Semarak Engineering Journal

Journal homepage:
https://semarakilmu.my/index.php/sej/index
ISSN: 3036-0145

Design and Experimental Evaluation of a Marker-Based Augmented Reality Solar System Learning System Integrating Cultural Values

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ARTICLE INFO

Article history:
Received 14 January 2026
Received in revised form 29 March 2026
Accepted 22 April 2026
Available online 11 May 2026

Keywords:
Augmented reality, educational technology engineering, experimental validation, marker-based tracking, solar system simulation

ABSTRACT

This study presents the design and experimental evaluation of solar system augmented reality interactive simulation (SolARis), a marker-based augmented reality (AR) learning system developed to enhance the visualization of solar system concepts in higher education. The system was engineered using Unity 3D integrated with the vuforia software development kit (SDK) and structured through the 4D development framework. The architecture consists of a content layer, AR engine layer, and application layer to ensure stable marker detection, real-time three-dimensional rendering, and efficient deployment on Android-based devices. Experimental validation was conducted across three higher education institutions to assess system validity, practicality, and effectiveness. Expert evaluation produced a very high validity score (4.85), while student responses indicated very high practicality (4.52). Learning effectiveness analysis yielded a medium normalized gain (N-Gain) value of 0.46, demonstrating measurable conceptual improvement after AR-assisted instruction. Rasch model analysis confirmed strong measurement consistency, with person reliability of 0.81 and item reliability of 0.85. The findings indicate that the integration of marker-based tracking, optimized 3D modeling, and structured instructional flow results in a technically robust and scalable AR learning system. SolARis contributes to engineering-oriented educational technology by providing a validated AR-based solar system learning platform suitable for multi-institutional deployment.

1. Introduction

The transformation of higher education in the twenty-first century requires not only cognitive excellence but also the strengthening of students' character and adaptability to technological advancement. Character education at the university level plays a strategic role in preparing graduates who are intellectually competent, socially responsible, and resilient in facing global challenges [4,7]. However, empirical findings indicate a decline in students' character values, including discipline, responsibility, and moral awareness [3,15,16]. This situation highlights the urgency of integrating

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https://doi.org/10.37934/sej.15.1.7488

character reinforcement into disciplinary learning processes, particularly in science and engineering education.

In parallel with these challenges, rapid technological development has significantly reshaped instructional practices. augmented reality (AR) has emerged as a promising technological innovation capable of enhancing the visualization of abstract scientific phenomena and increasing learner engagement [6]. AR integrates digital three-dimensional objects into real-world environments, enabling interactive and immersive learning experiences. In physics education, AR has demonstrated effectiveness in improving conceptual understanding, particularly for topics that require spatial reasoning and dynamic representation [2,6,9,11,18,20]. By transforming symbolic or static representations into manipulable 3D visualizations, AR reduces cognitive barriers associated with abstract scientific content.

Despite its potential, most AR-based learning applications in physics primarily focus on improving cognitive outcomes such as conceptual mastery or motivation [2,6,9,11,18,20]. The integration of AR with character development and cultural context remains limited. Meanwhile, incorporating local wisdom into science learning has been shown to enhance relevance, sustainability awareness, and students' sense of identity [1,3,10,14,17]. Education grounded in cultural values strengthens responsibility and perseverance, aligning scientific understanding with societal needs. In South Kalimantan, the Wasaka value (waja sampai kaputing), which emphasizes persistence, commitment, and responsibility, represents a local cultural principle that can support character formation in higher education.

Another persistent challenge in physics and astrophysics education lies in teaching solar system concepts. Planetary motion, astronomical scales, and spatial relationships are inherently abstract and difficult to represent using conventional media such as textbooks or two-dimensional diagrams. Prior implementations of digital simulation tools, including solar system applications, have demonstrated improvements in student motivation and understanding [18]. Furthermore, AR-based visualization can provide realistic representations of celestial bodies and their relative motions, supporting deeper conceptual comprehension [2,6,9,11]. However, existing AR applications for solar system learning rarely integrate local cultural values or explicitly target character development as measurable outcomes.

From an engineering perspective, a significant research gap remains. First, many AR applications in education are developed as isolated visualization tools without a systematic system architecture design and experimental validation. Second, studies integrating AR with local wisdom tend to emphasize pedagogical narratives rather than technological implementation and system performance. Third, limited research reports comprehensive validation metrics, including validity, practicality, and effectiveness testing within real classroom environments. Consequently, there is a need for an engineering-oriented development study that designs, implements, and experimentally evaluates an AR-based learning system integrating local wisdom while measuring its impact on both learning outcomes and character formation.

