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# Leveraging augmented reality and gamification for enhanced self-regulation in science education

Hüseyin Ateş[1] · Merve Polat[2]

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## Abstract
This study investigates the efficacy of integrating augmented reality (AR)-based gamification with self-regulated learning (SRL) strategies to enhance middle school students' academic performance, engagement, satisfaction, and self-efficacy in science education. Employing immersive AR technologies alongside gamification elements, this approach is designed to cultivate an engaging and learner-centered environment that promotes essential SRL competencies including goal-setting, self-monitoring, and reflective thinking. Utilizing an experimental research design, the study engaged 60 middle school students who were allocated into two groups: one experiencing self-regulated AR-based gamification and the other experiencing traditional AR-based gamification without self-regulation components. The findings reveal that students in the self-regulated AR-based gamification group demonstrated significantly enhanced levels of academic achievement, engagement, self-efficacy, and overall satisfaction compared to their peers in the traditional group. These outcomes suggest that the strategic integration of AR-based gamification with SRL strategies not only fosters significant improvements in educational performance but also enriches the learning experience, thereby providing critical insights for the development of innovative educational technologies that support comprehensive understanding and foster student autonomy in science education.

**Keywords** Augmented reality · Gamification · Self-regulated learning · Science education · Middle school · Academic achievement · Student engagement · Motivation · Self-efficacy

✉ Merve Polat
merve.polat@cbu.edu.tr

Hüseyin Ateş
huseyin.ates@ahievran.edu.tr

[1] Department of Science Education, Kırşehir Ahi Evran University, Kırşehir, Turkey

[2] Faculty of Education, Department of Science Education, Manisa Celal Bayar University, Manisa, Türkiye

## 1 Introduction

In the rapidly evolving educational landscape, the integration of technology has fundamentally transformed how students engage with content and develop essential competencies. Among the myriad of emerging technologies, Augmented Reality (AR) has emerged as a particularly compelling tool, garnering significant attention for its ability to create immersive and interactive learning experiences in diverse fields (Lin & Yu, 2023). For example, research in language education has demonstrated the efficacy of digital game-based methods, such as those utilizing platforms like Quizziz, in enhancing engagement and self-regulation (Kazu & Kuvvetli, 2023). Similarly, in the science education, by overlaying digital information onto the physical world, AR allows learners to visualize and manipulate complex concepts in real time, facilitating a deeper understanding and retention of knowledge (Ateş, 2024a; Ateş & Garzón, 2023).

The potential of AR in science education is significantly enhanced when integrated with gamification—a pedagogical approach that incorporates game-like elements such as points, levels, and rewards into learning contexts (Prasittichok et al., 2024; Wang, 2022). Gamification leverages the intrinsic motivation and engagement that games provide, fostering active and sustained participation among students in scientific learning (Kalogiannakis et al., 2021). By combining AR with gamification, educators can create immersive and interactive learning environments that not only enhance student motivation but also cultivate essential skills like collaborative problem-solving and critical thinking (Czok et al., 2023a; Lampropoulos et al., 2022). For instance, AR simulations can enable students to visualize and manipulate complex scientific concepts, such as biological processes or physical laws, that might otherwise be abstract or difficult to comprehend (Czok et al., 2023b; Turhan & Gümüş, 2022). When gamified elements like challenges and rewards are added, students are further motivated to solve problems, complete tasks, and collaborate with peers to achieve learning objectives (Chaiyarat, 2024; Ho et al., 2022; Redondo-Rodríguez et al., 2022). Despite these advantages, the full potential of this integration has not been systematically explored, particularly in terms of fostering self-regulated learning (SRL). SRL strategies, such as goal-setting, self-monitoring, and reflection, are critical for enabling students to take ownership of their learning, yet the interplay between AR, gamification, and SRL remains underexplored. Addressing this gap is vital, as a deeper understanding of how these technologies can synergistically support SRL practices will allow educators to design more effective and engaging science education interventions. By engaging students in inquiry-based learning—where they can formulate hypotheses, conduct virtual experiments, and reflect on their findings—this approach has the potential to revolutionize how scientific principles are taught and learned (Yu et al., 2022).

Despite the promising benefits of augmented reality (AR) and gamification in science education, a significant gap exists in understanding how these approaches impact diverse learning outcomes, particularly self-regulated learning (SRL). SRL is a vital component of modern education, empowering students to actively manage their learning through goal-setting, self-monitoring, and reflection (Zimmerman, 2002). These practices are critical for fostering autonomy, enhancing engagement with scientific material, and building skills essential for lifelong learning (Ateş, 2024b). However, the integration of SRL strategies within AR-based gamification in science education remains underexplored. Existing research has largely focused on the standalone benefits of AR—such as improving visualization of complex scientific concepts (Yoon et al., 2017)—and gamification—such as increasing student motivation and participation in science-related activities (Ateş & Kölemen, 2024). Few studies have examined the synergistic potential of combining these technologies with SRL practices to optimize learning outcomes. Moreover, much of the existing literature lacks depth in addressing how SRL can be effectively fostered through specific features of AR and gamification. For example, gamification mechanisms, such as reward systems, can encourage goal-setting, while AR environments can provide real-time feedback during simulations or experiments. However, limited research has explored how these features can be systematically designed to develop students' self-regulatory skills in scientific contexts (e.g., Chen et al., 2023a, b, 2024a, b). This oversight risks underutilizing the transformative potential of these technologies in creating personalized, engaging, and effective learning experiences. Without clear guidance on integrating SRL into AR-based gamification, educators may miss the opportunity to design interventions that not only captivate students but also build their capacity for independent and reflective learning. Additionally, the interplay between AR, gamification, and SRL is likely to vary across scientific disciplines and educational contexts, further emphasizing the need for targeted research. Investigating how these technologies can be tailored to address the diverse needs of learners in different scientific domains is crucial for maximizing their educational impact. Addressing these gaps is essential to develop robust frameworks that empower educators and instructional designers to create innovative science learning environments that combine technological affordances with evidence-based pedagogical practices.

This gap underscores the pressing need for comprehensive studies that investigate how self-regulation can enhance the effectiveness of AR-based gamification specifically within the context of science education. The current lack of research on integrating self-regulatory strategies into AR and gamification frameworks leaves educators without clear guidance on leveraging these technologies to foster deeper learning. Systematic integration of SRL practices—such as goal-setting, self-monitoring, and reflection—within AR-based gamification could enable students to set achievable learning goals, monitor their progress through interactive AR experiences, and reflect on their outcomes in a structured way. For instance, AR applications designed to prompt students to define clear objectives at the beginning of a lesson, track their achievements during simulations, and engage in reflective journaling could significantly enhance engagement and academic performance. Understanding these dynamics is critical for creating tailored educational interventions that fully utilize the unique affordances of AR and gamification in science education. By addressing these gaps, this research can equip educators and instructional designers with actionable insights to develop learning environments that not only capture students' interest in scientific inquiry but also empower them to take ownership of their learning processes, ultimately preparing them for lifelong learning.

