Teaching the Solar System with a Video Game

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Abstract: This paper presents the design and development of an educational game centred on the solar system, aiming to combine scientific accuracy with engaging gameplay. With the advancement of technology, Game-Based Learning (GBL) has gained increasing traction as an effective supplement to traditional education. Digital games set in virtual environments have demonstrated their ability to boost learner engagement and enhance knowledge retention. However, topics like the solar system often remain abstract and challenging for students, due to complex concepts such as planetary motion, gravitational forces, and spatial scales. To address these challenges, this project leverages GBL principles and scientific simulation techniques to create an immersive learning experience. Players engage in exploratory missions where they defend the solar system's resources while learning core astronomical concepts. The game environment is designed to promote active learning through interaction, strategy, and problem-solving, fostering a deeper understanding of planetary science. This paper explores the theoretical foundations behind game-based learning and its application to science education. It further details the design methodology, including scientific modelling, gameplay mechanics, and narrative elements that support learning outcomes. The game integrates interactive features such as dynamic simulations, visual storytelling, and progressive challenges that align with key educational goals. Special emphasis is placed on ensuring that educational content is seamlessly embedded within the game experience, avoiding didactic interruptions that may hinder player immersion. The research is guided by four key questions: How can complex astronomical knowledge be effectively conveyed through a game? How can developers maintain a balance between scientific accuracy and engaging gameplay? Can this game improve players' comprehension and interest in solar system science? What methods can be used to assess the game's impact on learning outcomes? The findings aim to contribute to the growing field of educational technology by providing insights into the integration of accurate scientific content within interactive digital games, ultimately enhancing science education through innovative and immersive methods.

Keywords: Game-Based learning (GBL), Solar system game, Education game, Game, STEM learning, Scientific simulation

1. Introduction

With the development of technology, Game-Based Learning (GBL) has gained widespread attention in the field of education (Situmorang et al., 2024) (Mikrouli, Tzafilkou, and Protogeros, 2024). In recent years, digital educational tools have gradually become an effective supplement to traditional classroom teaching (Anastasiadis, Lampropoulos & Siakas, 2018) (Mayer, 2019) (Squire, 2003) (Team, 2017). Among these, games based on virtual environments have been proven to enhance learners' interest and better for keeping their knowledge. Astronomy is an important topic in basic science education, but due to the abstract nature of the astronomical concepts involved, and hard for experience, many students face difficulties in understanding concepts such as planetary motion, or the construction and scale of the universe.

Against this background, this project designs and develops an educational game based on the solar system, combining game-based learning theory and scientific simulation technology, to help players learn solar system-related knowledge through an immersive gaming experience.

Moreover, many educational games face difficulty in getting a balance between scientific rigor and entertainment (Egert and Phelps, 2022) (Cadiz et al., 2023). As a result, the content is either too monotonous and lacks engagement or overly entertaining, which causes inefficient knowledge transmission. For example, some existing space-themed games like Universe Sandbox, Kerbal Space Program, and NASA Eyes on the Solar System, focus more on observation rather than immersive exploration. Therefore, this project attempts to integrate a well-designed task system, storyline, and interactive exploration mode to enable players to learn and understand scientific concepts of the solar system through an immersive gaming experience.

2. Related Work

For GBL development, the virtual environments (VE) play a core role, virtual environments provide powerful tools for immersive learning, allowing students to engage with complex concepts in an interactive and intuitive way. These environments are particularly valuable in science education, where they enable learners to visualize and manipulate abstract concepts that are otherwise difficult to grasp through traditional methods. (Falloon, 2011)

In astronomy education, these virtual environments help develop spatial awareness by allowing learners to visualize and understand the relative positions and movements of celestial bodies. Furthermore, VEs help to promote scale perception, enabling users to observe and explore the vast astronomical distances and the immense sizes of celestial bodies. Crucially, these environments support conceptual learning by providing intuitive ways to explore complex physics features, such as orbital mechanics and fundamental astrophysics principles, these may be difficult to study through traditional methods. (Yu, K.C., 2005)