To address these gaps, this study develops solar system augmented reality interactive simulation (SolARis), an AR-based learning system designed to visualize solar system concepts through interactive three-dimensional planetary models while embedding Wasaka character values within the instructional flow. The development adopts a systematic Research and Development approach using the 4D model, which includes analysis of learner characteristics, objective formulation, media selection, utilization, learner participation, and evaluation stages [8,12,21]. This structured framework ensures that technological implementation aligns with instructional objectives and learner needs.

From a system engineering standpoint, SolARis is designed using Unity 3D as the primary development platform and integrated with the Vuforia SDK to implement marker-based AR tracking. The system architecture consists of three main layers: (i) the content layer, which stores astronomical data, planetary models, and instructional materials; (ii) the AR engine layer, which manages marker recognition, real-time object rendering, and user interaction; and (iii) the application layer, which provides user interface navigation, interactive menus, and feedback mechanisms. The AR module enables students to scan predefined markers to trigger three-dimensional visualizations of celestial objects, including the Sun and planets, along with relevant astronomical data. This architecture transforms abstract astrophysical concepts into interactive and scalable digital representations deployable on Android-based mobile devices.

The contribution of this study is threefold. First, it presents the design and implementation of an AR-based solar system learning system that integrates local cultural values within its instructional structure. Second, it provides experimental validation of the system in terms of content validity, practicality, and effectiveness through multi-institutional classroom implementation. Third, it empirically measures character outcomes alongside learning gains using quantitative analysis. By combining technological system development with contextualized character integration, this research contributes to engineering science and technology education by offering a validated AR learning system that supports both conceptual mastery and culturally grounded character reinforcement.

2. System Architecture and Design

2.1 System development framwork

The development of SolARis (Solar System Augmented Reality Interactive Simulation) was conducted using a structured Research and Development approach based on the 4D model, which consists of analyze, state objectives, select methods and media, utilize media, require learner participation, and evaluate and revise stages [8,12,21]. This model was selected to ensure systematic alignment between technological implementation and instructional objectives while maintaining iterative evaluation. To illustrate the structured development procedure of SolARis, the overall development workflow is presented in Fig. 1.

As shown in Fig. 1, the development process began with learner analysis and technological readiness assessment, followed by instructional objective formulation. The design stage translated pedagogical requirements into system architecture components, while the implementation stage focused on AR integration using Unity 3D and Vuforia SDK. The final phase involved evaluation and refinement to ensure system feasibility and instructional effectiveness. This structured development approach is consistent with prior technology-based physics learning innovations that emphasize systematic design and validation [8,12,21].

2.2 Development of the AR learning media

The development of SolARis was carried out using Unity 3D as the main development platform and Vuforia SDK as the augmented reality engine. Unity 3D was utilized to design the application interface, integrate learning content, manage three-dimensional (3D) planetary models, and control user interactions. Meanwhile, Vuforia SDK was employed to implement marker-based tracking technology that enables virtual objects to be displayed when a specific image marker is detected by a smartphone camera.

The development process began with the preparation of educational content related to the solar system and the integration of Wasaka character values. Subsequently, 3D planetary models were created and optimized to ensure smooth performance on Android devices. Each planetary object was then associated with a unique image marker registered in the Vuforia database. The marker database was imported into Unity and connected to the corresponding 3D objects through the AR Camera and Image Target components provided by Vuforia. After the AR components were successfully integrated, interactive features such as planetary information panels, navigation menus, animations, and learning instructions were developed within Unity. Functional testing was conducted to evaluate marker recognition accuracy, object rendering stability, and application responsiveness under various lighting conditions and viewing angles. Several revisions were performed to improve system performance and user experience. Finally, the application was exported into Android Package Kit (APK) format and installed on Android smartphones for implementation and evaluation. The use of Unity 3D and Vuforia SDK enabled the development of a stable marker-based augmented reality learning environment capable of visualizing abstract solar system concepts through interactive three-dimensional representations in real time. Table 1 shows the SolARis creation process.

