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Applying Augmented Reality Technology to Build Serious Games in STEM Education

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Abstract

Serious games are increasingly recognized as an innovative pedagogical tool in STEM education, thanks to their ability to create engaging, interactive and competency-based learning environments, thereby improving student learning outcomes. In this context, Augmented Reality (AR) technology has emerged as a breakthrough in science and technology, allowing learners to interact directly with vivid 3D models in real space, thereby strongly promoting the ability to explore and learn by experience. Integrating learning games (Serious games) with AR technology in teaching science subjects not only brings a new learning experience, but also opens up a promising approach to developing creative thinking, problem-solving skills and systematic thinking in learners. This study aimed to: (1) design AR-enhanced serious games aligned with the EDP framework using the CoSpaces Edu platform; and (2) evaluate their impact on students' engagement, perceptions of STEM, and development of engineering design skills. The mixed-method research design used in this study. In this study, we applied the CoSpaces Edu platform to design and deploy twelve AR-integrated learning games, corresponding to key topics in the Natural Science and Physics curriculum at middle and high school levels. The games were built to integrate academic content with virtual interactive experiences, thereby exploiting the potential of AR technology in improving the quality of science teaching in the direction of STEM education.

Keywords: Serious Game, Augmented Reality (AR), STEM Education.

INTRODUCTION

The rapid advancement of science and technology necessitates continual innovation in education to ensure alignment with emerging developments (Sudraja et al., 2022). In response, recent educational reforms in Vietnam, —most notably the 2018 General Education Program—, have marked a significant paradigm shift from content-based instruction to a competency- and quality-oriented approach. Within this context, pedagogical innovation is particularly critical in subjects such as natural sciences and physics, which are often perceived by students as abstract and disconnected from everyday life (Duc & Anh, 2024). STEM education has the potential to increase student engagement, facilitate experiential learning, and enhance problem-solving and critical thinking skills. Consequently, it has become a promising educational platform (Furner & Kumar, 2007). The STEM approach encourages students' critical and creative thinking through a student-centered, problem-solving approach (Ardianti et al., 2020).

However, science education still faces significant challenges in helping students understand complex and abstract scientific concepts (Hu et al., 2021). Often, students lose interest in STEM tasks due to these difficulties (Nguyen et al., 2024). Over the past few decades, numerous studies have shown that students' interest in science has declined. This is primarily due to a lack of intrinsic motivation and a lack of connection between instructional content and real-world applications (Osborne et al., 2003; Porter & Parvin, 2008; Van Aalsvoort, 2004). STEM education in Vietnam remains hampered by outdated teaching methods and a lack of context-based learning resources, despite being a crucial component of global education. Furthermore, few empirical studies have investigated how emerging educational technologies, particularly augmented reality (AR), can be pedagogically integrated into games (Duc et al., 2024; Son, 2024). To address these issues, a game-based learning model based on the engineering design process (EDP) is considered an effective pedagogical tool (Nguyen et al., 2024; Winarno et al., 2020).

Through the process of design, prototyping, and testing, these models enhance students' communication, creativity, and collaboration skills. They also help them understand science and technology concepts (Kolodner et al., 2003; Nurtanto et al., 2020). The Engineering Design Process (EDP) is a crucial component of the STEM curriculum. Therefore, incorporating EDP elements into STEM-based learning games is crucial for enhancing students' problem-solving and design thinking skills (Mangold & Robinson, 2013).

Educational digital games can enhance STEM education (Gui et al., 2023). The integration of digital games with educational content suggests that these games aim to encourage learning through engaging play experiences (Sudarmilah & Siregar, 2019). The goal of digital educational games is to increase student engagement and involvement by incorporating motivational elements such as clear rules, defined goals, interactivity, and competition. While this type of game has developed rapidly, there is no empirical evidence that they can improve educational outcomes (Baigi et al., 2022; De Freitas, 2018). Serious games, which are intended to enhance educational and cognitive abilities in addition to entertainment, have received increasing attention in this context (Elder, 1971). Serious games can encourage active learning experiences, improve knowledge retention, and increase motivation to learn (Michael & Chen, 2005).