This study aims to address the current gap by investigating the effects of self-regulated AR-based gamification on multiple facets of student outcomes in science education, including academic achievement, student engagement, satisfaction, and self-efficacy. The integration of self-regulation strategies within AR-based gamification offers a promising approach to enrich not only cognitive learning outcomes but also motivational, emotional, and behavioral aspects of the educational experience. By focusing on these four key constructs, the study seeks to provide a comprehensive understanding of how self-regulated AR-based gamification can be leveraged to create more effective and meaningful learning experiences for students. The first objective of the study is to explore how self-regulated AR-based gamification impacts students' academic achievement compared to traditional AR-based gamification without self-regulation components. By proposing and developing an approach that integrates self-regulation strategies into AR-based gamified learning environments, the study aims to determine whether such integration enhances learning outcomes, specifically focusing on academic achievement which is in science is critical, as it serves as a foundational measure of how well students can understand and apply scientific concepts. By integrating self-regulation strategies—such as goal-setting, progress monitoring, and self-reflection—into the AR-based gamified environment, students are encouraged to take ownership of their learning. This structured approach is expected to enhance their ability to engage with complex scientific topics, leading to improved academic outcomes. The second focus is on assessing differences in student engagement levels between students who use self-regulated AR-based gamification and those who use a traditional AR-based approach. Engagement is a key predictor of academic success and includes multiple dimensions, such as behavioral engagement (participation in learning activities), emotional engagement (interest and enthusiasm for learning), cognitive engagement (effort and investment in learning), and social engagement (interaction with peers and teachers). This study aims to evaluate whether the incorporation of self-regulation elements can foster a deeper level of engagement, as students are encouraged to set personal goals and actively reflect on their progress throughout the learning process. Enhanced engagement, facilitated by gamified rewards and interactive AR content, is hypothesized to result in more sustained interest and active participation in science learning. The third objective is to determine how student satisfaction with the learning experience differs between the self-regulated AR-based gamification group and the traditional AR-based group. Student satisfaction is a significant factor in the effectiveness of any educational intervention, as it influences motivation and long-term commitment to learning. By providing students with an engaging AR environment that includes elements of choice, personal goal-setting, and gamified feedback, this study anticipates that students in the self-regulated group will report higher satisfaction levels. Satisfaction data will provide insights into the quality of the learning experience, including whether the students found the AR features enjoyable, useful, and supportive of their learning goals. Higher levels of satisfaction can also indicate that students perceive the learning activities as relevant and meaningful, which is crucial for promoting lifelong interest in science. Finally, the study will examine the effect of self-regulated AR-based gamification on students' self-efficacy in science learning, as compared to a traditional AR-based approach. Self-efficacy, or students' belief in their ability to succeed in specific learning tasks, is a critical construct that affects academic motivation, resilience, and performance. In the self-regulated AR-based environment, students are expected to develop a stronger sense of self-efficacy as they successfully complete challenging AR tasks, achieve personal learning goals, and receive immediate feedback. Positive experiences and successes within the AR-based platform are likely to enhance students' confidence in their ability to master scientific concepts, which can have a lasting impact on their willingness to engage with and persist in science-related activities.

The following research questions will guide this study:

1. How does self-regulated AR-based gamification impact students' academic achievement in science compared to traditional AR-based gamification without self-regulation components?
2. What differences in student engagement levels are observed between the self-regulated AR-based gamification group and the control group using traditional AR-based gamification?
3. How does student satisfaction with the learning experience differ between students exposed to self-regulated AR-based gamification and those using a traditional AR-based approach?
4. What effect does self-regulated AR-based gamification have on students' self-efficacy in science learning compared to traditional AR-based gamification?

## 2 Literature review

The integration of technology into education has significantly transformed the teaching and learning landscape, particularly within science education. Among the most influential technological advancements are AR and gamification. This literature review explores the individual and combined impacts of AR and gamification on student learning, with a specific focus on how these technologies support SRL in science education.

### 2.1 Augmented reality in science education

AR creates unique learning environments by overlaying digital information onto the physical world, thus enhancing students' engagement and comprehension of complex scientific concepts (Lai et al., 2019). Research indicates that AR can improve spatial reasoning, increase motivation, and facilitate deeper learning by allowing students to visualize abstract scientific phenomena (Abdinejad et al., 2021; Arici et al., 2019; Ateş, 2024a). For instance, studies have demonstrated that AR applications in science education can lead to higher levels of knowledge retention and a more profound understanding of challenging topics such as biology, chemistry, and physics. Interactive and immersive AR experiences enable students to explore complex structures (e.g., molecular configurations in chemistry) and processes (e.g., photosynthesis in biology) in a hands-on manner (Jiménez, 2019; Yao & Wang, 2024).

Moreover, AR fosters collaborative learning in science education by allowing students to work together in real-time, manipulating digital content while interacting with their peers (Zhang & Wang, 2021). This collaborative aspect is critical for promoting social interaction and enhancing communication skills, which are essential for successful learning in scientific disciplines (Jesionkowska et al., 2020). For instance, students can collaboratively conduct virtual experiments, share findings, and solve problems in a shared AR environment, thus reinforcing their understanding through peer discussion and teamwork.

### 2.2 Gamification in science education

Gamification, defined as the use of game design elements in non-game contexts, has gained traction as a powerful pedagogical tool in science education (Kalogiannakis et al., 2021). By incorporating elements such as points, badges, and leaderboards, gamification aims to increase student motivation and engagement (Hellín et al., 2023). Research has shown that gamified learning experiences in science can lead to improved academic performance, as students become more motivated to participate actively in their learning (Zourmpakis et al., 2023). For instance, students engaged in gamified science activities are often more inclined to take risks, experiment, and explore scientific concepts creatively.

Additionally, gamification encourages students to set personal learning goals and monitor their progress, aligning closely with principles of SRL (Qiao et al., 2022). By integrating competition and reward systems, gamification fosters a sense of achievement that can boost students' self-efficacy in their scientific capabilities (Ahmed & Asiksoy, 2021). This aspect of gamification is particularly relevant in science education, where students often face challenging material and may require additional motivation to persevere through complex topics (Zourmpakis et al., 2023).

### 2.3 Enhancing self-regulated learning in science education through AR-based gamification: a novel approach

This study introduces the Augmented Reality-Based Gamification Self-Regulated Learning (ARBG-SRL) approach, a newly developed framework aimed at enhancing student engagement in science education through AR based gamification. Building on the foundational work of Lai and Hwang (2016); Chen et al. (2024a, b), and applying it in a contemporary context by Ateş (2024b), this novel approach integrates effective self-regulation strategies to address gaps found in earlier models that lacked comprehensive SRL features.