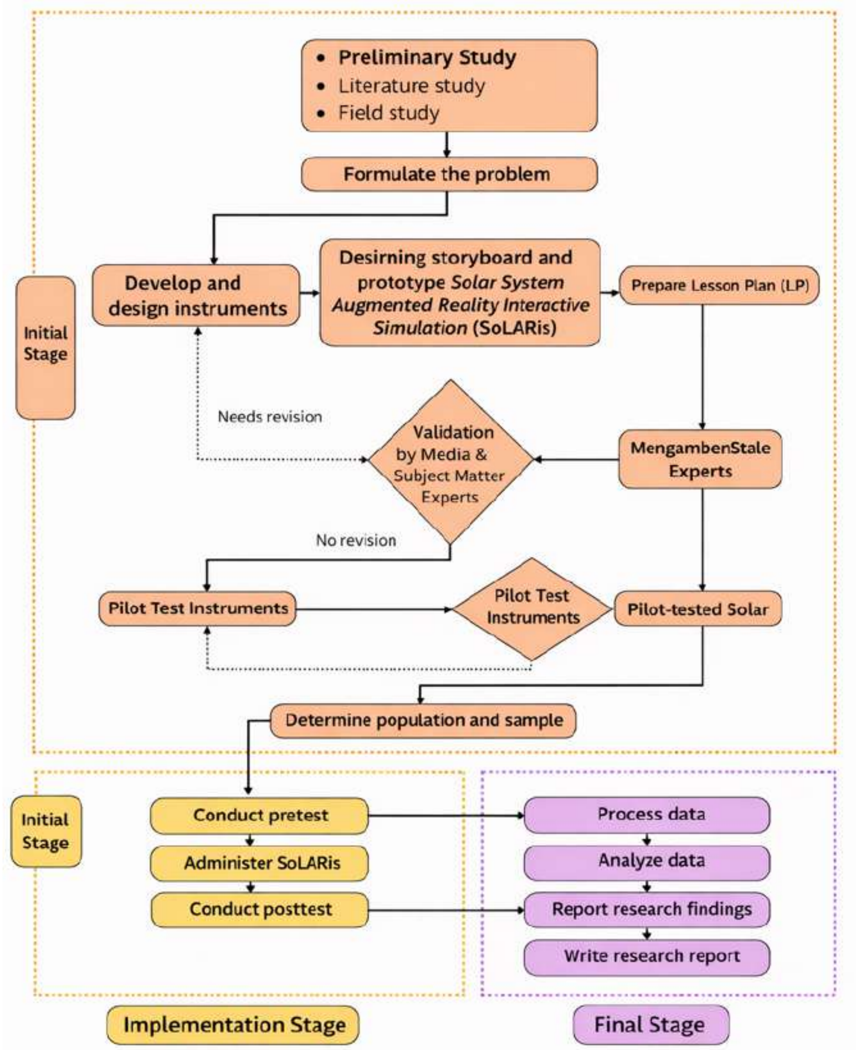
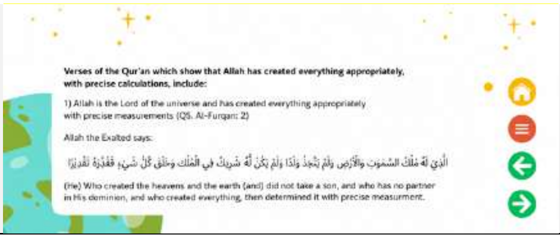


Fig. 1. Development flow of SolARis based on the 4D model

Table 1
SolARis creation process

Picture	Information
	SolARis initial view on unity
	About developer on unity
	AR barcode scan menu display on unity
	AR menu display of astronomical data of the planet Mars on a smartphone
	AR menu display of solar astronomy data on smartphone
	Display of the Al-Quran verse menu on a smartphone

2.3. Overall system architecture

From an engineering perspective, SolARis is structured into three primary layers: the content layer, the AR engine layer, and the application layer. The content layer stores astronomical datasets, planetary metadata, instructional materials, and three-dimensional models representing celestial bodies. Each object includes embedded parameters such as diameter, orbital characteristics, and relative positioning, enabling contextual and dynamic visualization. To provide a clearer understanding of the technical implementation environment, the development interface within Unity 3D is presented in Fig. 2.