However, educational games are still limited in secondary schools in Vietnam, despite their growing popularity worldwide. This highlights the importance of examining how contextualized and curriculum-aligned digital tools, such as AR-enabled serious games, can further support competency-based education reform in the country.

Students are increasingly engaged in technology-rich environments amidst the era of digital transformation, which influences their cognitive and learning behaviors. They prefer interactive, hands-on experiences with instant feedback (Unger & Meiran, 2020). This aligns with the development of 21st-century skills such as creativity, problem-solving, critical thinking, and collaboration (Videnovik et al., 2023).

Augmented reality technology—also known as augmented reality—has recently emerged as a tool that will transform education. This technology enables real-time interaction in contextual environments. It also provides clear instructional guidance and increases student motivation and attention (Azuma, 1997; Di Serio et al., 2013; Riva et al., 2016). With AR platforms, learning experiences can be integrated into physical structures at both the macro and micro levels (Kum-Biocca et al., 2020), allowing students to explore various problem-solving pathways and learn at their own pace (Acosta et al., 2019). Academics have shown that AR education supports scientific inquiry skills, conceptual understanding, spatial reasoning, and practical skills (Bujak et al., 2013; Cheng & Tsai, 2013; Dunleavy et al., 2009; Wu et al., 2013). AR enables easy-to-understand learning experiences and simulates abstract phenomena, particularly in physics education. However, recent research on the impact and influence of AR on STEM education is limited (Ibáñez & Delgado-Kloos, 2018). Additionally, rather than incorporating AR into a structured pedagogical framework such as serious games for engineering design development, recent research has often focused on delivering isolated content.

To address all of the research gap, the present study aims to: (1) design AR-enhanced serious games aligned with the EDP framework using the CoSpaces Edu platform; and (2) evaluate their impact on students' engagement, perceptions of STEM, and development of engineering design skills. Our study investigates the design and implementation of AR-integrated serious games in teaching natural sciences and physics at secondary and high school levels. A total of twelve AR-enhanced serious games modules were developed on the CoSpace Edu platform to support STEM-based experiential learning. These games aim to provide an engaging learning environment, enhance student motivation, and assess changes in student perceptions toward STEM subjects and the development of 21st-century learning skills.

This study is guided by the following research questions:

- *How are serious games (SG) combined with augmented reality (AR) for STEM education built and developed?*
- *How effective are these AR-integrated serious games in changing students' perceptions of STEM subjects and in developing 21st-century skills?*
- *To what extent do AR-based serious games enhance students' engagement and promote the development of engineering design competencies?*

METHOD

The mixed-method research design used in this study to design AR-enhanced serious games aligned with the EDP framework using the CoSpaces Edu platform; and (2) evaluate their impact on students' engagement, perceptions of STEM, and development of engineering design skills (Cohen et al., 2018).

A Process for Designing Serious Games to Support the Application of Virtual Reality in STEM Education

Many serious games have been developed and implemented in educational settings. According to (Ávila-Pesántez et al., 2017), after reviewing various studies and publications, the process of designing a serious games generally includes four main stages: Analysis, Design, Development and Evaluation. (Nussipova et al., 2020) also reported that the integration of Augmented Reality (AR) into STEM-related learning environments has yielded positive outcomes and enhanced students' learning experiences. Furthermore, empirical research has shown that incorporating AR into physical education improves students' conceptual understanding (Altmeyer et al., 2020; Malone et al., 2023). In Vietnam, a process called EPDPE was proposed for the design of board games for physical education (Nguyen et al., 2024). Meanwhile, (Duc et al., 2024) introduced a design process for applying AR in teaching chemistry, including the steps: Determine the target, Create an outline, Create the content, Artistic design, and Evaluation.

Based on these existing frameworks and the specific characteristics of physics education within the context of STEM in Vietnam, we have developed a process for designing serious games tailored to STEM education. This process (Figure 1) consists of five stages, collectively referred to as PADPE: Purpose, Analysis, Design, Prototype, and Evaluation.