The ARBG-SRL approach consists of several essential components designed to foster an interactive and supportive learning environment, as outlined in Table 1. The core element is the AR-Based Learning Application (Virtuali-Tee), which provides students with immersive learning experiences, allowing them to explore complex scientific content—such as the circulatory, respiratory, and digestive systems—using detailed and engaging 3D models. The self-regulated monitoring platform enables students to set personalized learning objectives, monitor their learning journey, and make adjustments as needed. This platform incorporates goal-setting tools, interactive quizzes, and a reflection process, all of which offer personalized feedback to help students effectively track and adapt their progress.

**Table 1** Summary of the AR-SRL system components and phases

| Component | Description |
|---|---|
| AR-Based Learning App | An app that allows students to interact with 3D AR models, helping them visualize complex scientific concepts (e.g., circulatory, respiratory systems) in an immersive manner. |
| Self-Regulated Monitoring Platform | A platform where students set personalized learning goals, track progress, and evaluate their performance. Includes tools for goal-setting, interactive quizzes, and self-reflection activities that promote self-directed learning. |
| Teacher Management System | Supports educators in uploading instructional materials, monitoring student progress, and providing individualized feedback based on real-time student learning data. Assists teachers in targeting specific areas for additional support. |
| Adaptive Feedback Module | Embedded within the app, this module provides continuous personalized suggestions and guidance to students, adapting content complexity based on individual progress to help them overcome difficulties. |
| Phases | **Process** |
| Forethought Phase | Students set clear, measurable learning goals for each unit, such as mastering scientific concepts or achieving target scores. This helps foster autonomy and purpose in their learning journey. |
| Performance Phase | Students engage with the AR app, exploring AR representations of biological systems. Gamified quizzes serve as formative assessments and include motivational features to keep students actively engaged. |
| Monitoring and Adjustment Phase | Students use the monitoring platform to compare their progress with initial goals. Encouraged to adjust learning strategies as needed, e.g., revisiting challenging content and modifying approaches based on tailored feedback from the system. |
| Self-Reflection Phase | At the end of each unit, students evaluate their learning outcomes by reflecting on goals, effectiveness of strategies used, and analyzing areas of strength or needing improvement. The feedback provided helps students plan future learning activities effectively. |
| Purpose and Outcome | **Goal** |
| Self-Regulated Learning | The system integrates AR-based gamification with SRL strategies to foster student autonomy, increase engagement, improve academic performance, and support students in mastering complex scientific content effectively. |
| Teacher Support | The teacher management system helps educators identify students' learning needs and provide targeted instruction and timely feedback, ensuring a comprehensive learning experience. |

Another important aspect of the ARBG-SRL approach is the teacher management system, which supports educators by allowing them to upload learning materials, monitor student progress, and provide individualized feedback based on real-time data from student learning logs. This system enables teachers to tailor their instructional methods, offering targeted interventions when students face challenges. The Adaptive Feedback Module, integrated within the AR app, provides continuous guidance and personalized suggestions. It ensures consistent support for students by adapting content complexity based on individual progress, thus helping learners overcome difficulties without feeling overwhelmed.

The ARBG-SRL learning process unfolds across multiple phases to ensure comprehensive student support (Zimmerman, 2002):

- **Forethought Phase**: The ARBG-SRL approach prompts students to establish clear, measurable learning goals for each unit. These objectives may include mastering specific scientific concepts or achieving target scores in quizzes. Setting these goals helps foster student autonomy and instills a sense of purpose in their learning journey.

- **Performance Phase**: During this phase, students engage deeply with the AR application, which provides an immersive and interactive representation of biological systems. By interacting with AR models, students gain a detailed understanding of intricate systems such as the circulatory, respiratory, and digestive systems, bridging the gap between abstract ideas and concrete understanding. Gamified quizzes embedded within the AR app serve as formative assessments and include motivational elements like points and digital badges to keep students actively engaged and participating in their learning process.
- **Monitoring and Adjustment Phase**: In this phase, students use the self-regulated monitoring platform to compare their progress with the goals they set during the forethought phase. They are encouraged to reflect on challenges they encounter and adjust their learning strategies accordingly. For example, if a student struggles with understanding a specific function of the circulatory system, they can revisit the 3D model or retake related quizzes provided by the AR app to reinforce their learning. The Adaptive Feedback Module provides tailored feedback, ensuring that students stay on track and modify their approaches as needed for improved understanding and mastery of the content.
- **Self-Reflection Phase**: At the end of each unit, students use the self-regulated monitoring platform to evaluate their learning outcomes. They assess whether they have met their initial goals and analyze the effectiveness of their strategies. This phase provides insights into areas of strength and those requiring further attention. The personalized feedback offered by the system helps students make informed decisions about future learning efforts, fostering skills essential for lifelong learning.

The ARBG-SRL approach supports a holistic approach to science education, promoting both SRL and classroom collaboration. Teachers leverage the teacher management system to gain insights from student progress data, allowing them to identify areas where further support or intervention may be needed. This helps educators adapt their lessons to meet individual students' needs, providing additional explanations for concepts that proved challenging during AR-based learning activities.

By integrating AR-based gamification with a structured SRL framework, this study aims to create a transformative educational experience for science students. The ARBG-SRL model not only enhances comprehension of scientific content but also empowers students to regulate their learning processes effectively. This approach demonstrates how combining AR technology with robust SRL practices can lead to greater engagement, improved academic outcomes, and a deeper understanding of science concepts for middle school students.

# 3 Method

## 3.1 Research design

This study adopts an experimental design centered on a pre-test/post-test control group framework, allowing for an in-depth examination of two different approaches to AR-based gamification. Participants were randomly assigned to one of two groups, stratified according to their levels of digital literacy. The primary goal was to assess how these differing methodologies impact middle school students' conceptual understanding of scientific topics.

The experimental group utilized a SRL approach integrated with AR-based gamification. This approach was specifically crafted to encourage students to take control of their learning journeys by setting personal objectives, actively monitoring their own progress, and reflecting on their learning experiences. By incorporating game-like elements—such as rewards and interactive challenges—this method aimed to create a vibrant learning environment that stimulates motivation and fosters deeper engagement with the science curriculum. In contrast, the control group engaged with an ordinal AR-based gamification experience that did not incorporate self-regulatory features. While this method still utilized interactive AR tools to present scientific content, it lacked the structured framework of self-regulation. This means that students in this group were not encouraged to set personal learning goals or reflect systematically on their learning, potentially limiting their engagement and effectiveness in grasping complex scientific concepts.

Through this carefully structured experimental design, the study aims to elucidate the impact of SRL within the context of AR-based gamification. The pre-test/post-test methodology facilitates a thorough evaluation of knowledge acquisition, providing insights into how self-regulation can enhance the educational experience.