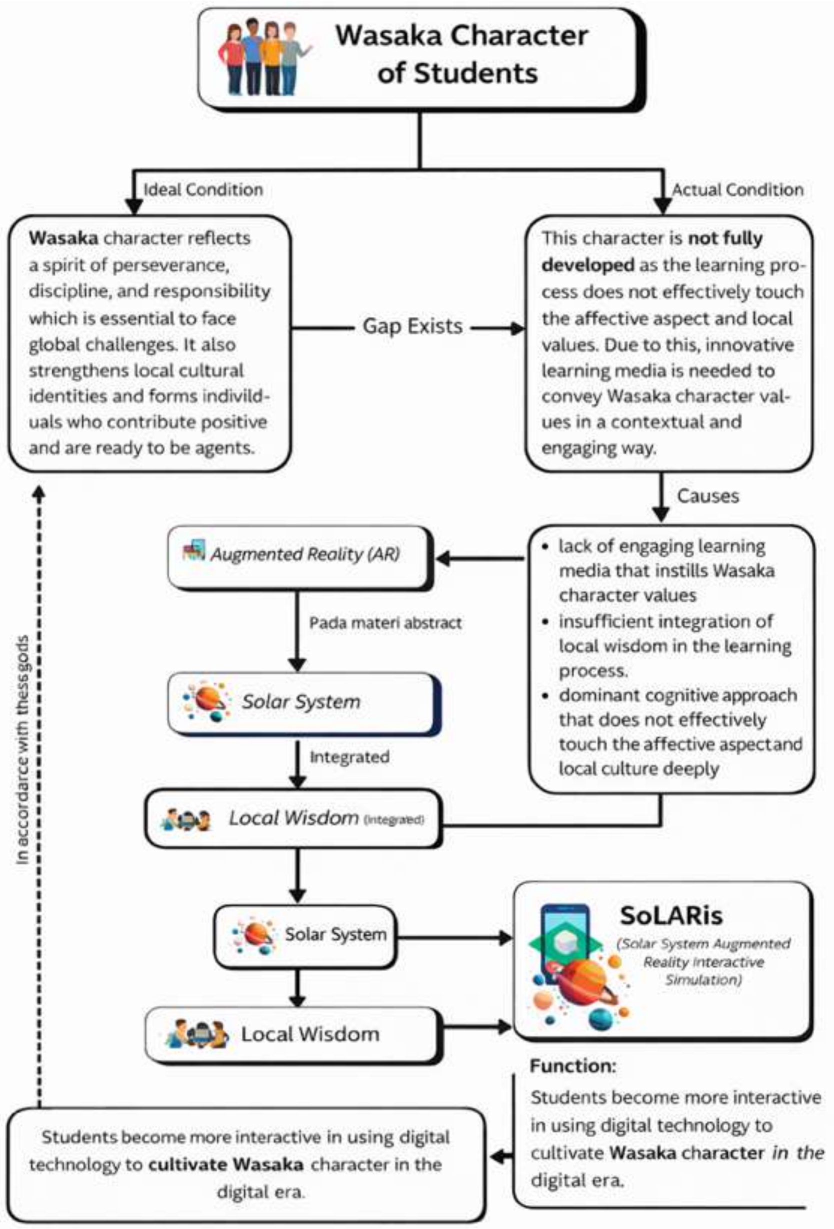


Fig. 2. Implementation of SolARis AR modules in the Unity 3D development enviroment

Figure 2 demonstrates the integration of planetary models, AR camera configuration, marker database linkage, and scene hierarchy within Unity. The AR engine layer utilizes the Vuforia SDK to perform marker detection, feature extraction, and real-time pose estimation. Once a marker is recognized, a transformation matrix determines the spatial alignment of the 3D object with the physical marker. Previous studies confirm that AR-based visualization significantly enhances spatial reasoning and conceptual understanding in science education, particularly for abstract topics such as astronomy [6,9,11,20]. Unlike visualization-only tools, SolARis applies a modular system architecture to ensure scalability and stable deployment.

2.4. Marker-based tracking and real-time rendering

SolARis implements a marker-based tracking mechanism to ensure stable and reliable detection under classroom conditions. Each celestial object is associated with a unique visual marker registered in the Vuforia database. During operation, the mobile device camera continuously captures image frames, which are processed through feature detection and pattern recognition algorithms. The real-time AR visualization output on a smartphone device is illustrated in Fig. 3.

