaluation methodology involves a comparison between traditional teaching and game-based learning approaches. The evaluation included two groups/classes of students: experimental group and control group. The experimental group was taught using the Final Frontier game, while the control group was taught in a traditional manner, where the teacher explained in the class the concepts related to the Solar System. For this purpose, detailed slides were prepared for presenting the same concepts illustrated in the game to the control group in order to ensure that the same learning content was delivered to both groups.

The evaluation meets all ethical requirements. Prior to running the case study, an approval was obtained from the relevant Ethics committees and all required forms were provided to the students and their parents: informed consent form (for the parents), informed assent form (for the students), plain language statement and data management plan. These documents include a detailed description of the testing scenario and testing procedure. The students were informed they could leave at any moment during testing if they wish so, with no repercussions.

Table 5
Evaluation process

Phase	Control group	Experimental group
Collection of the consent forms (signed by the parents)	x	x
Description of the research study	x	x
Collection of assent forms	x	x
Learning experience	Teacher based learning	Computer game learning
Post-test	x	x
Extra-learning activity	Computer game-based learning	-
Survey	x	x

The flow of the evaluation is depicted in Table 5 that presents in detail the steps followed by each of the two groups, experimental and control group respectively. It can be seen that prior to beginning the evaluation, the consent forms signed by parents were collected. Then the children were introduced to the evaluation and were asked to review and sign the assent form. The children had about 20 minutes to play the game or until they finished the game before doing a survey. Note that the duration of pre/post-tests is about 5 minutes each. The survey duration is about 10 minutes. The major differences in the steps followed between the two groups are as follows:

- The teaching session was different: teacher-based session in which students were presented with the aforementioned slides in case of the control group and computer game-based learning in which the students were taught following our proposed approach.
- The control class also participated in the computer game-based learning after their knowledge was assessed.

The pre-test and the post-test were each composed of four questions: one Yes/No question, one open question, and two unique choice questions. In the pre-test questions, students could select "I don't know" answer. The pre-test and post-tests questions assessed the same knowledge but questions in each test are different. The questions were designed with the teachers from a primary school that teach the Geography subject to students and that participate to the design of the Final Frontier game.

The case study investigated the learning impact of the game, the user experience with the game and the game usability (Table 6).

Table 6
Evaluation codes and labels

Criteria	Criteria label
C1	Learning impact of the game
C2	User experience with the game
C3	Game usability

4.1.2. Participants

A total of 53 children 9-10 years old from Saint Patrick Boys National School located in Dublin, Ireland took part in the case study.

The participating students were divided in two groups, according to the class they attend: one of the two classes was randomly assigned to be the experimental group, which was composed of 27 students, and the other class was assigned to be the control group, which was composed of 26 students. Note that at the beginning, the two groups had the same number of students but one student from the control group did not get the parents' approval, so he did not participate in this research study.

4.1.3. Data collection

As presented in Table 4, the evaluation process involved a number of stages. First, the student consent form was collected. Then, the students were exposed to the learning activity (teacher-based or game-based). A learner satisfaction questionnaire and a post-test, assessing if the participating students gained knowledge on the presented topics was provided to students immediately after the learning experience. The post-test was offered to students after the learning experience questionnaire in order to ensure that their response toward the application was not affected by the possibility of not knowing answers to some of the post-test questions. All tests and questionnaires were provided on paper, following which these were transcribed in digital format.

The survey questionnaire is presented in Table 7, where it has to be noted that standard emoji were associated with each answer to the questionnaire's questions.

Another aspect to be noted in relation to the survey questionnaire is that only control group had to answer Q9. As the control group was exposed to both forms of teaching (see Table 5), it was valuable in the context of our evaluation to see which of the two teaching approaches the students preferred: teacher-based leaning or computer game based learning.