## 3.2 Sample

The sample for this study consisted of 60 middle school students from various public schools in Turkey, specifically focusing on the 6th grades, where students typically range from 13 to 14 years of age. Participants were equally divided into two groups, with 30 students in the experimental group utilizing an ARBG-SRL approach and 30 students in the control group experiencing an ordinal AR-based gamification method without self-regulation components.

Demographically, the sample maintained a balanced gender distribution, comprising approximately 28 male and 32 female students. Academic performance was also assessed prior to the intervention. Participants were stratified based on their average science grades from the previous academic year. Approximately 30% of the students had high achievement levels, with grades of 85% or above. In contrast, 50% of participants had moderate performance levels, scoring between 70% and 84%, while 20% of students faced challenges, with average grades below 70%. This stratification ensured a representative sample, allowing for meaningful comparisons between the two groups and a clearer understanding of the effectiveness of the SRL strategies integrated with AR-based gamification.

### 3.3 Data collection tools

To effectively evaluate the impact of the AR-based gamification intervention on middle school students' outcomes in science education, the study employed various tools to assess academic achievement, student engagement, satisfaction, and self-efficacy. Each tool was adapted or developed to fit the context of the study and provide robust insights into the students' experiences and learning outcomes.

#### 3.3.1 Academic achievement tests

The academic achievement tests were developed by the research team based on the specific content of the science curriculum covered during the intervention. The primary goal of these tests was to evaluate changes in students' understanding of scientific concepts before and after the AR-based gamification intervention. Both pre-test and post-test assessments were administered to collect data on student learning progress. The assessments consisted solely of 25 multiple-choice questions, each focusing on fundamental and critical scientific concepts that were part of the learning units. The maximum possible score for the test was 100 points, allowing for a standardized comparison of achievement across all participants. Each question was carefully designed to assess students' understanding of key concepts, ranging from basic recall of facts to applying knowledge in novel contexts. Since the achievement test consisted of multiple items that were all aimed at measuring the same underlying construct—namely, students' knowledge of scientific concepts—it was appropriate to use Cronbach's alpha to assess the reliability of the test. The Cronbach's alpha value for the academic achievement test was calculated to be 0.87, indicating a high level of internal consistency.

#### 3.3.2 Student engagement scale

The student engagement scale used in this study was adapted from the Student Engagement Scale developed by Wang et al. (2016). The scale comprised 33 items rated on a five-point Likert scale ranging from "strongly disagree" to "strongly agree," with 17 positively worded and 16 negatively worded questions. This scale was designed to evaluate four key dimensions of engagement: cognitive engagement, emotional engagement, behavioral engagement, and social engagement. Cronbach's alpha values for each dimension indicated high internal consistency and reliability, demonstrating that the items reliably measured each construct. Cognitive Engagement focused on the depth of students' learning strategies and their ability to apply self-regulated techniques to tackle complex ideas. A sample item for this dimension was: "I think about different approaches to solve a science problem." The Cronbach's alpha value for cognitive engagement was 0.88, indicating strong reliability in capturing students' use of deep learning strategies and problem-solving abilities. Emotional Engagement assessed students' emotional responses towards learning science, including interest in and enthusiasm for learning new topics. A sample item for this dimension was: "I enjoy learning new things about science." The Cronbach's alpha value for emotional engagement was 0.90, which showed high internal consistency in measuring positive and negative emotional reactions to the learning material. Behavioral Engagement measured the level of participation in academic activities, including the effort that students put into completing their learning tasks. A sample item for this dimension was: "I put effort into learning science topics covered in the AR-based activities." The Cronbach's alpha value for behavioral engagement was 0.85, which reflected a good level of reliability in assessing student participation and persistence in their academic efforts. Social Engagement evaluated the interactions students had with their peers and teachers, focusing on collaboration and support during the learning process. A sample item for this dimension was: "I try to help my classmates who are struggling with science concepts." The Cronbach's alpha value for social engagement was 0.89, indicating high reliability in assessing the quality and frequency of social interactions that supported learning. The Cronbach's alpha values for all four dimensions of the engagement scale—cognitive engagement (0.88), emotional engagement (0.90), behavioral engagement (0.85), and social engagement (0.89)—demonstrate that each aspect of engagement was measured with a high degree of reliability.

#### 3.3.3 Satisfaction questionnaire

The satisfaction questionnaire used in this study was adapted from the Learning Satisfaction Scale developed by Wiers-Jenssen, Stensaker, and Grogaard (2002). This questionnaire, consisting of 20 items, assessed students' satisfaction with different aspects of the AR-based gamification learning experience, including the ease of use of AR tools, the enjoyment derived from the learning activities, and the overall relevance of the content. The responses were collected on a five-point Likert scale, ranging from "very dissatisfied" to "very satisfied." Example items included statements such as "The AR-based activities helped me understand science concepts more clearly" and "I found the AR features enjoyable and engaging during my science lessons." By collecting data on satisfaction, the study sought to understand how well the intervention met students' expectations and to evaluate the extent to which the gamified AR environment was conducive to enjoyable and effective science learning.

#### 3.3.4 Self-efficacy scale

The self-efficacy scale used in the study was adapted from Bandura's Science Self-Efficacy Questionnaire (2006). This tool was designed to assess students' confidence in their ability to learn and perform science-related tasks with the support of AR-based gamification. The scale included eight items that gauged students' beliefs in their capacity to understand and succeed in science, such as "I am confident that I can understand the concepts taught using the AR-based tools" and "I can solve science problems even if they are challenging because of my AR-based experiences." Responses were recorded on a four-point Likert scale ranging from "not confident at all" to "very confident." This tool was integral to determining whether the AR-based gamification intervention positively impacted students' self-belief in their ability to succeed in science learning, which is a key predictor of academic success.

The research instruments, along with their aspects, validity, and reliability results, are summarized in Table 2, which provides an overview of the tools used to assess academic achievement, engagement, satisfaction, and self-efficacy in this study.

### 3.4 Ethical considerations

This study adhered to ethical guidelines for research involving human participants. Prior to the commencement of the study, ethical approval was obtained. Written informed consent was obtained from the parents or legal guardians of all participating students, ensuring their understanding of the study's purpose, procedures, and potential risks and benefits. To ensure the anonymity and confidentiality of the participants, all personal identifiers were removed from the data. Each participant was assigned a unique code for data collection and analysis purposes, and access to the data was restricted to the research team. Additionally, participation in the study was entirely voluntary, and students had the right to withdraw at any time without any negative consequences. The study also complied with the Declaration of Helsinki, ensuring that the rights and well-being of all participants were prioritized throughout the research process. By incorporating these measures, the study aimed to uphold the highest standards of ethical research in educational contexts.