Fig. 3. Real-time marker-based AR visualization of planetary objects in SolARis in Indonesia

As shown in Fig. 3, once a marker is detected, the corresponding three-dimensional planetary model appears anchored to the physical surface, accompanied by astronomical information. Marker-based tracking was selected due to its lower computational complexity and greater robustness compared to markerless tracking in indoor environments. This approach ensures stable rendering performance across commonly available Android devices. The effectiveness of immersive 3D AR visualization in supporting abstract scientific comprehension has been widely documented in STEM learning research [6,9,11,20].

2.5. 3D modeling and performance optimalization

To maintain smooth performance on mobile platforms, the planetary models were optimized through polygon reduction, texture compression, and frame rate stabilization. These optimization strategies minimize graphical processing unit (GPU) load while preserving essential astronomical characteristics. Lighting and shading configurations were carefully adjusted within Unity to enhance depth perception without significantly increasing computational demand.

Such performance optimization ensures that SolARis operates efficiently on devices with moderate hardware specifications, supporting broader institutional implementation. These engineering considerations align with prior educational technology development studies emphasizing system robustness and scalability [8,12,21].

2.6. Instructional and cultural integration

Although SolARis is primarily engineered as an AR-based visualization system, it integrates contextual reinforcement of Wasaka values within its instructional workflow. When students activate AR visualization, scientific explanations are accompanied by contextual prompts emphasizing perseverance, responsibility, and commitment in scientific inquiry. The integration of local cultural values into digital learning environments reflects culturally responsive educational principles supported by previous research [1,3,10,14,17].

Prior studies on character-based physics learning media indicate that embedding contextual values within technological platforms enhances learning relevance and sustainability [21]. In SolARis, this integration is implemented at the content layer without interfering with AR tracking or rendering performance.

2.7. Development and technical specifications

SolARis was deployed as an Android-based application to maximize accessibility and scalability. The system operates offline after installation, as AR databases and planetary models are embedded locally within the application package. Minimum technical requirements include Android OS 8.0 or higher, at least 3 GB RAM, and camera support for marker detection.

The offline deployment model enhances feasibility in diverse classroom environments and reduces dependency on network connectivity. This portability-oriented engineering design aligns with prior technology-based learning system developments, emphasizing scalability and implementation robustness [8,12,21].

The shape of a projectile is generally selected based on combined aerodynamic, guidance, and structural considerations. The choice of seeker, at supersonic speeds, requires careful selection of the nose and tail shapes, which is mandatory to ensure performance and operation of the overall system.

3. Experimental Evaluation Method
3.1. Research design

This study employed a research and development (R&D) methodology combined with experimental implementation to evaluate the technical and instructional performance of the SolARis system. Detailed information regarding this method is explained elsewhere [22]. The development process followed the ASSURE model, which includes analyze, state objectives, select methods/media/materials, utilize media/materials, require learner participation, and evaluate and revise stages [8,12,21].

The evaluation phase was conducted after the system architecture and AR modules were fully implemented. The objective of this phase was to determine whether the engineered AR system met quality standards in terms of validity, practicality, and effectiveness within real classroom settings. This approach is consistent with prior physics learning media development studies that integrate system design and empirical validation [8,21].

3.2. Participants and implementation procedure

The experimental implementation involved undergraduate students from three higher education institutions: Physics Education students at Universitas Lambung Mangkurat (ULM), Tadris Physics students at UIN Antasari Banjarmasin, and Electrical Engineering students at Politeknik Negeri Banjarmasin (Poliban).

The multi-site implementation was designed to test system scalability and operational robustness across different institutional contexts. During the implementation, students used Android-based smartphones compatible with the technical specifications described in Section 2.6. The learning activities involved pre-testing, AR-assisted learning using SolARis, and post-testing to measure conceptual and character outcomes.

3.3. Research instruments

Four instruments were used to evaluate system performance:

a) Validation Sheet – Used by expert validators to assess content accuracy and media feasibility.
b) Student Response Questionnaire – Used to measure system practicality and usability.
c) Learning Achievement Test – Used to measure students' conceptual understanding of solar system material.
d) Character Observation Sheet – Used to measure Wasaka character indicators during learning activities.

Instrument preparation followed structured procedures consistent with previous educational technology development studies (Juliana et al., 2023; Wahyuni et al., 2024). Reliability of validation instruments was tested using Cronbach's Alpha coefficient as described in educational evaluation literature.

3.4. Data analysis techniques

3.4.1 Validity analysis

Content and media validity were determined using expert judgment scores measured on a five-point Likert scale. The average score was interpreted based on established validation criteria. To clarify the validation category thresholds, Table 2 presents the criteria used in this study.