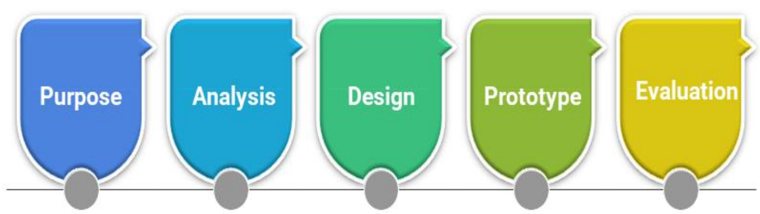

Figure 1. PADPE process

The initial step in designing a serious games that integrates Augmented Reality (AR) involves identifying the educational objectives, which forms the foundation of the entire development process. At this stage, it is essential to clearly define the intended learning outcomes in terms of knowledge acquisition, competency development, and the cultivation of learner attributes, ensuring alignment with national curriculum standards. Additionally, the overarching game mechanics—such as context, collection-based challenges, and competitive elements—must be conceptualized. This step also includes determining the product requirements, which will guide all subsequent design phases.

In the second phase, AR-specific interactions are analyzed and aligned with the game's rule structure to ensure coherence and pedagogical relevance. Key tasks include identifying the types of 3D virtual objects and simulations needed to represent subject matter effectively. The interaction analysis proceeds through the following steps: (1) formulating game rules, (2) sourcing and downloading relevant 3D assets from platforms like Sketchfab, and (3) mapping character movements and in-game challenges. These elements ensure that AR content is pedagogically meaningful and functionally integrated into gameplay.

The third step focuses on product design, where the AR environment is constructed using CoSpaces Edu. A 3D space is created, complete with contextual elements, characters, and interactive learning objects. CoBlocks, a block-based programming language, was used to create character behaviors such as movement and interaction. Additionally, interactive quiz elements were integrated, allowing for instant feedback, and sound effects were added to enhance immersion.

A trial version of the game was used in STEM learning activities while the prototype was being developed. The aim is to develop a rapid prototype that allows students to engage with the game and test its logic, gameplay mechanics, and AR interaction appeal. A STEM-oriented lesson is designed to facilitate this stage, structured into four activities: (1) identifying real-world problems, (2) introducing the game and providing guidance on AR usage, (3) engaging in gameplay across multiple stages aligned with the engineering design process (Review – Design – Build – Test – Evaluate), and (4) conducting reflection, assessment, and proposing improvements.

The final step is evaluation, which aims to determine whether the serious games fulfills its original educational intentions. For STEM-related games, this involves assessing whether students comprehend the content, demonstrate creativity, and engage in problem-solving aligned with the targeted learning outcomes. The evaluation also gauges the students' interest in the AR interface and identifies areas for further refinement or redesign.

Serious Games for STEM learning activities

Table 1 presents an overview of game developed "Địa đạo" which is designed by apply PADPE process , detailing the game structure, learning objectives, instructional components, and gameplay mechanics.

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Table 1. Serious Games for STEM Learning Activities

Overview	The AR-based serious game "Địa đạo" is inspired by the historical military engineering of the Vietnamese people during the Anti-American resistance War in Vietnam. Through gameplay, students are required to apply their knowledge of optics to design and construct a functional periscope.
Learning Objectives	1. Identify the direction of the reflected ray in various situations 2. Design and build a periscope model to demonstrate the principles of light reflection.
Game Components	Game Board: The game board (Figure 2) is designed based on the PADPE development process, in which each zone on the board corresponds to a step in the design cycle. Question Sets: The questions (Figure 3) are focused on the law of reflection and the fundamental knowledge required to build a periscope. These are structured as multiple-choice questions with a single correct answer. AR-Based 3D Simulations: The AR models (Figure 4) include 3D representations of light paths in a periscope and cross-sectional visualizations that help students better understand the internal structure and function of the device.
Game Rules	Players roll the dice to move, the number of spaces moved is equal to the number of dice rolled. Move through each area and perform tasks in each area. The game ends when the player completes the product and reaches the destination.

Beyond the development of "Địa đạo," additional AR-enhanced serious games namely "Little Astronaut" (Figure 2) , Star War (Figure 3), Luninova (Figure 4), were also created to further advance the application of augmented reality in STEM educational contexts.