Some examples of virtual environments utilized in astronomical education include Google Earth VR, which enables users to explore planetary surfaces and celestial landscapes, and the Solar System Scope, it is a 3D model that visually represents planetary orbits and astronomical events. Other VR apps allow users to virtually visit the international space station, explore the surfaces of Mars and the Moon, and even experience the birth of a star. These experiences often utilize spatial audio and haptic feedback to further enhance immersion, making the learning experience more engaging and memorable. (Keet, 2023) This can transform learning from a passive reception of information to an active and enjoyable process. (Yu, 2005) (Rasheed, Onkar, & Narula, 2016) (Cooper, Thong, & Kok-Sing, 2024)

Simulating the solar system with high scientific accuracy is very important for educational purposes, as it allows learners to understand complex astronomical phenomena through interactive and observable experiences, otherwise, this may become impossible. Accurate simulations enable the visualization of celestial mechanics, the exploration of the huge scales, and the observation of phenomena with different timescales. (Yu, 2005)(Matovu et al., 2023)(Rasheed, Onkar, & Narula, 2016)

To ensure the scientific accuracy and credibility of educational games, real astronomical data and physical simulations are required. This is achieved through the integration of several key components: applying principles such as Kepler's Laws and Newtonian Mechanics to predict planetary motion based on gravitational forces and orbits; (Russell, J.L., 1964) N-Body Simulations are utilized for modeling the complex gravitational interactions between multiple celestial bodies, to provide a dynamic representation of the system's evolution;(Musgrave, 2025) and incorporating astronomical data integration by collecting datasets from sources like NASA, CNSA, and other institutions.(Haque et al, 2024) These data sets typically include precise parameters like orbital parameters, masses, sizes, and surface characteristics of planets, moons, asteroids, and comets. Integrating these real-world data can make sure that the simulation environment can reflect the actual solar system as accurately as possible within the simulation.

There are some educational games and tools that have been developed with the aim of teaching astronomical concepts, each possessing has strengths and limitations in engaging learners and conveying scientific knowledge. The representative existing solar system educational games and visualization tools will show their characteristics, so that to evaluate their effectiveness in facilitating learning, and identify areas for potential improvement, thereby providing valuable insights for the design of future educational tools in this domain.

Universe Sandbox, an interactive physics simulation game, serves as a powerful tool for demonstrating large-scale universe phenomena, such as planetary collisions, gravitational interactions, and stellar evolution. However, it can be a problem to start for learners who lack a foundation in astronomical concepts or prefer a more guided learning experience. Additionally, as a game, it may lack structured objectives and may require a higher configuration to run smoothly. Kerbal Space Program (KSP) is a complex spaceflight simulation game based on realistic orbital mechanics and rocketry, it focuses on scientific accuracy in simulating physics relevant to space travel. Players can design, build and launch spacecrafts to complete missions to learn orbital dynamics and space engineering. Even though, it may lack detailed information about the planets and moons themselves, which may lack educational value about the composition, history, and characteristics of the solar system, and it also has a steep learning curve. NASA Eyes on the Solar System, which is developed by NASA. It is a robust 3D visualization software with real astronomical data to provide a scientifically accurate, real-time or simulated-time representation of celestial body positions, movements, and space missions. It is an invaluable resource for visualizing the scale and spatial arrangement of the solar system and tracking real-world astronomical events and missions. Nevertheless, it lacks interactive challenges, explicit learning objectives, and reward systems inherent in educational game design to drive learning through active gameplay and structured progression. Its strength is in observation and visualization, not in interactive learning or knowledge assessment.

3. Game Design

The game is designed as an immersive educational experience that combines astronomy learning with an engaging storyline and interactive gameplay. This game is named *Wentian*, meaning “Asking the Heavens,” is inspired by Qu Yuan’s ancient Chinese poem *Tianwen* (Qu Yuan, 2011), symbolizing humanity’s pursuit of cosmic knowledge. It also references the “Wentian” module of China’s Tiangong Space Station, and by using this name in the title of a solar system educational game represents the player's journey in exploring the universe and learning astronomy.