Table 2
Validation and practicallity criteria

Score Range	Category	Interpretation
$x > 4.2$	very good	very valid / very practical
$3.6 < x \leq 4.2$	good	valid / practical
$2.4 < x \leq 3.6$	fair	sufficiently valid / practical
$1.2 < x \leq 2.4$	poor	less valid / less practical
$x \leq 1.2$	very poor	not valid / not practical

Reliability of expert validation scores was calculated using Cronbach's Alpha coefficient. A coefficient greater than 0.70 indicates acceptable internal consistency.

3.4.2 Practicallity analysis

Practicality was measured using student response questionnaires administered after implementation. The average score was interpreted using the same categorical criteria shown in Table 1.

This evaluation determines whether the system is user-friendly, operationally stable, and suitable for classroom deployment.

3.4.3 Effectivenees analysis

Effectiveness was evaluated using normalized gain (N-Gain) analysis calculated from pre-test and post-test scores. The N-Gain formula proposed was applied [23]:

$$N - Gain = \frac{Posttest - Pretest}{Maximum\ Score - Pretest} \quad (1)$$

The gain value was categorized into high, medium, or low levels based on standard thresholds. This analysis measures the magnitude of learning improvement resulting from AR-assisted instruction.

3.4.4 Rasch model analysis

To strengthen measurement rigor, Rasch modeling was applied to analyze person reliability and item reliability. Rasch analysis transforms ordinal Likert-scale data into interval logit measures and provides detailed diagnostics on instrument performance.

The use of Rasch modeling enhances psychometric validity by evaluating item consistency and respondent ability distribution beyond classical test theory assumptions. This approach complements Cronbach's Alpha reliability analysis and strengthens the credibility of system validation results.

3.4.5 Evaluation indicators

The performance of SolARis was evaluated based on three primary indicators:

a) Validity – The system is considered valid if expert validation scores fall within the "valid" or "very valid" category.
b) Practicality – The system is considered practical if student responses reach at least the "good" category.
c) Effectiveness – The system is considered effective if the N-Gain score reaches at least the medium category and character indicators demonstrate measurable improvement.

These evaluation indicators ensure that the engineered AR system is not only technically functional but also educationally impactful, consistent with prior technology-based learning system validation research (Juliana et al., 2023; Wahyuni et al., 2024).

4. Results and Discussion

4.1 Expert validation results

The validity evaluation of SolARis was conducted by four expert validators consisting of two subject-matter experts and two media experts. The assessment focused on content accuracy, AR functionality, interface design, and instructional alignment. The evaluation used a five-point Likert scale interpreted according to the validation criteria. The summary of validation results is presented in Table 3.

Table 3
Expert validation results

Aspect evaluated	Mean score	Category
Content validity	4.87	Very Valid
Media validity	4.83	Very Valid
Overall average	4.85	Very Valid

As shown in Table 2, the overall mean score of 4.85 places SolARis in the "very valid" category (x > 4.2). This result indicates that the system content is scientifically accurate and that the AR interface and system integration meet expert standards. Reliability testing using Cronbach's Alpha produced a coefficient exceeding 0.70, confirming strong internal consistency among validators.

From an engineering perspective, these findings verify that the system architecture, marker integration, and rendering mechanisms operate according to design specifications. Similar validation procedures have been applied in previous physics learning media development studies [8,21].

4.2. Practicality and usability evaluation

Practicality was evaluated through student response questionnaires administered after implementation. The evaluation covered ease of operation, clarity of visualization, system stability, and interface navigation. The practicality results are summarized in Table 4.

Table 4
Practicality evaluation results

Indicator	Mean score	Category
Case of operation	4.55	very practical
Interface clarity	4.48	very practical
System stability	4.53	very practical
Overall average	4.52	very practical

The overall practicality score of 4.52 categorizes SolARis as "very practical". Students reported stable marker detection, smooth object rendering, and intuitive interface interaction.

These results indicate that the system design effectively supports real-time AR performance without significant technical disruptions. Prior AR-based STEM studies emphasize that usability and interface clarity significantly influence technology acceptance and learning engagement [6].

4.3. Learning effectiveness analysis

The effectiveness of SolARis was evaluated using normalized gain (N-Gain) analysis based on pre-test and post-test scores. The calculated N-Gain value was 0.46, categorized as medium according to Hake's criteria [5]. The summary of learning improvement is presented in Table 5.