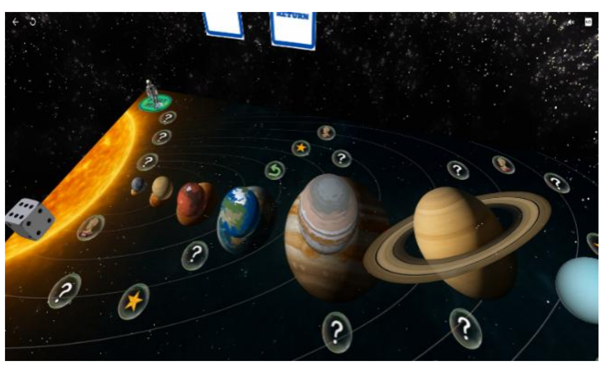

Figure 2. Little Astronaut Gameplay

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Figure 3. Star War Gameplay

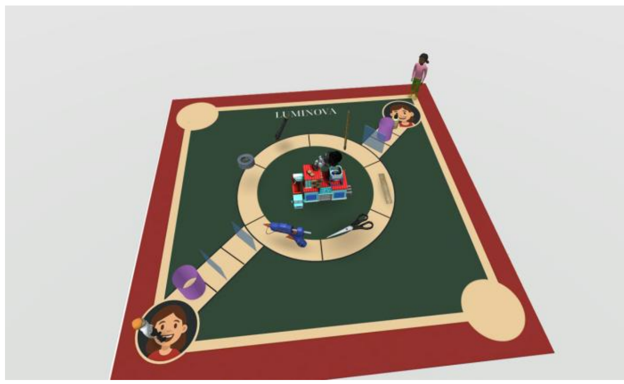

Figure 4. LUMINOVA Gameplay

It is evident that the integration of AR into serious games substantially enhances the learning environment by extending beyond the physical and static limitations of traditional board games. The immersive AR features—such as spatial navigation, dynamic 3D interactions, and real-time feedback—not only contextualize scientific concepts but also engage learners in authentic problem-solving and design-based thinking. As a result, students are not merely interacting with virtual elements, but are actively applying and refining their conceptual understanding and technical skills within a simulated, yet meaningful, learning context.

Procedure and Sample

We surveyed students' motivation and engagement after their participation in AR-integrated serious games within STEM education. A survey comprising 35 five-point Likert-scale items—ranging from strongly disagree (1) to strongly agree (5)—was administered in paper form during class sessions. The instrument was designed to assess shifts in students' perceptions toward STEM subjects and their 21st-century learning competencies. It was adapted from the *Middle and High School STEM Student Survey* by the Friday Institute for Educational Innovation (Faber et al., 2013) and translated into Vietnamese.

Additionally, a second questionnaire was developed to capture students' evaluations of the AR-enhanced serious games, focusing on key elements such as content, gameplay mechanics, and user interface. This instrument was informed by the theoretical frameworks of (Tene et al., 2025; Nguyen et al., 2024)

Data collection occurred in May 2025 and involved 53 seventh-grade students from lower secondary schools in Vietnam, all of whom were enrolled in natural science courses. Of the participants, 51% were female and 49% male. All students participated in the serious game "Địa đạo" across two class periods, following the completion of instructional content on optics. The intervention was structured to support experiential STEM learning and provided a suitable context for the pedagogical experiment.

Instruments

The questionnaire consisted of 35 items on a five-point Likert scale ranging from "strongly disagree" to "strongly agree". The KMO values were above 0.5 on both the STEM and 21st-century competency scales, and Bartlett's test was significant at the $p < 0.01$ level, indicating sufficient correlation between the items (Cohen et al., 2018). The four-factor rotation matrix generated by the EFA accounted for 51.8% of the total variance. All factors had Cronbach's alpha coefficients above 0.80, indicating good internal consistency.

For the AR serious games perception scale, EFA revealed a one-factor solution, with a KMO value greater than 0.5 and a significant Bartlett's test ($p < .01$). The cumulative variance explained was 46.1%. Cronbach's alpha for this scale was above 0.90, demonstrating excellent reliability.

Data Analysis

To evaluate the effectiveness of serious games on students' motivation and engagement, both quantitative data from 35 survey items and qualitative responses from open-ended questions were examined. The changes in students' perceptions of STEM subjects were assessed through a paired-samples t-test. Data analysis was conducted with JASP for quantitative data and NVIVO version 14 for qualitative data.

