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Enhancing Conceptual Understanding of the Solar System Through 3D Augmented Reality in Primary Education

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Abstract: The development of digital technology has opened new opportunities in the field of education, one of which is through the utilization of Augmented Reality (AR). However, astronomy learning methods—especially those related to the solar system—in many educational institutions still rely on conventional two-dimensional models, which limit student visualization and interaction. To address this challenge, EduPlanet was developed—a 3D Augmented Reality (AR)-based educational application for learning about the solar system. This application is designed to transform how students learn by presenting planetary and celestial models in an interactive and immersive three-dimensional format that can be projected into the real environment. Through EduPlanet, users can engage in virtual exploration, observe the rotation and revolution of planets, and access detailed information about each object in the solar system in real-time. The aim of this application's development is to increase learning interest, simplify the understanding of complex concepts, and provide a deeper and more enjoyable learning experience. EduPlanet is expected to serve as an effective teaching aid for both teachers and students and become an innovative solution for science education in the digital era.

1. INTRODUCTION

The integration of digital technology in education has accelerated in recent years, with Augmented Reality (AR) emerging as an effective medium to enhance the visualization of abstract scientific concepts. AR has been shown to significantly improve student engagement and comprehension, especially in science-related subjects that involve spatial understanding, such as astronomy [1], [2].

Astronomy education, particularly the solar system topic, poses challenges for elementary school students due to its inherent abstraction and the difficulty of perceiving the scale and motion of celestial bodies. Conventional teaching methods using static diagrams or two-dimensional illustrations often fail to adequately convey the complexity of planetary systems [3], [4].

To address these pedagogical gaps, this study presents EduPlanet, a mobile-based AR learning application designed to support interactive, visual learning of the solar system. The

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application integrates three primary components: a learning module, multiple-choice quizzes, and AR-based 3D planetary visualizations. While the AR objects are not fully interactive, their ability to rotate on their axes provides users with a more immersive experience in observing planetary motion. The design of EduPlanet is grounded in cognitive and constructivist learning theories, which emphasize the importance of active engagement and contextualized experiences in building scientific knowledge. According to recent studies, AR-based tools support these theories by providing spatial cues and hands-on interaction that improve conceptual understanding and long-term retention [5], [6].

Recent developments further reinforce AR's effectiveness. A 2024 study demonstrated that AR media significantly improved sixth-grade students' understanding of the solar system in Indonesia [1]. Another development, the ARSEN platform, tailored for students with special education needs, showed that 70.1% of experts rated it positively in terms of content accuracy, usability, and curricular relevance [7]. Moreover, quasi-experimental research conducted in Spain found that AR-based astronomy learning applications significantly outperformed traditional teaching in terms of student learning outcomes [8]. Therefore, EduPlanet is positioned as an innovative solution to support science learning in upper elementary grades (4–6), where visual and interactive tools are especially critical for cognitive development and engagement.

2. THEORETICAL FRAMEWORK

2.1 Constructivist and Cognitive Learning Theories

Modern learning paradigms emphasize that knowledge is not simply transferred from teacher to student but constructed actively by learners through engagement and contextual experiences [1]. Constructivist theories proposed by Piaget and Vygotsky highlight the significance of active involvement, especially through media that allow exploration and interaction with content [2], [3]. In the context of elementary science education, Augmented Reality (AR) aligns with these principles by providing contextualized, visual, and exploratory learning experiences. This is especially important for students at the concrete operational stage, who benefit from concrete visual aids and interactive environments to understand abstract scientific concepts [4].

2.2 Augmented Reality in Education

Augmented Reality (AR) refers to a technology that overlays digital objects onto the real world in real time, often using smartphones or tablets. In educational contexts, AR has been shown to enhance understanding, motivation, and long-term retention of information [5]. It is particularly useful in visualizing complex and spatial topics such as the solar system, which are difficult to convey through traditional media [6].

Putra et al. [5] demonstrated that AR-based instructional media significantly improved elementary students' comprehension of solar system content. AR enables learners to visualize 3D planetary models from multiple angles, fostering deeper understanding through experiential learning.

2.3 Interactive Educational Media

Interactive learning media not only present information but also enable active student participation through feedback and engagement. Interactivity has been shown to increase cognitive efficiency and student motivation [7]. By integrating textual content, quizzes, and AR visualization, applications like EduPlanet meet the criteria of effective interactive educational

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media. According to Mayer's multimedia learning theory, effective learning occurs when verbal and visual materials are combined and actively processed by learners, leveraging dual coding and reducing cognitive load [8]. The combination of text and AR-rendered 3D models in EduPlanet supports this principle, enabling students to process information more effectively.