**Table 2** Research instruments, aspects, validity and reliability results

| Instrument | Aspect/Indicator | Number of Items | Validity Results | Reliability (Cronbach's α) |
|---|---|---|---|---|
| Academic Achievement Test | Knowledge of Scientific Concepts | 25 | Expert Review: Content alignment confirmed by curriculum specialists. | 0.87 |
| | | | CFA: $\chi^2$/df = 1.89 (excellent fit), CFI = 0.95 (high model fit), RMSEA = 0.05 (close fit). | |
| Engagement Scale | Cognitive Engagement | 9 | CFA: $\chi^2$/df = 1.89 (good fit), CFI = 0.95, RMSEA = 0.05. Indicates strong construct validity. | 0.88 |
| | Emotional Engagement | 8 | | 0.90 |
| | Behavioral Engagement | 8 | | 0.85 |
| | Social Engagement | 8 | | 0.89 |
| Satisfaction Questionnaire | Enjoyment of AR-Based Activities | 10 | Content Validity Index (CVI) = 0.90: Items comprehensively represent satisfaction dimensions. | 0.88 |
| | Ease of Use | 10 | | |
| Self-Efficacy Scale | Confidence in Solving Science Tasks | 8 | CFA: $\chi^2$/df = 1.95 (acceptable fit), CFI = 0.94 (strong model fit), RMSEA = 0.05 (close fit). | 0.84 |

### 3.5 Data collection process

The experimental procedure spanned eight weeks in total, divided into distinct phases, with some weeks combined to ensure a comprehensive and well-structured intervention for both the experimental and control groups. The primary objective was to evaluate the effects of self-regulated AR-based gamification on middle school students' academic achievement, engagement, satisfaction, and self-efficacy in science education. This structure aimed to provide an in-depth analysis of how integrating self-regulation with AR-based gamification could impact various dimensions of students' learning experiences and outcomes in the field of science.

#### 3.5.1 Week 1: orientation and pre-testing

During the first week, an orientation session was conducted for both groups. The teacher introduced the study, explaining its objectives, how the AR-based gamification technology would be used, and the importance of learning in a self-regulated manner for the experimental group.

Students from both the experimental and control groups completed a pre-test that assessed their baseline understanding of science concepts relevant to the study. Additionally, students filled out self-efficacy questionnaires to measure their initial confidence and attitudes toward learning science. Furthermore, students were also assessed for engagement levels using a student engagement scale to evaluate their initial behavioral, emotional, cognitive, and social engagement in science learning activities. A satisfaction survey was also administered to gauge their initial perceptions and expectations regarding the learning experience, including their anticipated enjoyment and relevance of the science content. These measures were taken to establish a comprehensive baseline, allowing for a thorough evaluation of the impact of self-regulated AR-based gamification on academic achievement, engagement, satisfaction, and self-efficacy throughout the intervention.

#### 3.5.2 Weeks 2–3: introduction to AR tools and goal setting

During the second and third weeks, students were introduced to the AR-based gamification tools, which formed the foundation of their learning experience (Fig. 1). Both the experimental and control groups were familiarized with the interactive 3D models provided by the Virtuali-Tee app, which was purchased by the research team. This app allowed students to interact with 3D models of anatomical systems, such as the circulatory, respiratory, and digestive systems, and facilitated self-regulated learning strategies. For example, students set specific learning goals, such as identifying components of the circulatory system, and tracked their progress using built-in quizzes and performance dashboards. The app's interactive features provided immediate feedback, enabling students to adjust their strategies in real time, such as revisiting models or repeating quizzes to reinforce understanding. Using either t-shirts or printed AR markers, students scanned these markers with their mobile devices to trigger immersive visual content, making scientific concepts both engaging and tangible.

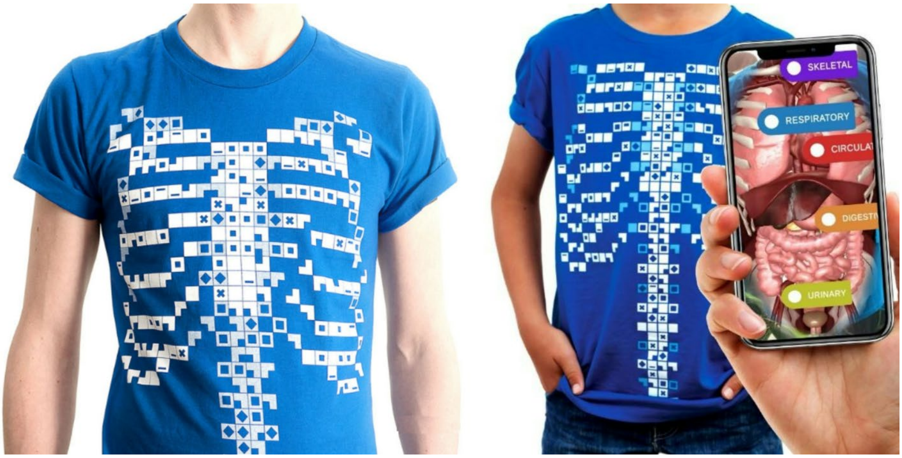


**Fig. 1** Virtuali-Tee AR Learning T-Shirt Featuring an Interactive Ribcage Design

For the experimental group, additional training was provided on how to integrate self-regulation tools into their learning journey. This included lessons on setting specific, measurable learning goals and utilizing the self-regulated monitoring platform integrated within the app. Teachers played a critical role in guiding students through these processes by setting clear expectations for goal-setting and providing real-time feedback during AR activities. For instance, teachers reviewed students' progress logs and suggested adjustments in learning strategies, such as revisiting 3D models or repeating quizzes to strengthen weak areas. This guidance helped ensure that students actively engaged with the self-regulated learning components and maximized the potential of the AR tools. Students learned how to develop personalized goals related to understanding the detailed workings of human body systems. Examples of objectives included "Identify the major components of the circulatory system" or "Understand the role of oxygen in cellular respiration."

Furthermore, students in the experimental group were guided on how to track their progress by documenting their goals and identifying the steps necessary to achieve them within the AR-based environment. The app offered designated spaces for students to log their target scores, track their understanding of key concepts, and outline specific strategies—such as revisiting particular 3D models multiple times or using quizzes to deepen their knowledge. The self-regulated monitoring platform facilitated ongoing goal-setting and progress tracking, promoting greater student autonomy and self-directed learning.

The Adaptive Feedback Module provided immediate and personalized feedback to students, enabling them to reflect on their progress and make adjustments to their learning strategies as needed. This continuous feedback loop allowed students to refine their approaches, improving their understanding and making their learning more efficient and effective. The goal-setting process was a critical component of the SRL approach, designed to foster student autonomy and a deeper commitment to mastering the material.