Implementation Testing

Students participated in the 'Địa đạo' serious game over two class periods, following the completion of instruction on the topic of optics.

Figure 5. Students Participate in Serious AR game “Tunnel”

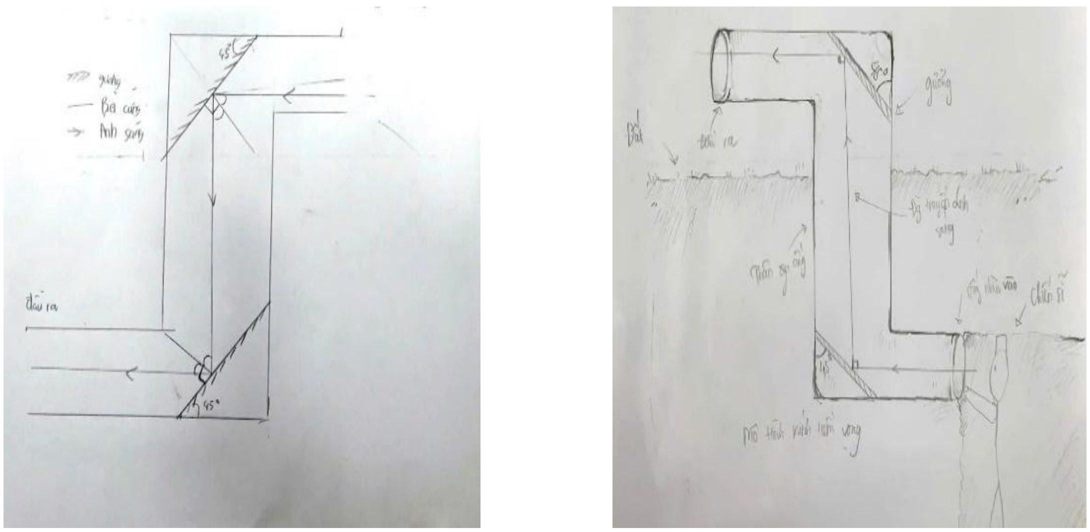

Figure 6. Periscope Product Design Drawing of Students

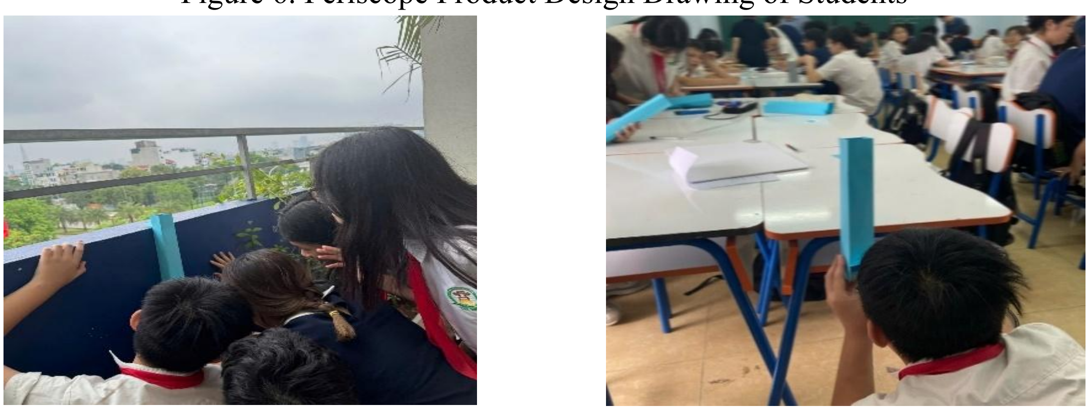

Figure 7. Students Participate in Testing STEM Products

RESULTS & DISCUSSION

Qualitative Results

During the implementation of AR game-based learning activities in STEM education, qualitative observations showed that students showed positive attitudes, interest, and proactive participation. The students' product designs were carefully invested in both content and aesthetics.

During the manufacturing stage, students handled the operations well, especially the mirror assembly step - which was predicted to be difficult. Some groups also showed creativity by adjusting the design such as drilling holes to replace binoculars or proposing a flexible rotation mechanism. Many groups focused on ensuring that the product met the requirements and was close to the design proposed in the game.