2.4 Prior Studies on AR for Solar System Education

Several recent studies have validated the effectiveness of AR in astronomy education. Zahran et al. [9] developed ARSEN, an AR application designed for students with special educational needs, which received a 70.1% expert validation score on content accuracy, usability, and alignment with curriculum standards. Another quasi-experimental study by Pérez-Pérez et al. [10] in Spain found that students using AR-based astronomy applications achieved significantly higher learning outcomes compared to those using traditional methods. These studies confirm that AR not only enhances visual engagement but also improves instructional effectiveness across diverse learning contexts.

3. METHODOLOGY

The development of EduPlanet was carried out using the Waterfall model of the Software Development Life Cycle (SDLC). This model was selected due to its sequential and structured approach, which is suitable for educational applications where functional requirements are predefined and content is closely aligned with the school curriculum [11], [12]. The development process consisted of the following stages:.

3.1 Requirements Analysis

The requirement analysis phase began by identifying curriculum-based science content for 4th to 6th grade elementary students, specifically focusing on solar system topics. Data was collected through direct observation and informal interviews with elementary school teachers to determine pedagogical needs and user preferences. Key insights included the need for:

1. Simple and age-appropriate language
2. Visually attractive, colorful, and animated elements
3. Interactive elements to support engagement
4. Marker-based AR features to enhance spatial understanding

These findings formed the foundation for the application's feature set and user interface design

3.2 System Use Case Diagram

To represent user interactions with the system, a use case diagram was developed (Figure 1). The primary actor is the student user, who accesses various modules: the main menu, learning materials, AR feature, and quizzes. Each use case contains sub-tasks such as scanning AR markers, accessing camera permissions, and receiving quiz feedback.

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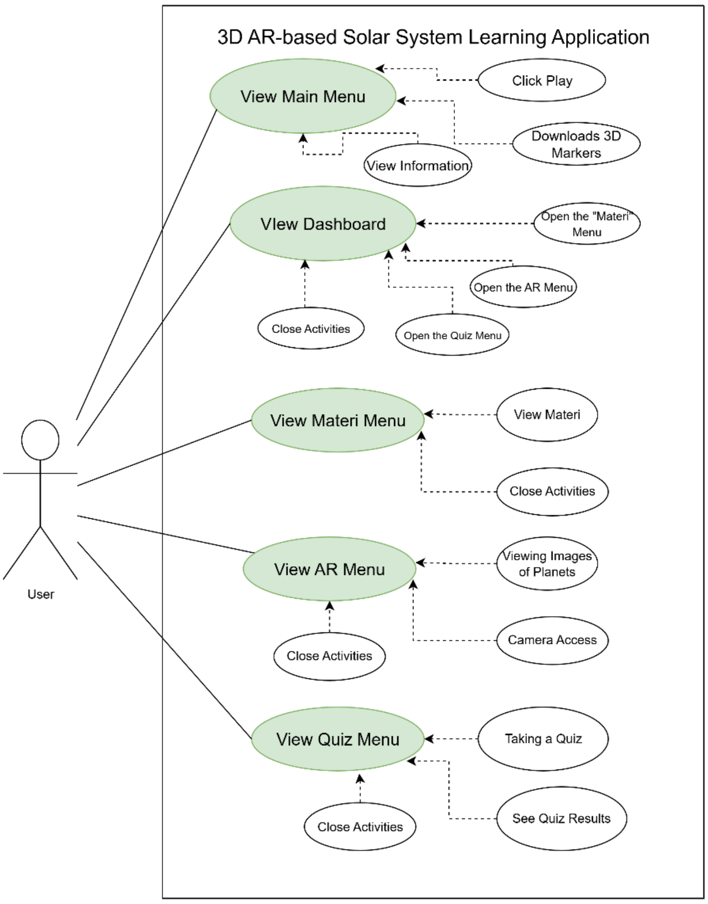

Fig 1. Use Case Diagram of EduPlanet Application

3.3 Design

The design phase focused on creating child-friendly mockups and interface structures. Visual elements were crafted using bright primary colors, cartoon-style illustrations, and large, readable fonts. Interface flow was intentionally kept minimal to reduce cognitive load for younger users.