3.1 Gameplay Overview

Unlike atmospheric flight, where aerodynamics plays a significant role, space flight in this game operates on principles suited to a vacuum environment. The space fighter is controlled by a player from a first-person cockpit perspective, and the fighter is equipped with vector engines, allowing for precise directional flight control, making use of force vectors rather than aerodynamic lift or drag (Keylor, E.K., 2014) (Roberts, S.A. & Lucas, S.M., 2012). The game is set during a future interstellar conflict in which alien invaders threaten the solar system’s essential resources. Players take on missions to protect these resources, fight enemies, and explore planetary systems.

The game combines serious educational content with immersive simulation. Its core modes include an exploration module with free roaming and celestial observation, a mission module with story-driven tasks tied to astronomy topics, and a challenge module containing physics-based fighting and exploration challenges.

The spaceflight system simulates zero-gravity motion by Newtonian mechanics, controlled by mouse for orientation (pitch/yaw) and keyboard inputs for specific actions. These keyboard controls include 'E' to turn on or turn off the vector engine, 'S' for engine reverse thrust, 'SPACE' to fire lasers with a cooldown, 'R' to stabilize orientation, 'SHIFT' to activate super boost with a cooldown, and '1-9' keys for teleportation to planets or the enemy space station.

3.2 User Interface (UI)

The user interface is a key teaching component of a game, since it provides the information display. The game’s UI adopts a modular design to ensure clear and intuitive presentation of information. There is a main panel to display a solar system overview, current mission objectives, and key UI components include several parts.

The radar system is a 2D user interface element designed to visualize the relative positions of objects around the player’s space craft in a 3D space. It provides spatial awareness by displaying targets within a specified range and color-coding (red to yellow) being based on their vertical distance relative to the player (see Figure 1).

The UI Information System provides real-time feedback to the player by displaying essential game data such as position, speed, orientation, health points (HP), boost cooldown status, and distances to nearby targets. This system ensures the player has the necessary data to navigate, manage resources, and make tactical decisions effectively. The HP and boosting cooldown status are designed by colour bar (from red to green) to display the status dynamically (see Figure 1).

Combat UI consists of a crosshair and an enemy indicator. The crosshair is positioned in the centre of the screen for aiming. The Enemy Indicator System is a UI component designed to provide visual feedback to the player about enemy positions relative to the camera’s viewport. This system helps enhance spatial awareness by displaying indicators when enemies are either off-screen or at a specific distance with a colour buffer (light red to dark red) (see Figure 1).

In this game, the mission UI serves as the core interface for displaying and managing the player's current tasks and introducing the current celestial body. It consists of the task list and the introductions. The mission list UI is designed to allow players to quickly understand the task's status and progress, while also providing easy access to detailed task information. According to the UI related figures, we could see how the mission list looks like (see Figure 1).

The core function of introduction UI is progressive reveal, to introduce the current celestial body to the player while showing related knowledge, the task's objectives, and its background. After the introduction, players can proceed by clicking the "Continue" button, which leads them into the game to begin the task. This approach allows the game to convey solar system knowledge while ensuring that players are clear about the upcoming task goals and game progression (see Figure 2).

Figure 1: Game UI with damaged VFX and recovering HP

YOU ARRIVED MARS!

Mars has a diameter of about 6,792 kilometers, which is about half the size of the Earth. Its surface gravity is about 38% of Earth's, so the weight of objects on Mars is significantly reduced. Mars has a rotation period of about 687 Earth days and a rotation period of 24 hours and 39 minutes, which is very close to the Earth's rotation period. Mars is a red planet, and this red color comes from the abundance of iron oxide on its surface. The atmosphere of Mars is very thin, consisting mainly of carbon dioxide (about 95%), nitrogen and argon. Due to its low atmospheric density, Mars is unable to retain heat efficiently, resulting in a huge temperature difference between day and night, with temperatures usually ranging from -140°C to 20°C. There are polar ice caps on Mars, which are composed of water ice and carbon dioxide ice. Scientists hypothesize that

Figure 2: Introduction UI for learning

3.3 Effects

The special effects component primarily enhances the game's immersion and interactivity through a series of visual and sound design elements. Special effects not only improve the game's artistic presentation but also effectively convey the dynamic changes of in-game objects and events.