Meanwhile, the control group also interacted with the AR content but without the guidance of structured self-regulation tools. They explored the same anatomical models and participated in similar quizzes and visualizations, but without the explicit focus on goal-setting, self-monitoring, or reflective activities. Consequently, their experience was characterized by passive engagement with the AR content, providing a direct comparison between a gamified AR experience with and without SRL components.

By equipping the experimental group with tools that enabled them not only to engage with the AR content but also to actively regulate and personalize their learning, this phase of the study aimed to determine how integrating self-regulation strategies into an AR-based environment could influence learning outcomes, engagement, and overall satisfaction. The distinction between the structured, self-regulated AR experience for the experimental group and the unstructured AR experience for the control group offered an opportunity to understand the added value of SRL practices within an immersive, technology-enhanced science education setting.

#### 3.5.3 Weeks 4–5: content learning with AR-based gamification

During weeks four and five, students from both the experimental and control groups engaged in an in-depth exploration of science topics using the AR-based gamification application. The app provided interactive 3D models that enabled students to visualize and explore the circulatory, respiratory, and digestive systems, transforming abstract biological processes into tangible, engaging content. The AR experience allowed students to see structures such as the heart, lungs, and digestive organs functioning in real time, making these scientific concepts more accessible and enhancing the immersive nature of the learning experience.

For the experimental group, the learning experience was significantly enhanced by the self-regulation features embedded within the AR-SRL system. Students in the experimental group were actively encouraged to track their progress, utilizing the app's self-regulated monitoring platform to reflect on their learning journey throughout this content learning phase. During the forethought phase, students were instructed to set specific, measurable goals, such as achieving a minimum score on the respiratory system quiz or identifying key functions of the heart in the circulatory system. In the performance phase, students engaged with interactive AR models to explore biological systems and completed quizzes to test their understanding. The monitoring phase involved students using the app's dashboard to track their quiz scores and compare them against their initial goals, while also revisiting challenging sections of the AR models as needed. Teachers facilitated reflective journaling during the reflection phase, prompting students to evaluate their learning strategies, identify areas for improvement, and plan next steps for mastering the content.

As students worked through the AR content, they used the self-regulated monitoring process to adjust their initial learning goals based on their current performance and the challenges they encountered. For instance, a student who struggled with identifying blood flow pathways in the circulatory system could modify their learning strategies—such as revisiting interactive 3D animations or spending more time on specific segments of the heart. This personalized learning adjustment was supported by the adaptive feedback module integrated within the app, which offered instant, individualized feedback. This feedback loop allowed students to reflect, self-assess, and adjust their learning approaches accordingly, enhancing their self-regulatory skills.

To further engage students, both groups participated in gamified quizzes that included various formats such as multiple-choice questions, matching activities, and fill-in-the-blank tasks. However, the experimental group experienced additional benefits from the gamification features integrated into the app, such as earning points, unlocking digital badges, and using leaderboards to promote engagement. For instance, a student who correctly answered questions on the function of the respiratory system earned points towards a "Respiratory System Expert" badge. These gamified elements acted as motivational tools, encouraging students to remain engaged and persevere through challenging material. The leaderboard allowed students to see their progress relative to their peers, fostering a sense of healthy competition and achievement.

The control group also participated in the same AR learning activities and completed the corresponding quizzes, but without the explicit self-regulation framework or motivational features provided to the experimental group. Although the control group benefited from the immersive AR content, their experience lacked the structured opportunities for goal setting, receiving motivational rewards, or reflecting on their learning progress. As a result, their interaction with the content was primarily reactive, focusing on the given tasks without actively regulating their learning journey.

The gamified quizzes served dual purposes: they acted as formative assessments that helped both teachers and students monitor learning progress and were designed to sustain student motivation by adding an enjoyable, competitive element to the learning process. For the experimental group, earning points, badges, and seeing progress on the leaderboard instilled a sense of accomplishment and provided additional motivation for improvement.

This phase of the intervention demonstrated how combining AR technology with gamification and SRL elements can transform learning from a passive experience into an active, student-driven process. By encouraging students to set their own goals, monitor their progress, and adjust their strategies, the experimental group not only engaged more deeply with the science content but also developed critical competencies in self-regulation and self-reflection. These features distinguished the learning experiences between the experimental and control groups, laying a foundation for assessing the effectiveness of AR-based gamified learning in fostering student autonomy, engagement, and a deeper understanding of scientific concepts. Figure 2 shows the AR-based tool, which students used to explore anatomical systems, including the circulatory, respiratory, and digestive systems during weeks four and five of the intervention.

#### 3.5.4 Weeks 6–7: in-depth learning and problem-solving activities

During weeks six and seven, students from both the experimental and control groups focused on exploring more complex science topics using the AR-based application.

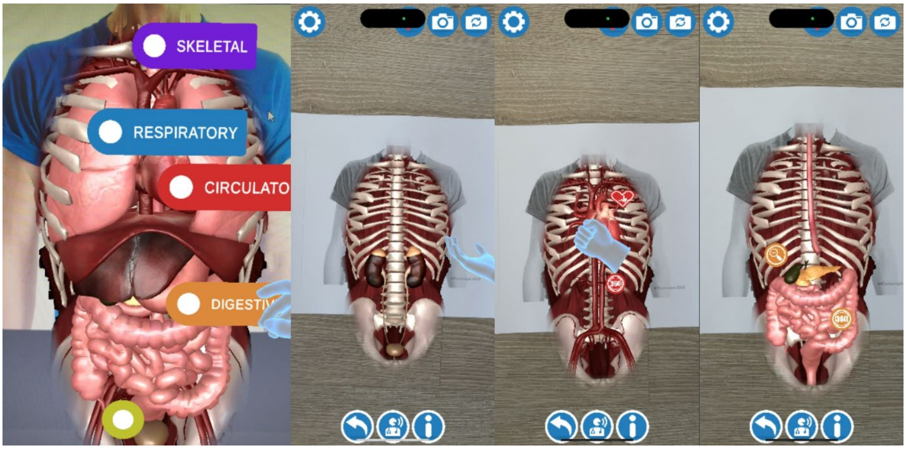


**Fig. 2** Examples of interfaces for the app providing AR-based gamification content learning tools

At this stage, the emphasis was on deepening their understanding of the circulatory, respiratory, and digestive systems, particularly targeting intricate processes such as gas exchange in the alveoli, nutrient absorption in the intestines, and the regulation of heart rate. The app provided an enriched, interactive visual experience, enabling students to observe these complex processes in detail, thus improving their comprehension of the intricacies of human anatomy and physiology.

The experimental group was continuously supported by the self-regulation techniques integrated into the AR-SRL system. Throughout these weeks, students actively engaged in evaluating their previous learning sessions by analyzing quiz performance and using progress-tracking data to reassess and refine their learning strategies. Based on their quiz results, students set new, more challenging learning targets for understanding complex concepts, such as the mechanisms behind oxygen and carbon dioxide exchange in the respiratory system. The self-regulated monitoring platform delivered personalized feedback, allowing students to identify areas requiring further attention and adjust their study approach accordingly.