UI/UX design tools such as Canva were used to prototype menu layouts, while 3D model placement in AR scenes was planned in wireframes. Unity UI elements and iconography were designed in accordance with early-stage educational usability standards. Visual and interaction design principles were based on Mayer's multimedia learning theory and Piaget's cognitive development stages, ensuring compatibility with the concrete-operational thinking typical of elementary school students[8].

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3.4 System Flowchart

A system flowchart (Figure 2) illustrates the logical flow of user interaction across modules. It maps the user journey from launching the app to accessing materials, using AR features, completing quizzes, or exiting the app.

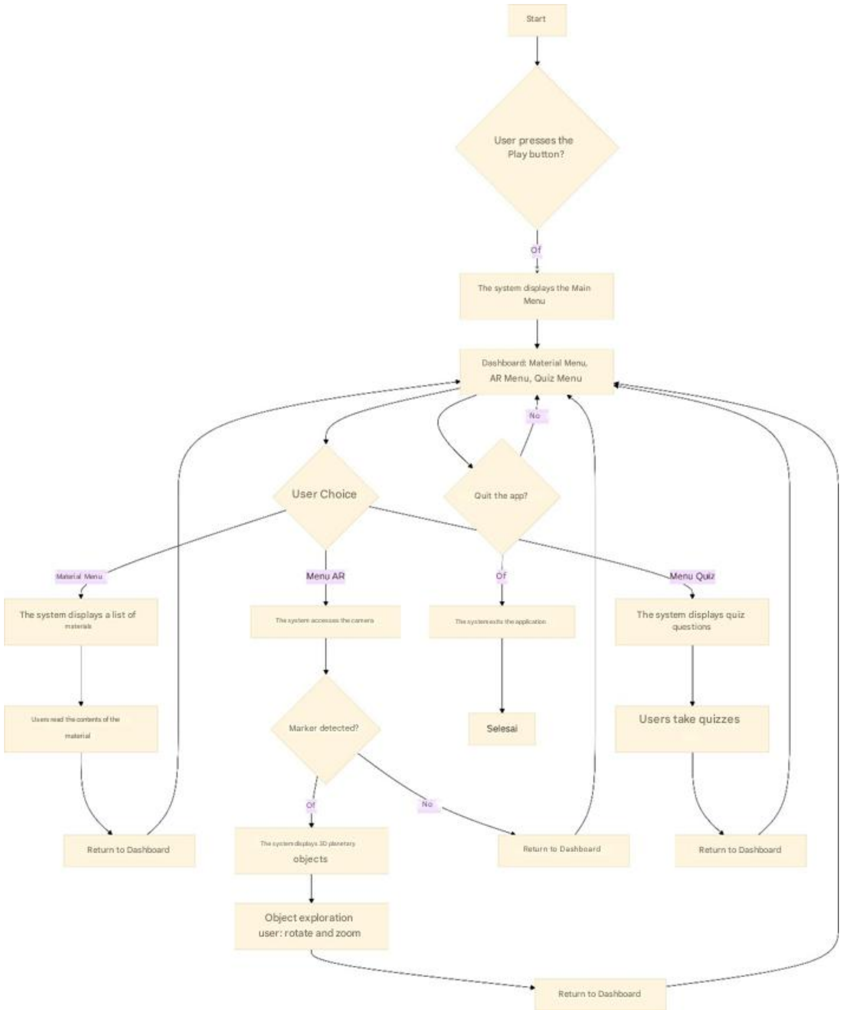

Fig 2. Use Case Diagram of EduPlanet Application

Figure 2 presents the Use Case Diagram of the EduPlanet application. The primary actor in this system is the user, represented by elementary school students, who engage with the system through five core interactions:

1. View Main Menu
   When the application is launched, the user is presented with a "Play" button which serves as the entry point to the core functionalities of the app.

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2. Access Dashboard
   Upon pressing "Play", the user is directed to the dashboard, which provides access to three key modules: Learning Materials, Augmented Reality (AR), and Quizzes.
3. Access Learning Materials
   This module presents textual and visual information about the solar system.
   a) *View Materials*: Users can read educational content, including planet descriptions.
   b) *Exit Activity*: Users may return to the dashboard at any time.
4. Access Augmented Reality (AR)
   This module enables users to view 3D solar system models using the camera and printed AR markers.
   a) *View Planet Model*: When a marker is detected, a 3D planet model is displayed.
   b) *Camera Access*: The system prompts for camera permission.
   c) *Exit Activity*: Users can return to the dashboard from the AR mode.
5. Access Quiz Module
   This module allows students to assess their understanding through multiple-choice questions.
   a) *Take Quiz*: Users answer interactive quiz questions.
   b) *Exit Activity*: Users may exit the quiz module and return to the dashboard