Visual effects (VFX) are crucial for enhancing player immersion and the overall gaming experience. This game implements various visual effects, including damage feedback (see Figure 1), explosion effects, and changes in the camera's field of view and teleportation effects (see Figure 3).

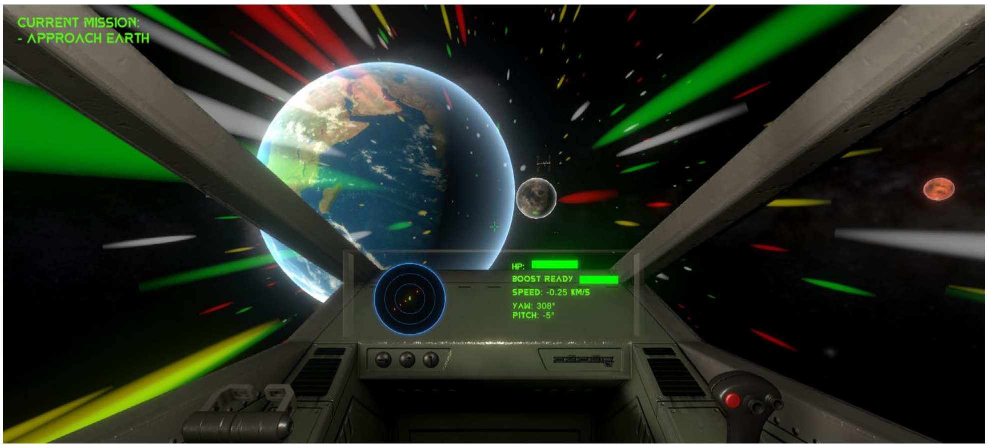


Figure 3: Teleport and FOV VFX

The implementation of sound is managed through *AudioSource* and *AudioClip*, with the goal of providing players an immersive gaming experience, enhancing the atmosphere and interactivity. The sound implementation includes background music, task sound effects, and combat sound effects. All sound effects are dynamically adjustable to adapt to different game scenes and task progress.

3.4 Teaching Content Overview

Firstly, the game helps players build an understanding of the overall structure of the solar system. Players can explore in a virtual environment, intuitively learning the relative positions and approximate distances of celestial bodies such as the Sun, the eight major planets and their main moons within the solar system. Through accurate simulation, the game presents a sense of the scale of the solar system, helping players overcome difficulties in abstractly understanding cosmic distances and the sizes of celestial bodies.

Secondly, the game provides detailed introductions to the characteristics and basic laws of motion of the main celestial bodies within the solar system. While performing tasks, such as planetary exploration, players learn about the composition, surface environment, atmosphere, geological features, and other knowledge concerning various planets, such as Earth, Mars, Jupiter, Saturn, and their moons, such as Earth’s Moon, Europa or Titan. At the same time, the game simulates the rotation, revolution, axial tilt, and orbital inclination of celestial bodies, and demonstrates their modes of motion based on Kepler's laws and Newton's laws, allowing players to understand how planets orbit the Sun and the causes of phenomena such as day and night.

The game not only presents natural celestial bodies but also incorporates artificial objects and elements of human exploration. For example, the game simulates China's Tiangong space station. At the same time, combined with a space fighter powered by a vector engine, it creates a futuristic yet reasonably simulated world. Through this method, players not only learn about the natural composition of the solar system but also understand human efforts to explore the universe, combining astronomical knowledge, mechanics and motion, and aerospace technology background.

4. Implementation

As a huge and complex system, the solar system involves various aspects such as celestial body modelling, orbital mechanics, physical laws, and rendering natural lights. To get a balance between education and entertainment, this project uses the Unity engine to develop a realistic and high-performance solar system simulation framework. By combining real astronomical data with modern graphics technology, it provides players with a realistic scientific learning experience.

4.1 Solar System Environmental Simulation

The simulation of the solar system environment is built on the Unity engine, using a scale ratio of 1:10,000 km for scene construction, which means that one unit in the game represents 10,000 kilometres in the real solar system. This scale ensures the preservation of spatial relationships between celestial bodies and visual realism within the visible space.