Quantitative Results

Reliability and standardization of questionnaire on attitudes towards STEM subjects and 21st century competencies. The questionnaire reliability for Cronbach's Alpha coefficient α is greater than 0,8.

Table 2. Cronbach's Alpha Reliability of the Scale

Content	Cronbach's Alpha
I find math the most difficult subject for me.	0.822
Later i can choose a job that requires Math.	0.815
I find math very difficult to learn.	0.825
I think I am a student who can do well in Math.	0.813
I can study other subjects, but I am not good at math.	0.818
I believe I can learn advanced math well.	0.817
I am confident that I can get high scores in Math.	0.824
I feel confident when studying Natural Scien ce.	0.813
Later I can choose a career related to Natural Sciences	0.811
I think when I grow up I will use knowledge of Natural Sciences.	0.807
Understanding Science will help you get a job.	0.803
I need to study Natural Sciences for my future job.	0.808
I believe I can do well in Natural Science.	0.808
Natural Sciences will be important for my future career.	0.802
I can study other subjects, but not Natural Sciences	0.828
I believe I can learn advanced Natural Science knowledge well.	0.806
I like to imagine and come up with new gadgets or products.	0.810
If you study engineering, you can make everyday objects better.	0.809
I find myself good at assembling or fixing things.	0.808
I like to learn how machines work.	0.807
Designing objects or building will be an important part of my future job.	0.809
I am curious to know how electronic devices work	0.811
I want to be creative and inventive in my future job.	0.801
Knowing how to combine Math and Science will help me create useful	0.811

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Content	Cronbach's Alpha
things.	
I believe I can be successful if I become an engineer.	0.814
I am confident that I can guide my friends to complete something together.	0.805
I am confident that I can encourage my friends to try their best.	0.803
I can respect the differences between me and other people.	0.808
I believe I can help my friends when needed.	0.808
I can listen to other people's opinions when making decisions.	0.809
I can change my approach if things don't go as planned.	0.812
I can set and manage my time wisely for self-study.	0.810
I know which homework assignments to complete first.	0.809
I am able to collaborate well with people from diverse backgrounds.	0.808
I can set and manage my time wisely for self-study.	0.805

The results of the Exploratory Factor Analysis (EFA) indicate that the questionnaire components converged into a four-factor rotation matrix. These variables will likely be used in factor analysis, as the Kaiser-Meyer-Olkin (KMO) sampling adequacy measure yielded a value above 0.5. With $p < 0.01$, Bartlett's sphericity test is statistically significant, indicating a fairly strong correlation between the variables. As indicated by the extracted variables, the cumulative explained variance is 51.8%. This indicates that the EFA model is appropriate and adequately represents the data structure in this study.

Reliability and Standardization of the Serious Games AR Attitude Questionnaire

For all scales, the questionnaire demonstrated high internal consistency, with Cronbach's Alpha coefficient exceeding 0.9. The results of Exploratory Factor Analysis (EFA) indicated that the single-factor rotation matrix contained the items. These variables were suitable for factor analysis because the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was greater than 0.5 (Cohan et al., 2018). The existence of adequate correlations among the variables was confirmed by Bartlett's sphericity test, which was statistically significant at the $p < 0.01$ level. Since the cumulative variable explained by the extracted factors was 46.1%, the EFA model was appropriate and in accordance with the research objectives.

Data Analysis and Processing Results

The Effectiveness of the Game in Influencing Students' Views on STEM Subjects and 21st Century Competencies

The results of the independent samples t-test indicated no statistically significant differences ($p > 0.05$) in students' perceptions toward STEM-related subjects and 21st-century learning competencies. However, the mean scores for both perceptions of STEM subjects and 21st-century competencies were relatively low (below 3.5), suggesting a generally modest level of agreement. Interestingly, qualitative findings revealed a contrasting pattern, with students demonstrating noticeable interest and engagement in learning activities. This discrepancy highlights the need for further in-depth research to better understand the underlying factors and to validate these initial findings.

Learner Evaluation of the Game

The average scores of the contents showed that learners actively participated in the game. Some contents clearly showed learners' interest, however, learners still had some low ratings on the images and movements of the characters in the game.