3.5 Implementation

The EduPlanet application was developed using a set of integrated software and hardware tools to support its interactive and AR-based features. The core development environment was Unity 3D (version 2021.x or newer), which enabled real-time rendering and modular scene management. Augmented Reality capabilities were implemented using the Vuforia SDK, allowing the system to detect printed markers and overlay 3D objects accordingly. To create 3D models of the planets, modeling tools such as Blender and Autodesk Maya were employed, while Visual Studio was used for scripting in C# to manage user interactions, scoring logic, and UI transitions. Canva was utilized during the prototyping phase to design the child-friendly interface layouts.

In terms of hardware, development and testing were conducted using a laptop equipped with an Intel Core i5 8th generation processor, 8 GB RAM, and a 256 GB SSD. For deployment, the application targets Android smartphones running version 10 or higher, with a minimum requirement of 4 GB RAM to ensure smooth AR performance.

The application was structured into three main modules:

1. The Learning Module, which provides textual and illustrated educational content about the solar system.
2. The AR Module, which enables users to visualize planetary objects in 3D using marker-based tracking. Upon detection, the planet model can be rotated and zoomed.

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3. The Quiz Module, which presents multiple-choice questions and offers immediate feedback along with a scoring system.

To enhance usability for elementary school students, the application features cartoon-style visuals, large buttons, and intuitive navigation. Each screen is designed to minimize cognitive load while maximizing engagement, particularly through the use of AR and interactive quizzes

Figure 3 shows the main menu of EduPlanet, which acts as the entry point for users. By clicking the central "Play" button, users are directed into the application's main dashboard.

Fig 3. Main menu of EduPlanet application with a prominent "Play" button as the entry point.

After pressing "Play," users are taken to an information panel, which introduces the application as an interactive learning platform for the solar system. This screen explains the use of AR and encourages users to explore.

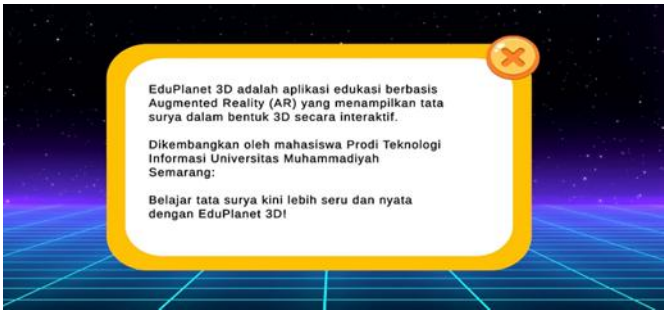

Fig 4. Introductory screen describing the app's purpose and learning concept.

To experience AR features, users are instructed to download a marker. Figure 5 presents the marker instruction panel, guiding users to print the marker and use it with the camera in the AR module.

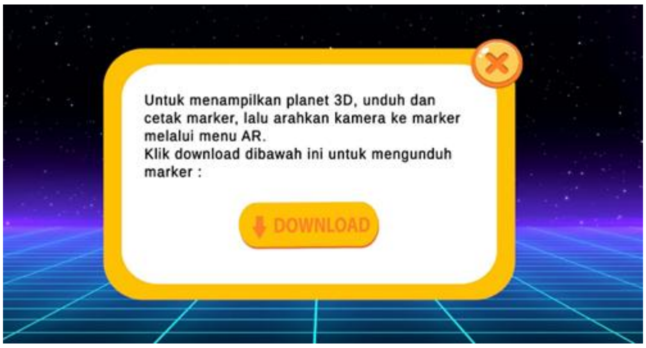

Fig 5. Marker instructions screen guiding users to download and print the AR marker.

Once inside the dashboard, users are presented with three main modules: Learning (Materi),

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AR, and Quiz, as seen in Figure 6. This hub enables students to choose the activity that aligns with their learning goals.

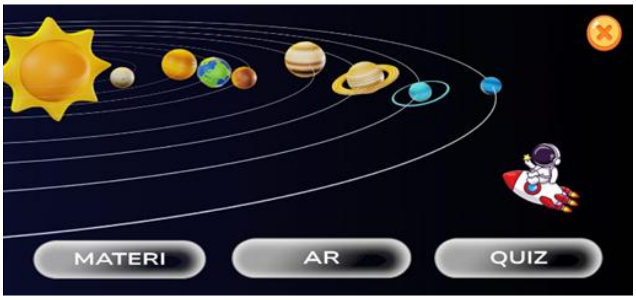

Fig 6. Dashboard screen offering access to Learning, AR, and Quiz modules.