Through modelling and creating a game environment based on the distances between celestial bodies and the Sun, players can intuitively observe the structure of the solar system and gain a direct understanding of the positions of celestial bodies within it.

Celestial body modelling is the basis of the solar system celestial bodies, ensuring that players can visually observe the shape, size, and surface features of the celestial bodies in an intuitive way. And the textures are publicly available images from NASA processed into 4K or 8K resolution.

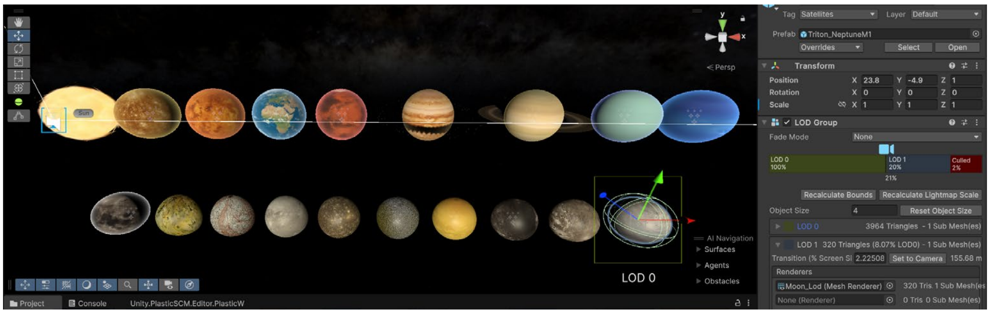
In this project, geometric bases of celestial bodies are spheres based. By applying different mesh details and material layers, implement visual representations of celestial bodies. Each celestial object maintains an independent *GameObject* hierarchy, facilitating subsequent physics property binding, script control, and visual optimization.

Other environmental details include:

- A dynamic cloud layer (transparent effect) is added to some planets like Earth.
- The asteroid objects belt near Jupiter, which is a set of asteroid objects.
- Saturn’s rings, which is multiple ring-shaped planes with a transparent texture.

Through these details, to enhance the game's visual realism and educational value.

The main natural celestial bodies are shown in Figure 4, including the sun, planets and moons (satellites).



Tag: Satellites
Layer: Default
Prefab: Triton_NeptuneM1
Position: X 23.8 Y -4.9 Z 1
Rotation: X 0 Y 0 Z 0
Scale: X 1 Y 1 Z 1
Fade Mode: None
LOD 0 100% | LOD 1 20% | Culled 2%
Object Size: 4
LOD 0 3964 Triangles - 1 Sub Mesh(es)
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Figure 4: Natural celestial bodies

Additionally, there are two artificial satellites: The human Space Station (Tiangong), is designed as the location where the human base and the exit of the game are (see Figure 5). The enemy space station is designed as the enemy base in the solar system, and there is a simple exploration mission for it.

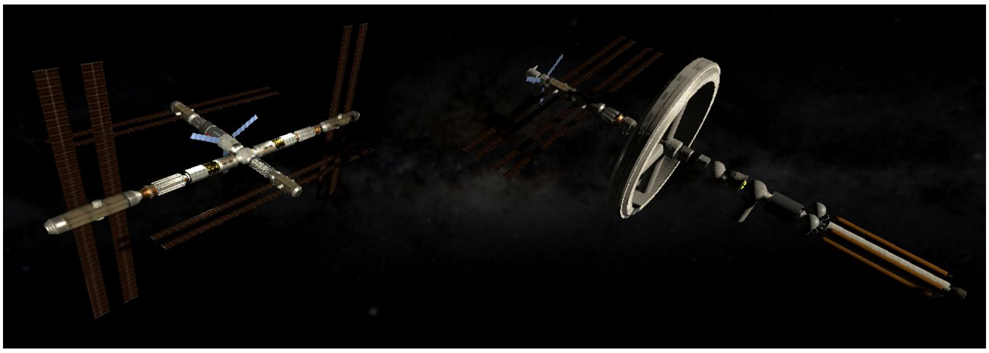

Figure 5: Tiangong space station (left) and enemy space station (right)

Orbital motion is key to simulating the dynamics of the solar system, ensuring celestial bodies move along accurate trajectories based on Kepler's laws and Newton's Law.