Table 5
Learning effectiveness (N-Gain)

Pre-test Mean	Post-test Mean	N-Gain	Category
—	—	0.46	Medium

To provide a clearer comparison of learning improvement, the pre-test and post-test score distribution is illustrated in Fig. 4.

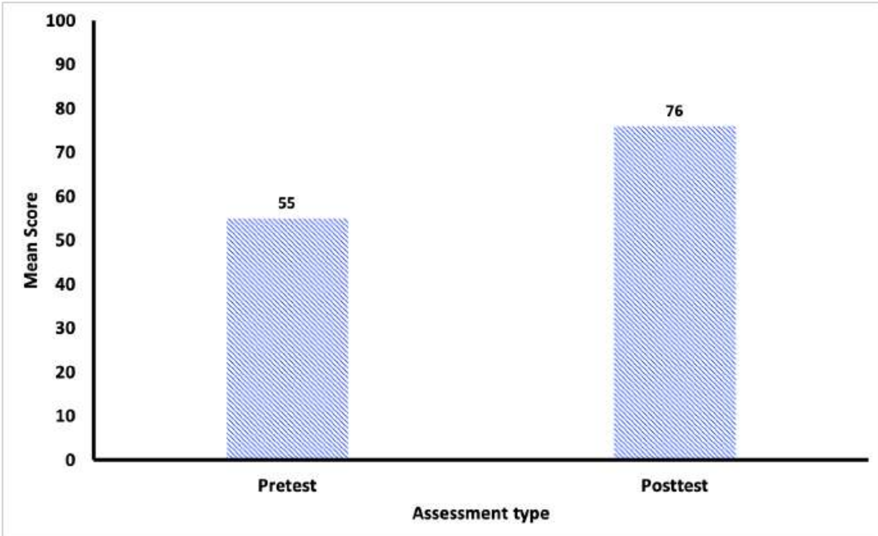


Fig. 4. Comparison of pre-test and post-test scores after AR-based solar system instruction

As shown in Fig. 4, post-test scores increased consistently after the implementation of the AR-based learning system. The medium N-Gain indicates measurable conceptual improvement facilitated by immersive 3D visualization. This finding is consistent with prior research demonstrating that AR enhances spatial reasoning and conceptual comprehension in physics and astronomy learning [2,6,9,11].

From an engineering validation standpoint, these results confirm that the AR rendering, interactive visualization, and system stability effectively support instructional objectives.

4.4. Rasch model measurement analysis

To strengthen psychometric rigor, Rasch modeling was applied to evaluate instrument consistency and respondent reliability. The analysis produced a person reliability coefficient of 0.81 and an item reliability coefficient of 0.85. The reliability summary is presented in Table 6.

Table 5
Rash reability results

Parameter	Reliability coefficient	Interpretation
Person reliability	0.81	good
Item reliability	0.85	good

To further illustrate the distribution of person ability and item difficulty, the Rasch person–item map is shown in Fig. 5.