The learning module provides textual and visual descriptions of planets. Figure 7 demonstrates the content for Mercury, including interesting facts, characteristics, and scientific context appropriate for elementary students.

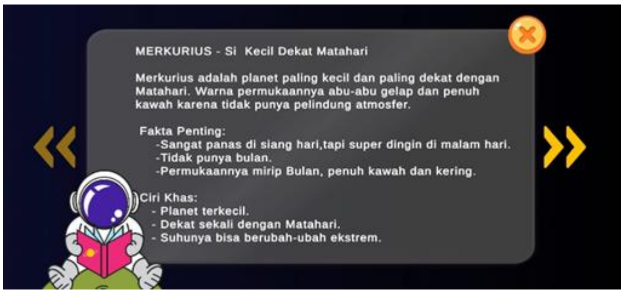

Fig 7. Example of planetary learning content for Mercury, displayed with visual cues and simple text.

3.6 Testing

The application underwent Black-Box Testing to ensure that all features functioned according to their requirements. Each feature was tested for navigation correctness, marker detection, scoring accuracy, and error handling.

User testing was also conducted with elementary students (Grades 4–6). Observations revealed user engagement levels and helped identify confusing or underperforming elements. Feedback resulted in UI simplifications, language adjustments, and improvements in AR marker response time.

Test scenarios included:

1. Pressing “Play” to enter the dashboard
2. Navigating to learning, AR, and quiz modules
3. Scanning markers to trigger AR models
4. Interpreting quiz responses and displaying scores
5. Exiting and returning to menus gracefully

All test cases passed successfully, as documented in the Black-Box Testing Table (see Section 4).

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3.7 Rationale for Using Waterfall

The Waterfall model was chosen due to its compatibility with education-focused software that:

- Has clearly defined learning outcomes and fixed content
- Benefits from step-by-step module development
- Requires stable testing before classroom deployment

Research by Sulfikar et al. [11] and Wan Yahaya et al. [12] shows that combining Waterfall with instructional design principles (e.g., ADDIE) supports structured digital learning environments with high usability and pedagogical alignment

4. RESULT AND DISCUSSION

To validate the performance and correctness of the EduPlanet application, a Black Box Testing approach was employed. Each core feature was tested independently to ensure it functioned as intended, in alignment with the specified requirements. Table 1 summarizes the test scenarios, expected outcomes, and actual results.

Table 1. Black Box Testing Results of EduPlanet

No	Test Description	Input / Action	Expected Output	Result
1.	Press "Play"	Click "Play"	Redirect to Dashboard	Passed
2.	Tap "?" icon	Tap "?" icon	Display app info panel	Passed
3.	Show marker download info	Tap star icon	Show download link and usage text	Passed
4.	View planet descriptions with navigation arrows	Tap right/left arrows	Show planet descriptions accordingly	Passed
5.	Answer quiz question	Select answer	Show correct/wrong feedback	Passed
6.	Show 3D planet after marker detection	Point camera at marker	Display 3D rotating planet	Passed
7.	Open camera and render 3D objects on marker	Access camera, scan marker	Show correct 3D model on screen	Passed
8.	Close panels using "X" icon	Tap "X"	Panel closes and returns to previous screen	Passed
9.	Display correct/incorrect response	Choose answer	Feedback indicator appears	Passed
10.	Display score after quiz completion	Finish quiz	Show total correct, incorrect and final score	Passed
11.	Exit score screen and return to quiz menu	Tap "X" on score panel	Return to quiz start menu	Passed

The results indicate that all key functionalities of the application performed as expected under test conditions, confirming that the system was functionally stable and met its design specifications.

Informal usability testing was conducted with 10 students from a local public elementary school (Grades 4 to 6), selected based on their familiarity with basic smartphone operations. These tests were observational in nature and provided valuable insights into the user experience. Students were able to navigate the interface without significant difficulties, showing particular enthusiasm toward the AR features and the interactive quizzes.

In addition to technical validation, informal usability testing was conducted with a group

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of elementary school students in Grades 4 to 6. These tests were observational in nature and provided valuable insights into the user experience. Students were able to navigate the interface without significant difficulties, showing particular enthusiasm toward the AR features and the interactive quizzes.