Kepler's laws define:

- Planetary orbits around the Sun are elliptical, with the Sun at one focus. (Russell, J.L., 1964)
- A planet moves slower when farther from the Sun and faster when closer. (Russell, J.L., 1964)
- The square of a planet's orbital period is proportional to the cube of its semi-major axis. (Russell, J.L., 1964)

Newton's Law defines: The object remains at rest or moves in a straight line at constant speed when no external force acts on it. (Encyclopedia Britannica, 2018)

Advanced graphics technologies simulate lighting, atmospheric effects, and material properties to enhance players' experience and learning interest. Main implementations include Physically Based Rendering (PBR) and Dynamic Lighting.

For Physically Based Rendering (PBR), there is a cosmic skybox in Unity using the Universal Render Pipeline (URP), rendering materials based on realistic lighting models. And surface textures, reflectivity, and roughness are implemented by physical maps to enhance realism.

Dynamic Lighting System simulated the Sun as the primary light source, which is a directional Light. Added a corona effect implemented by particle-based light glow. Based on Scattering Shader, simulate day/night transitions and atmospheric rim glow for Earth, Venus, and other celestial bodies with atmospheres.

4.2 Celestial Bodies Motion Simulation

All movements are driven by scripted programming and are adjusted based on the physical characteristics of the celestial bodies themselves, ensuring that their trajectories and velocities align with real astronomical features. Each celestial body's motion is based on its physical properties, ensuring that its rotation and revolution align with real astronomical data.

Different celestial bodies have different initialization logics. The sun’s and planets’ positions are set in the game world, and the moons' (satellites) positions are initiated by script. The sun is always at the world's centre at coordinates (0, 0, 0). Celestial bodies' initial positions are set relative to the Sun using the game's scale. All planets and the Sun align initially. Moons' (satellites) initial positions are calculated and generated by the script based on their parameters, like orbital radius and inclination, to avoid overlap or identical spawn points.

In real-world physics, celestial bodies orbit a central body (such as the Sun) along elliptical paths. However, in a game environment, where the world scale is much smaller than the real universe, the effect of orbital eccentricity becomes negligible. Therefore, we abstract these orbits as circular to reduce computational complexity, while still preserving core physical characteristics such as orbital inclination, orbital period, and radius dependency.

The spatial computation of orbital inclination is achieved through quaternion rotation, ensuring the establishment of non-coplanar orbits in 3D space. To build a physically accurate orbital system in a game, it is necessary to construct a rotation axis with an inclination, which serves as the orbital normal direction for revolution. Firstly, initiate the inclined axis, and each celestial body will revolve around this axis, resulting in an inclined orbital motion. In each frame, the revolution angle is updated based on the defined orbit speed.

Rotation is based on the configured *rotationSpeed*, and the object rotating around *Vector3.up* each frame. Revolution is implemented by Unity's *RotateAround*, the target as the centre, and a tilted *Vector3.up* (after applying orbital inclination) as the axis, then achieving inclined orbital motion. The inclined orbital axis is constructed using *Quaternion.Euler(0, 0, orbitInclination)*, allowing for a layered distribution of orbits with different inclinations.

4.3 Flight Simulation

Spaceflight simulation is a key component of this project that combines scientific accuracy and interactive gameplay. Players will use fundamental principles of dynamics to complete missions by piloting the fighter. The fighter's movement also follows Newton's laws with assist functions, rotations are implemented by quaternions.

The movement of the fighter in space follows real physical principles, including inertial motion and a propulsion system, following these rules: If no external forces (like boosting) act on it, the fighter is at rest or drifts in space. If an impact on the player’s space craft occurs, the impacting force immediately affects the space craft until the player stabilizes it. The stabilization function simulates an effect like that of a reaction wheel, and it is designed for gameplay balance. Also, mouse inversion is used to simulate realistic joystick pitch control.