To support this in-depth learning, the teacher utilized data collected from both groups—such as common quiz errors and areas where students struggled—to identify prevalent misconceptions among students. This data-driven approach enabled the teacher to provide targeted support to both groups, addressing specific issues that could impede further understanding. For example, if a significant number of students demonstrated difficulty in understanding how nutrients are transported through the bloodstream, the teacher conducted a focused instructional session to clarify these points, utilizing the AR visuals to make the concepts more concrete and accessible.

In week seven, students participated in collaborative problem-solving sessions that were designed to deepen their understanding of the complex scientific concepts they had been exploring individually. The experimental group was encouraged to take responsibility within their teams by employing collective goal-setting and engaging in group reflection on their learning processes. They worked together to set specific group objectives, such as "Fully understand how the respiratory and circulatory systems work together to supply oxygen to the body." During these problem-solving sessions, the system was used collaboratively, allowing team members to interact with the 3D models, share insights, and address each other's questions.

The self-regulation framework used by the experimental group added value to these collaborative sessions by emphasizing the importance of reflection and adjustment. Students not only tackled content challenges but also discussed their learning strategies, evaluated what worked effectively and what did not, and made collective decisions to enhance their group performance. This approach fostered a heightened level of accountability and responsibility, contributing significantly to their development of both content knowledge and essential collaborative skills.

The control group also participated in these collaborative sessions but focused primarily on completing assigned tasks and activities without a structured self-regulation framework. While they benefited from the AR-based exploration of complex topics and the collaborative setting, they lacked the emphasis on reflective practices and strategic goal-setting that characterized the learning process of the experimental group. As a result, their interaction with the content was more reactive and lacked the explicit processes of evaluating progress or setting learning goals that could have led to a deeper understanding.

The problem-solving activities conducted during weeks six and seven highlighted notable differences between the groups in terms of how they approached learning. The experimental group, utilizing a combination of AR-based gamification, SRL, and collaborative activities, demonstrated higher levels of engagement and autonomy. By using the AR-SRL system as both an individual and group learning tool, these students were able to actively explore scientific concepts, evaluate their understanding, and modify their learning strategies collectively, thereby maximizing the educational benefits of the AR content and their collaborative efforts.

#### 3.5.5 Week 8: post-testing and reflection

In the final week, both groups completed a post-test, similar to the pre-test, to evaluate the overall changes in their academic achievement regarding the science concepts covered during the study. In addition to the post-test, students also completed self-efficacy questionnaires, engagement surveys, and satisfaction questionnaires to measure the intervention's impact on their confidence, level of engagement, and satisfaction with the learning experience. This allowed for comparison of learning gains between the experimental and control groups. The experimental group engaged in a comprehensive self-reflection exercise. They reviewed their progress against the goals set at the beginning of the study and provided a detailed self-evaluation of what strategies worked for them, which didn't, and what they would do differently. The control group participated in a similar but less structured reflection activity. The comprehensive database generated personalized feedback reports for the experimental group, based on their learning logs, quiz performances, and reflective evaluations. These reports included suggestions for further improvement. The control group received general feedback based on their quiz performance and in-class activities. Detailed summary of the experimental procedure is involved in Table 3.

**Table 3** Detailed summary of the experimental procedure

| Week(s) | Activities for Experimental and Control Groups | Specific Activities for Experimental Group | Specific Activities for Control Group |
|---|---|---|---|
| Week 1 | Orientation and Pre-Testing: Introduction to study objectives, AR tools, self-efficacy, engagement, and satisfaction questionnaires, pre-test assessments. | Explained the importance of self-regulation and goal setting. | Understood basic procedures without emphasis on self-regulation or goal setting. |
| Weeks 2–3 | Introduction to AR Tools and Goal Setting: Introduction to AR-based tools and an app to explore human body systems. | Training on setting personalized learning goals using the self-regulated monitoring platform. Practiced tracking learning progress and logging goals within the app. | Interaction with AR content but without structured tools for goal setting or progress tracking. |
| Weeks 4–5 | Content Learning with AR-Based Gamification: Deep engagement with AR models to understand the circulatory, respiratory, and digestive systems. | Used self-regulation features for goal setting, monitoring, and reflection. Adaptive Feedback Module provided instant feedback, badges earned as motivational elements. | Participated in AR activities and quizzes without structured opportunities for self-regulation or personalized motivational elements. |
| Weeks 6–7 | In-Depth Learning and Problem-Solving Activities: Focused on more complex topics (e.g., gas exchange, nutrient absorption, heart rate regulation). | Self-regulation framework emphasized progress tracking and reflection on learning sessions. Collaborative sessions emphasized group reflection and collective goals. | Engaged in problem-solving tasks but without structured self-regulation, focusing only on completing activities. |
| Week 8 | Post-Testing and Reflection: Completion of post-test and reflection exercises to evaluate overall changes in learning outcomes and other measures. | Comprehensive reflection on learning strategies and progress against goals, guided by the monitoring platform. Personalized feedback reports provided. | Less structured reflection activity, with general feedback provided based on quiz performance and in-class activities. |

### 3.6 Data analysis

To analyze the effects of ARBG-SRL on students' academic achievement, engagement, satisfaction, and self-efficacy, various statistical methods were employed. The data analysis process included prerequisite tests to ensure the validity of the chosen statistical techniques, followed by hypothesis testing to evaluate the research objectives.

Before conducting hypothesis tests, several assumptions were examined to validate the statistical approach. The Shapiro-Wilk test was used to assess the normality of the data distribution for dependent variables, including academic achievement, engagement, satisfaction, and self-efficacy. This ensured that the data met the assumptions required for parametric tests. Levene's Test was conducted to confirm that the variances of the dependent variables were equal across the experimental and control groups. This is a critical assumption for the use of analysis of covariance (ANCOVA). For ANCOVA, the homogeneity of regression slopes was tested to ensure that the relationship between the covariates, such as pre-test scores, and the dependent variables, such as post-test scores, was consistent across groups.

The following statistical methods were applied to test the study's hypotheses. ANCOVA was utilized to compare the post-test scores of the experimental and control groups for academic achievement, engagement, satisfaction, and self-efficacy. Pre-test scores were included as covariates to control for baseline differences between the groups. Adjusted means were calculated for post-test scores to provide a more accurate comparison. Partial eta-squared ($\eta^2$) was calculated for each ANCOVA result to determine the magnitude of the observed effects. When significant differences were identified, pairwise comparisons with Bonferroni adjustments were conducted to identify the specific groups contributing to the differences.

All statistical analyses were performed using SPSS. The significance level ($\alpha$) was set at 0.05 for all tests. Descriptive statistics, such as means and standard deviations, were reported to provide a comprehensive overview of the data.