Figure 8 illustrates a sample quiz interface. After selecting an answer, users receive immediate feedback—either a check mark (✓) or a cross (✗)—to indicate correctness.

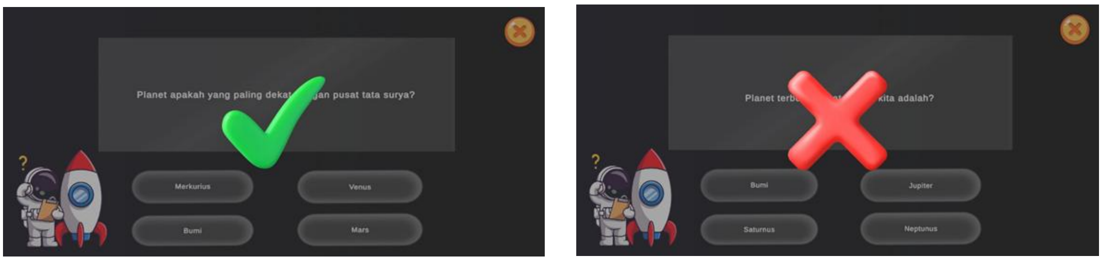

Fig 8. Quiz interface showing a multiple-choice question and real-time feedback (✓ or ✗) based on user selection.

At the end of the quiz, users are presented with a score summary, as shown in Figure 9. This display includes the number of correct and incorrect answers, and a final score to help users track their learning progress.

Fig 9. Quiz score summary showing total correct answers, incorrect answers, and the final score.

The Augmented Reality feature was one of the most engaging aspects of the application. After granting camera access and scanning a printed marker, users could view a 3D object—such as a planet—on their screen in real time. As shown in Figure 10, the AR output for the planet Mercury provided a rich, spatial visualization that enhanced students' understanding of planetary characteristics.

Fig 10. Augmented Reality view displaying a 3D Mercury object when the marker is scanned.

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The results align with existing research emphasizing the benefits of AR and gamification in elementary education. AR technologies have consistently been shown to increase learner motivation and spatial understanding, particularly when visualizing abstract scientific concepts such as planetary motion or solar system scale [5], [10]. Moreover, the instant feedback provided by the quiz module reinforces learning and encourages repeated interaction.

These findings not only confirm the system's functionality but also provide a basis for comparative analysis with other AR-based educational applications. This observed effectiveness is consistent with other recent AR-based learning systems. For example, the ARSy application was evaluated using user experience questionnaires and received favorable ratings, confirming both technical performance and user satisfaction [13]. Unlike ARSy's multi-marker system, EduPlanet adopts a simplified single-marker approach, which may enhance accessibility and ease of use for younger learners, while still delivering immersive AR experiences. Compared to similar tools, EduPlanet places greater emphasis on intuitive navigation for young users and integrates a lightweight AR engine, making it highly compatible with mid-range Android devices.

Furthermore, experimental studies in Spain (n = 130) found that students exposed to AR-based astronomy applications demonstrated significantly greater learning gains compared to traditional instruction groups, suggesting that AR offers measurable pedagogical advantages in STEM contexts [14]. Similarly, a recent literature review reported that elementary and preschool-age students showed improved understanding, motivation, and engagement when AR was integrated into natural science learning—highlighting AR's role in scaffolding experiential and exploratory learning [15].

In contrast, some studies suggest potential drawbacks of AR, such as cognitive overload from excessive visual elements or technical delays due to hardware limitations [16]. In EduPlanet's context, these issues were mitigated through simplified visuals, cartoon-style icons, and performance testing on devices with minimum specifications (Android 10, 4 GB RAM). Overall, the evaluation confirms that EduPlanet meets both technical and pedagogical expectations, providing an effective, engaging, and accessible platform for early science education.

5. CONCLUSION

The development of EduPlanet demonstrates the effective integration of Augmented Reality (AR) and interactive quizzes to support elementary-level learning about the solar system. The application's three main modules—learning content, AR visualization, and quizzes—were successfully implemented and passed all functional tests. User observations showed that students were engaged and able to navigate the app easily, with AR features enhancing spatial understanding and motivation. Compared to other AR-based learning tools, EduPlanet offers a simpler, more accessible interface suitable for younger users. Its design aligns with educational goals by combining visual interactivity and immediate feedback. Future improvements may include expanded content, voice guidance, and learning analytics to further support personalized and inclusive learning experiences.

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