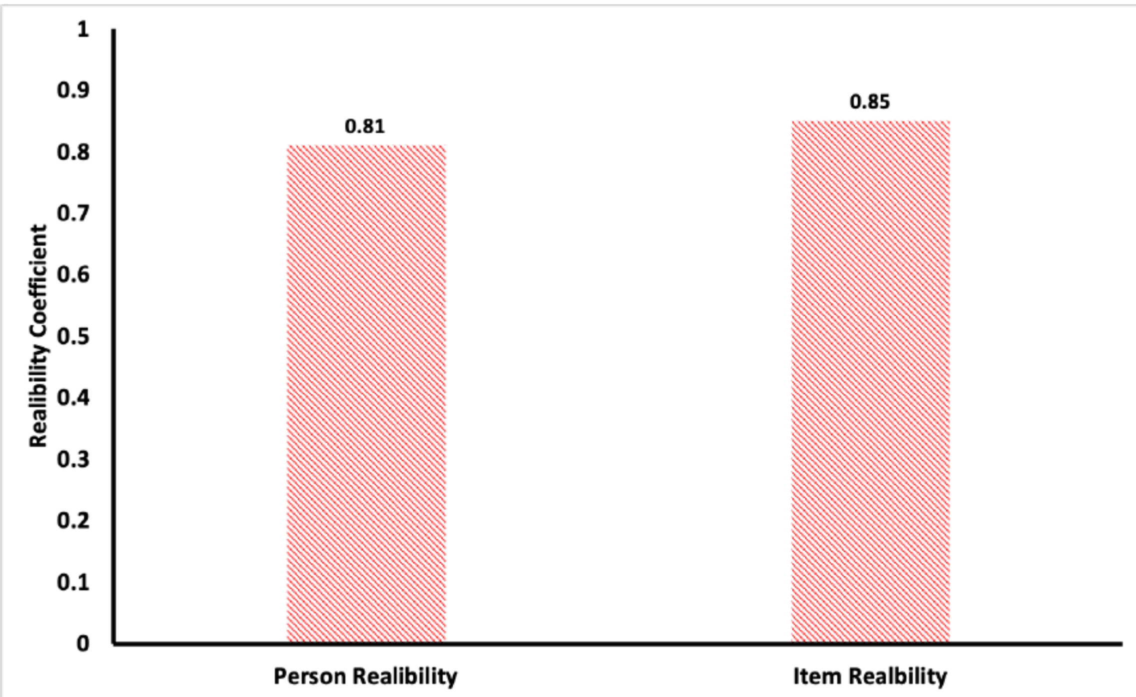


Fig. 5. Rasch person–item distribution map of the SolARis evaluation instrument

As illustrated in Fig. 5, the distribution indicates a balanced distribution of item difficulty relative to student ability levels. Reliability values above 0.80 demonstrate strong measurement consistency. Rasch modeling provides interval-level measurement, strengthening validation beyond classical test theory.

The integration of Rasch analysis enhances the robustness of system evaluation and confirms that outcome measurements are statistically reliable and not influenced by ordinal scale limitations.

4.5. Integrated engineering discussion

The combined results demonstrate that SolARis satisfies three essential performance indicators: high validity (4.85), high practicality (4.52), and moderate effectiveness (N-Gain = 0.46), supported by strong Rasch reliability (0.81 and 0.85).

The high validity confirms proper system design, accurate content integration, and stable AR functionality. The high practicality score indicates smooth real-time marker tracking and user-friendly operation of the interface. The medium effectiveness result reflects meaningful conceptual improvement through immersive 3D visualization.

The integration of Unity-based rendering, Vuforia marker tracking, optimized 3D modeling, and structured instructional flow contributes to measurable educational outcomes. These findings are consistent with previous AR-based physics learning system studies [2,6,8,9,11,21].

Overall, SolARis demonstrates technical robustness, operational stability, and measurable instructional impact, positioning it as a validated AR-based learning system suitable for multi-institutional deployment in higher education.

5. Conclusions

This study presented the design, implementation, and experimental evaluation of SolARis, a marker-based augmented reality (AR) learning system developed to visualize solar system concepts in higher education. The system was engineered using Unity 3D integrated with the Vuforia SDK and structured through the ASSURE development framework. The modular architecture ensured stable marker detection, real-time three-dimensional rendering, and efficient deployment on Android-based devices.

Experimental validation demonstrated that SolARis achieved a very high validity score (4.85) and a very high practicality score (4.52), confirming the technical feasibility and usability of the system in classroom environments. Reliability analysis using Cronbach's Alpha indicated consistent expert evaluation results. The effectiveness evaluation yielded a medium N-Gain value (0.46), demonstrating measurable improvement in students' conceptual understanding of solar system material. Rasch model analysis further confirmed strong person reliability (0.81) and item reliability (0.85), indicating robust measurement consistency.

From an engineering perspective, the findings verify that the integration of marker-based AR tracking, optimized 3D modeling, and structured instructional design can transform abstract astrophysical concepts into interactive digital representations while maintaining system stability and scalability. The combination of classical test theory and Rasch analysis strengthens the credibility of system validation.

Although the effectiveness result was categorized as medium, the system demonstrated significant potential for enhancing visualization-based learning and character reinforcement in physics education. Future development may incorporate adaptive feedback mechanisms, expanded astronomical simulations, and broader cross-institutional trials to further improve system performance and learning outcomes.

Overall, SolARis contributes to engineering-oriented educational technology by providing a validated AR-based solar system learning system suitable for multi-institutional implementation in higher education.

Acknowledgement
This research was not funded by any grant.

Conflict of Interest Statement
The authors declare that there is no conflict of interest regarding the publication of this paper. No financial support, grants, or other forms of compensation were received that could have influenced the outcomes of this work. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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