The direct control of translational force in the forward direction simulates the acceleration. The acceleration is a throttle-based increase in speed, limited by *maxSpeed*, simulating realistic propulsion constraints, which means closer to get the maximum speed, the acceleration becomes slower. In a vacuum, deceleration is controlled manually at a constant rate to simulate a reverse thruster.

5. Evaluation

The effectiveness and player experience evaluation of this Solar System educational game is tested through a user study, with 13 collected responses. The participants were aged between 20 and 30 years old. The majority were current students, with a smaller portion being working professionals. Regarding gender, there were 11 male and 2 female participants. All participants had fundamental gaming experience, with the male players having extensive gaming backgrounds.

This evaluation utilized a questionnaire survey to gather player feedback on various aspects of the game. The questionnaire consisted of 10 questions covering core game mechanics, audiovisual experience, challenge level, controls, reward system, educational value, integration of learning and gameplay, clarity of learning content, balance between learning and gaming, and game narrative. Each question used a 4-point Likert scale with options: "Strongly Disagree", "Disagree", "Agree", and "Strongly Agree".

The questionnaire results indicate a generally positive reception of the educational game among the players. Questions 1, 3, 4, and 5 received 10 positive responses each. Questions 7 and 9 received 11 positive responses each. Question 2 received 12 positive responses. Questions 6, 8, and 10 received 13 positive responses (totally positive feedback).

To determine if the positive feedback was statistically significant, a one-sided binomial test was carried out for each question. The test assessed the probability of observing the number of positive responses (Agree and Strongly Agree), if players were choosing randomly between positive and non-positive feedback (null hypothesis: p=0.5). The test parameters were *binomtest(number of positive feedback responses, total feedback number, p=0.5, alternative='greater')*. A p-value of less than 0.05 indicates statistical significance, i.e., the observed level of positive feedback for a question is unlikely to have occurred by mere chance, suggesting that players genuinely had a positive sentiment regarding that specific aspect of the game.

The following table summarizes the p-value results for each question:

Table 1: P-value result for each question

Q#	Question Summary	Positive Feedback	P-value	Significant
1	The combat mechanics make me feel excited and engaged.	10	0.0461	Yes
2	The visual effects and sound design enhance my immersion	12	0.0017	Yes
3	The gameplay is too challenging	10	0.0461	Yes
4	The controls are smooth and easy to learn	10	0.0461	Yes
5	The reward system motivates me to keep playing	10	0.0461	Yes
6	I learn knowledge about the Solar System	13	0.0001	Yes
7	The combination of the study and gameplay is done well	11	0.0112	Yes
8	The study part is clear and easy to read and learn	13	0.0001	Yes
9	There is a good balance between learning and playing	11	0.0112	Yes
10	The game story is logical and engaging	13	0.0001	Yes

As shown in the table, the positive feedback for all 10 questions reached statistical significance ($p < 0.05$). This strongly suggests that the players' positive ratings were not random and reflect a genuine appreciation for these aspects of the game. The extremely low p-values for questions related to learning (Q6, Q8) and story (Q10) indicate a particularly strong positive consensus.

Overall, the quantitative feedback and the statistical analysis demonstrate a significantly positive reception for the game. Players found the core gameplay engaging, the controls accessible, and the audiovisuals immersive. Crucially, the educational goals were met effectively: players felt they learned about the Solar System, the learning content was clear, and the integration with gameplay, along with the overall balance and story, was highly successful according to the participants. However, we acknowledge the low number of participants, which is reflected by the level of significance, which is in some cases just enough.

6. In Conclusion

Educational game is scientifically accurate and engaging to effectively enhance learning interests. This paper outlines the design and development of a solar system-themed educational game, illustrating how game-based learning principles can be applied to complex scientific content. These guidelines and methodologies provide a reference for researchers and developers interested in educational games. By these design principles, we can support understanding in science education to educational institutions and learners. Next steps involve a larger roll out in schools with more participants.

Ethics declaration: The development and research described in this paper did not involve human participants, personal data collection, or any procedures requiring ethical approval. Therefore, no ethical clearance was necessary for this study.

AI declaration: AI tool was used during the preparation of this paper to assist in the drafting and refinement of academic language, grammar correction, and structure optimization. AI tool is also used for converting the references into the required academic format.

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