Table 3. Means and the Standard Deviations of Each Item

Content	Mean	SD
I know how to achieve the goal in the game.	3.660	0.939
I find the rules of the game very easy to understand.	4.019	0.866
I find the game play time reasonable (not too long or too short).	3.660	1.037
I really want to know what the next development of the story in the game will be.	3.415	1.200
I find the steps to go through in the game to be logical.	3.755	0.939
I understand the content and mission of the game.	4.057	0.795
I very like this game.	3.377	1.113
I feel happy when I overcome challenges in the game.	3.547	1.136
I enjoy learning through the game.	3.615	1.051
I can be creative when playing this game.	3.528	1.187
I discovered many new things in the game.	3.627	0.999
I think I learned how to design and make STEM products from the game.	3.547	1.011
I find the models displayed in the game look realistic.	3.377	1.042
I like the character movement effects in the game.	2.769	1.131
I like the funny, vivid images in the game.	3.302	1.137
I like the game because it gives immediate feedback when I do something in the game.	3.151	1.008
I find the images in the game very beautiful.	2.962	1.270
I think the images in the game are very suitable for the content and setting	3.566	1.047
I feel successful when I overcome challenges in the game.	3.396	1.025
I better understand how to create STEM products through play the game.	3.623	0.904

Content	Mean	SD
I find my design and crafting skills better after playing.	3.471	0.946
I really like learning games that incorporate AR because the learning content is easier to understand and more vivid.	3.698	0.992
I am excited to participate in learning through this game.	3.717	0.948
I find the game help me review knowledge more easily.	3.679	0.936
I find the game helps me practice communication and cooperation skills.	3.491	1.085
I find the game helps me practice my calculation skills.	2.981	1.152
I find the game helps me practice problem solving skills.	3.311	0.973
The learning activities in the game help me achieve the learning objectives of the subject.	3.528	0.932
This game helps me connect knowledge content in new ways.	3.566	0.930
This game helps me engage in learning activities in different ways which enhances my learning ability.	3.615	0.889
When playing the game, I get to experience the work of an engineer	3.212	1.143
I am interested in learning more about Natural Sciences.	3.453	0.911
I find this STEM game helps me to actively learn and apply the knowledge I have learned to real-world problems.	3.528	1.049
I find it interesting to play STEM games because the knowledge is no longer dry and the knowledge is more practical.	3.623	0.945
Through the game, I get to experience the work of engineers, apply knowledge to design, manufacture and test my own products.	3.528	1.085

Advantages of Serious Games Combined with Augmented Reality (AR) in Education

Compared to traditional educational games such as board games- which are inherently limited by physical space and constrained interactivity- augmented reality (AR) offers a novel, immersive, and flexible learning environment. AR enables a seamless integration between the real world and virtual content, thereby facilitating interactive, contextualized, and experiential learning experiences. In AR-integrated educational games, core features are vividly presented through:

- AR Maps: These simulate real-world spaces by displaying locations and destinations directly onto the surrounding physical environment via mobile device screens. This provides learners with a sense of free movement and purposeful navigation—an experience that traditional board games are often unable to replicate.
- 3D Obstacles and Tasks: Learning challenges are visualized in three dimensions, allowing learners to directly interact with virtual objects by "touching" or "scanning" them. This enhances the realism of physical science phenomena far beyond what can be achieved with

static 2D printed models used in board games.

- Digitally Overlaid Questions and Tasks: Instructions and challenges are presented as digital overlays—such as text, 3D images, icons, or technical data—which not only support more effective information retention and concept modeling, but also automate feedback delivery. This immediate response system eliminates the need for a human moderator and promotes autonomous learning.

This study investigated the development and implementation of AR-integrated serious games designed to promote STEM engagement and 21st-century skills among lower secondary students. While quantitative results indicated no statistically significant changes in students' perceptions toward STEM subjects and competencies, the qualitative findings clearly demonstrated positive learner engagement, creativity, and collaboration throughout the intervention process.