Table 7
Survey questions

Question	Answer/Scale
Q1. The video game helped me to better understand the characteristics of different planets.	- Strongly Disagree (SD) - Disagree (D) - Neutral (N) - Agree (A) - Strongly Agree (SA)
Q2. The video game helped me to learn easier about planets.	- Strongly Disagree

	- Disagree - Neutral - Agree - Strongly Agree
Q3. I enjoyed this lesson that included the video game on planets.	- Strongly Disagree - Disagree - Neutral - Agree - Strongly Agree
Q4. The quizzes that I did in the game helped me better remember what I learned.	- Strongly Disagree - Disagree - Neutral - Agree - Strongly Agree
Q5. The video game distracted me from learning.	- Strongly Disagree - Disagree - Neutral - Agree - Strongly Agree
Q6. I would like to have more lessons that include video games.	- Strongly Disagree - Disagree - Neutral - Agree - Strongly Agree
Q7. What did you like most about the game?	- Strongly Disagree - Disagree - Neutral - Agree - Strongly Agree
Q8. Comments / Suggestions (optional)	- Strongly Disagree - Disagree - Neutral - Agree - Strongly Agree
Q9. What way of learning you would like (tick one answer)?	- Teacher based learning - Computer game-based learning

4.2. Results analysis

4.2.1. Learning impact of the game

The purpose of this section is to evaluate the criteria "Learning impact of the game" (C1). The evaluation was based on an analysis of the post-test results for the control and experimental groups.

The post-test results are displayed in Fig. 4, were the percentage of correct answers and the corresponding number of students are provided for the control and experimental groups. In the control group (Fig. 4a), 4 students (15%) answered correctly all post-test questions and 13 students (50%) provided correct answers to at least 3 questions out of 4 in the post-test. 4 students (16%) provided incorrect answers to either all questions or answered correctly only one question out of 4.

A better post-test outcome was noted in the experimental group (Fig. 4b), where 13 students (48%) provided correct answers to all post-op questions and 21 students (78%) answered correctly to at least 3 questions out of 4. Only one student (4%) answered incorrectly to 3 out of 4 post-test questions and no student in the experimental group failed to answer all questions.

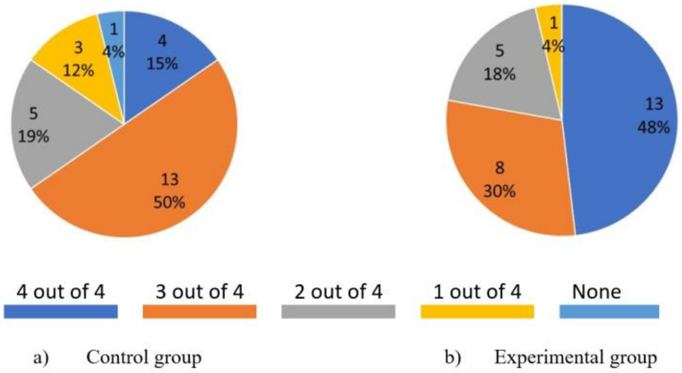

Fig. 4. Percentage of students vs. number of correct answers in the post-test assessment for (a) Control group and (b) Experimental group

When comparing the two groups, a clear advantage is seen in the experimental group, where the novel learning activity was employed. It leads to nearly half of the experimental group answering correctly all post-test question, compared to only 15% in the control group. At the other end of the scale, in the experimental group, only 4% of students answered incorrectly 3 questions out of 4, compared to 12% in the control group.

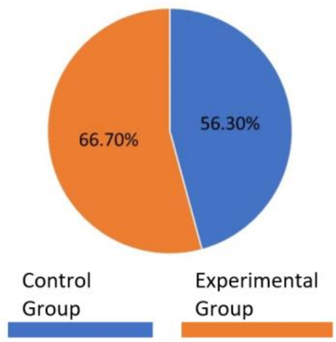

Fig. 5. Changes in scores in control and experimental groups (per question)

The learning impact of the game was evaluated by calculating the percentage of correct answer per post-test questions for each group and computing the mean of correct answers in each group, experimental and control, after the learning experience. This is displayed in Fig. 5. We can see that 56.3% of questions were answered correctly by the control group after being exposed to the teacher-based learning. In comparison, 66.7% of questions were answered correctly by the experimental group after being exposed to the computer-game based learning. The results of a t-test for independent groups showed that the post-test results for the experimental group were statistically significant higher than for the control group but only with alpha = 0.1 significance level ($t(50) = 1.912$, $p = 0.062$). This showed that using game for teaching the Solar System concepts increased the mean of correct answers by 10.4% compared to classical learning approach. This is a positive outcome obtained after only one teaching session.