Such a discrepancy between statistical data and classroom observations is not uncommon in short-term educational interventions. Research has shown that attitudes, beliefs, and perceptions—particularly regarding STEM—are often resistant to change over brief periods, even when immediate behavioral improvements are evident. As highlighted by (Albarracín et al., 2014), attitudes tend to be deeply rooted and context-dependent, often requiring sustained exposure and reinforcement before measurable change is reflected in survey instruments. Similarly, (Fishbein & Ajzen, 2011) theory of reasoned action suggests that belief systems evolve gradually and are not easily shifted by single interventions.

In our case, students' mean scores for STEM-related perceptions hovered just below the midpoint ($M < 3.5$), yet during the game-based lessons, learners exhibited proactive problem-solving, product iteration, peer collaboration, and genuine curiosity—clear signs of affective and cognitive engagement. Several groups creatively modified their periscope designs, proposed structural enhancements, and expressed pride in the aesthetic and functional outcomes of their work. These behaviors confirm the motivational and immersive qualities of AR-supported learning, consistent with prior research (Di Serio, Ibáñez, & Kloos, 2013; Riva et al., 2016), who emphasized the affective benefits of contextualized, interactive AR environments

Another contributing factor may lie in instrument sensitivity. While the 35-item Likert-scale survey was adapted from validated instruments, it may have been insufficiently sensitive to detect short-term perceptual shifts, especially among students unfamiliar with reflective self-assessment. Previous studies (Unger & Meiran, 2020) also reported that self-reported survey scores often lag behind real behavioral engagement, a phenomenon referred to as the value-action gap (Kollmuss & Agyeman, 2002)

Moreover, the design structure of the AR-integrated games, based on the PADPE process aligned with the Engineering Design Process (EDP), supported learning through challenge-based, hands-on experience. This approach mirrors the learning-by-design model (Kolodner et al., 2003), which has been shown to enhance students' ability to connect theory with application. Unlike traditional AR uses that focus primarily on visualizing content (Kim & Irizarry, 2021) our study embedded AR as a core interactive element throughout the design, prototyping, and evaluation cycle—allowing students to explore scientific principles in both virtual and physical spaces. Despite the promising engagement outcomes, limitations were noted. Some students reported low satisfaction with the visual fidelity and character animation, highlighting the importance of enhancing graphic design and user experience in AR learning environments. Additionally, device limitations and inconsistent internet access posed challenges for full participation—barriers that must be addressed for broader scalability, especially in public schools.

CONCLUSION

AR-integrated serious games (SG) have demonstrated their potential to meet the core requirements outlined in the 2018 Vietnamese General Education Curriculum. These games effectively support the development of 21st-century competencies and enhance students' engagement in learning Natural Sciences and Physics. Notably, through AR-based games embedded in STEM activities, learners expressed increased interest, attributing it to the authentic learning environment, immersive experiences, and the presence of healthy competition—factors that transformed the classroom into a more dynamic and stimulating space. This study developed twelve AR-integrated learning games following the PADPE (Purpose–Analysis–Design–Prototype–Envaluation) instructional design model, with a focus on challenge-based and hands-on STEM experiences. The games were designed to align with the learning objectives specified in the science education curriculum, particularly in the Vietnamese context. Findings confirmed that both the development process and the quality of the AR-integrated games successfully fulfilled the intended curricular goals. The games were grounded in real-world relevance and closely follow the EDP design process, reflecting the core characteristics of STEM education. While playing, students were required to solve context-based tasks that naturally guided them through the sequential stages of the EDP. These games provided learners with an engaging, interactive experience that facilitated the acquisition of fundamental knowledge and skills necessary for completing STEM-related tasks and navigating their own design processes.

This study acknowledges several limitations during the pedagogical experimentation process. First, the AR-integrated learning game faced several technological challenges. These included limited access to smartphones and tablets (iPads), and unstable internet connectivity. These challenges limited students' full engagement in the game-based learning experience. Second, due to time constraints, the experimental phase focused primarily on evaluating the game's effectiveness in enhancing students' interests and 21st-century skills. No attempt was made to study the game's impact on long-term academic achievement.

These results suggest that AR-integrated serious games are useful in education, despite their limitations. Some compelling evidence for the benefits of AR technology includes increased student motivation and increased student engagement during gameplay. Student interaction in group assignments also helps them collaborate and communicate effectively. Consequently, incorporating augmented reality (AR) into serious game (SG) design for STEM education has the potential to create immersive and engaging learning environments.

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