4.2.2. User experience

In this section, the “User experience” (C2) criteria when using the Final Frontier game is discussed. It was evaluated through 6 questions for both groups, Q1 to Q6, from the survey detailed in section 4.1.3. The experience was analysed in terms of number of Strongly Agree / Agree answers for Q1, Q2, Q3, Q4, and Q6 and Strongly Disagree / Disagree for Q5.

Fig. 6 provides the User Experience survey answers for the control group, where 96.2% of students confirmed that the video game would have helped them better understand the characteristics of different planets. The same percentage of students (96.2%) thought that the video game would have helped them to learn easier about planets. 88.5% of students enjoyed the lesson that included the video game on planets. 88.5% of students agreed on the fact that quizzes in the game helped them better remember what they learned. 84.6% of students disagreed that the video game distracted them from learning. 96.2% of students would enjoy having more video games-based lessons.

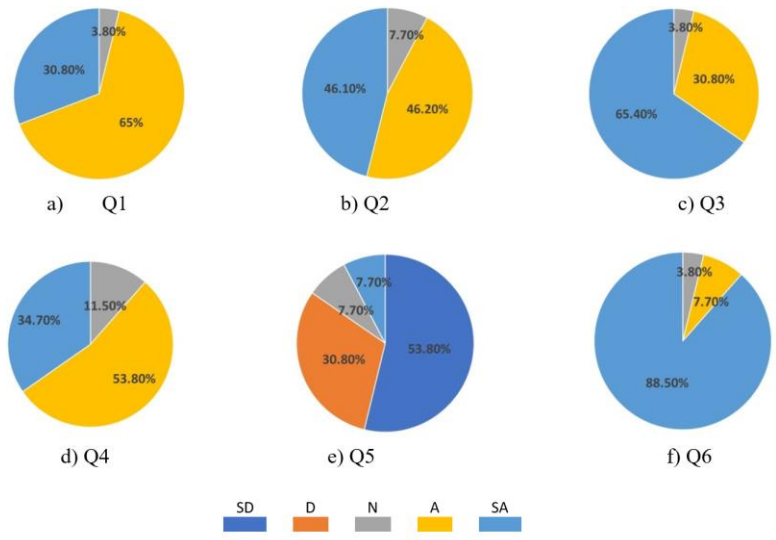

Fig. 6. Students’ answers on the user experience survey (control group)

The user experience of students in the experimental group is presented in Fig. 7, showing great results as well. 88.9% of students confirmed that the video game helped them to understand better the characteristics of different planets. 85.2% of students thought that the video game helped them to learn easier about planets. 100% of students enjoyed the video game-base lesson on planets. 81.5% of students agreed on the fact that quizzes in the game helped them better remember what they learned. 55.6% of students disagreed that the video game distracted them from learning. 96.3% of students liked to have more lessons that include video games.

Note that in Fig. 6 and Fig. 7 the following abbreviations are used: SD for Strongly Disagree, D for Disagree, N for Neutral, A for Agree, and SA for Strongly Agree.

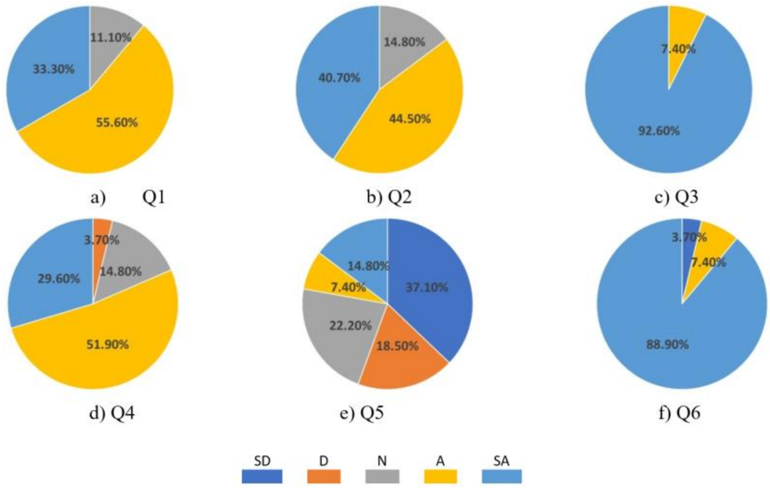

Fig. 7. Students' answers on the user experience survey (experimental group)

Table 8 presents the mean and standard deviation ratings for the first six questions of the user experience survey, as well as the results of statistical analysis using a t-test for independent groups. The results show that the experimental group had statistically significant higher rating than the control group for Q3 (i.e., I enjoyed this lesson that included the video game on planets.) at 0.05 confidence level, and a weaker difference for Q5 (i.e., the video game distracted me from learning.) at 0.1 confidence level. No statistically significant difference was found between the experimental and control groups for the other four questions.

Table 8
T-test results between the control and experimental groups for the user experience survey

	Control Group		**Experimental Group**		***t*-Test Results**		
Question	*Mean*	*STD*	*Mean*	*STD*	*t*	*df*	*p*
Q1	4.27	0.53	4.22	0.64	0.291	50	.772
Q2	4.38	0.64	4.26	0.71	0.676	50	.502
Q3	4.62	0.57	4.93	0.27	-2.520	50	.016 **
Q4	4.23	0.65	4.07	0.78	0.794	50	.431
Q5	1.77	1.14	2.44	1.45	-1.887	50	.065 *
Q6	4.85	0.46	4.78	0.80	0.382	50	.704

Note. **** $p < .001$; *** $p < .01$; ** $p < .05$; * $p < .1$

4.2.3. Game usability

The “Game usability” (C3) criteria is discussed in this section. The game usability of the Final Frontier was evaluated through Q7 and Q8 for the experimental group and through Q7, Q8 and Q9 for the control group) from the survey detailed in section 4.1.3.

An analysis of the answers provided for Q7 and Q8 shows that 88.88% of students from the control group and 96.29% of students from the experimental group mentioned that they enjoyed the game, in particular the fun aspect, the learning aspects, the stars and meteors collection, the Non Player Character, the use of jetpacks, and the interactive puzzle rooms in the game.

Regarding Q9, 88% of students from the control group mentioned that they prefer computer game-based learning compared to classical learning (i.e. teacher-based).

5. Conclusion and perspectives

This study addresses the problem of motivating and engaging students on one hand and improving learning experience for students studying STEM subjects. We present the game methodology, functionality design, and game architecture of the Final Frontier, a new 3D interactive educational video game for primary school students developed by the authors. The game supports knowledge acquisition on planets Mercury and Venus, and Earth’s satellite Moon through direct experience, active recall, challenge activities and fun. A case study has been conducted on 53 primary school students in order to investigate three criteria: game learning impact, game user experience, and game usability. In this use case, the evaluation included two groups of students, an experimental group and a control group. The experimental group was taught though the Final Frontier game, while the control group was taught in a traditional manner. Post-test questionnaires and a game review survey were used to assess the evaluation criteria. An analysis of post test results has shown that the Final Frontier educational game has a positive impact on students learning. 50% of the students have answered correctly at least 3 out of 4 questions from the post-test in the control group, while 78% of the students have answered correct at least 3 out of 4 questions from the post-test in the experimental group. In addition, the two groups had a great user experience: 92.5% of students confirm that they had a great learning experience when using the Final Frontier game. Furthermore, they were satisfied about the game usability: 92.6% of students enjoyed the game and appreciated the game features including the fun aspect, learning aspects, stars and meteors collection, Non-Player Character, use of jetpacks, and interactive puzzle rooms in the game.

Future work will aim to expand the research study on the Final Frontier game as well as on the game methodology. Further research will include all planets of the Solar System in the game. Other features like adaptation will also be designed and developed in order to address the problem of learners’ diversity, their difference in terms of prior knowledge and learning experience. The Final Frontier game will also be deployed on the NEWTON platform and new case studies on the learning experience of the proposed game in other European primary schools will be performed.

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