By employing rigorous statistical techniques, including assumption testing and hypothesis evaluation, the study ensured the reliability and validity of its findings. These analyses aimed to provide robust insights into the effects of ARBG-SRL on key educational outcomes.

# 4 Findings

## 4.1 Academic performance

To evaluate the impact of the ARBG-SRL approach compared to the traditional AR-based gamification approach on students' academic performance in science, the one-way analysis of covariance (ANCOVA) was utilized. The post-test scores served as the dependent variable, the learning approach was the independent variable, and the pre-test scores were used as the covariate to control for initial differences in academic performance between groups.

First, the basic assumptions of ANCOVA were tested. The homogeneity of variances was assessed using Levene's test for equality of error variances, which resulted in $F(1, 58)=1.45$, $p=0.23>0.05$. With a p-value greater than 0.05, the null hypothesis of equal variances was accepted, indicating homogeneity between groups. Additionally, the homogeneity of regression slopes was tested to verify that the relationship between the pre-test and post-test scores was consistent across groups. The test yielded $F(1, 56)=0.78$, $p=0.38>0.05$, confirming that the assumption was met, allowing ANCOVA to proceed.

Table 4 presents the ANCOVA results for the academic performance of students in both the ARBG-SRL approach and traditional AR-based gamification approach. The results showed that the mean post-test score for the experimental group was 78.9 with an adjusted mean of 79.1, while the mean post-test score for the control

**Table 4** ANCOVA results for academic performance

| Group | *N* | Mean | SD | Adjusted Mean | Std. Error | F | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|---|---|
| Experimental | 30 | 78.9 | 4.3 | 79.1 | 0.78 | 10.25 | 0.002 | 0.15 |
| Control | 30 | 72.4 | 5.6 | 72.6 | 0.78 | | | |

Note. $p<0.01$

group was 72.4 with an adjusted mean of 72.6. After adjusting for the covariate (pre-test scores), the difference between the two groups was statistically significant, as indicated by $F(1, 57) = 10.25$, $p = 0.002 < 0.01$, $\eta^2 = 0.15$. This result suggests that the ARBG-SRL approach significantly improved students' academic performance compared to the traditional AR-based approach, accounting for 15% of the variance in post-test scores.

The significant differences in adjusted means indicate that students in the ARBG-SRL approach group demonstrated higher academic achievement, benefiting from the integration of self-regulation strategies alongside AR-based gamification. The self-regulated environment likely encouraged students to set specific learning goals, monitor their progress, and engage deeply with the content, leading to superior outcomes compared to those who did not utilize self-regulation techniques.

### 4.2 Student engagement

To evaluate the impact of the ARBG-SRL approach on student engagement in comparison to the traditional AR-based gamification approach, the ANCOVA was conducted. The student engagement levels were measured using an engagement scale that covered four dimensions: behavioral, emotional, cognitive, and social engagement. The post-test engagement scores were used as the dependent variable, while the pre-test engagement scores were treated as covariates, with the learning approach being the independent variable.

Before proceeding with the ANCOVA, the assumptions were tested. Levene's test was conducted to verify the homogeneity of variances, resulting in $F(1, 58) = 2.01$, $p = 0.16 > 0.05$, which indicated that the assumption of equal variances was met. Furthermore, the homogeneity of regression slopes was also tested and yielded $F(1, 56) = 0.93$, $p = 0.34 > 0.05$, confirming that ANCOVA could be appropriately conducted.

Table 5 presents the ANCOVA results for student engagement levels. The results indicated that the mean post-test engagement score for the experimental group was 4.12 with an adjusted mean of 4.15, while the mean post-test score for the control group was 3.65 with an adjusted mean of 3.68. After accounting for pre-test engagement scores, the difference between the two groups was statistically significant, as shown by $F(1, 57) = 12.48$, $p = 0.001 < 0.01$, $\eta^2 = 0.18$. This suggests that the ARBG-SRL approach led to significantly higher engagement levels compared to the traditional AR-based approach, accounting for 18% of the variance in engagement scores.

The significant difference in engagement levels indicates that the inclusion of self-regulation components—such as goal-setting, self-monitoring, and reflective learning—enhanced student engagement across all dimensions (behavioral, emotional, cognitive, and social). The experimental group demonstrated greater involvement, enthusiasm, persistence, and collaborative effort during the learning process, show-

**Table 5** ANCOVA results for student engagement

| Group | *N* | Mean | SD | Adjusted Mean | Std. Error | F | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|---|---|
| Experimental | 30 | 4.12 | 0.41 | 4.15 | 0.05 | 12.48 | 0.001 | 0.18 |
| Control | 30 | 3.65 | 0.52 | 3.68 | 0.05 | | | |

ing that the combination of AR-based gamification and SRL effectively fostered more profound engagement with the material.

### 4.3 Student satisfaction

To explore the impact of ARBG-SRL approach on student satisfaction compared to the traditional AR-based gamification approach, a ANCOVA was conducted. The student satisfaction levels were assessed through a questionnaire administered at both the beginning and the end of the study, with the post-test scores used as the dependent variable, pre-test satisfaction scores serving as the covariate, and the learning approach (self-regulated AR-based gamification vs. traditional AR-based gamification) as the independent variable.

Before performing ANCOVA, the assumptions for analysis were verified. Levene's test for homogeneity of variances was conducted, resulting in $F(1, 58) = 1.78$, $p = 0.19 > 0.05$, indicating that the assumption of equal variances was met. Additionally, the homogeneity of regression slopes was confirmed, with $F(1, 56) = 0.82$, $p = 0.37 > 0.05$, allowing for ANCOVA to proceed.

Table 6 presents the ANCOVA results for student satisfaction. The mean post-test satisfaction score for the group using the ARBG-SRL approach was 4.25, with an adjusted mean of 4.28, while the mean post-test satisfaction score for the traditional AR-based gamification group was 3.78, with an adjusted mean of 3.81. After adjusting for the covariate (pre-test scores), a significant difference was observed between the groups, with $F(1, 57) = 14.05$, $p = 0.0005 < 0.01$, $\eta^2 = 0.20$. These results indicate that the ARBG-SRL approach significantly increased student satisfaction compared to the traditional approach, accounting for 20% of the variance in satisfaction levels.

The higher adjusted mean satisfaction scores in the group exposed to ARBG-SRL approach suggest that students found the learning experience more enjoyable, engaging, and effective when self-regulation strategies—such as goal-setting, progress tracking, and reflection—were incorporated. The interactive, gamified learning environment coupled with elements of self-directed learning made the activities more relevant and meaningful, thereby enhancing students' overall satisfaction with the learning process.

### 4.4 Student self-efficacy

To investigate the impact of the ARBG-SRL approach on students' self-efficacy in science learning compared to the traditional AR-based gamification approach, ANCOVA was performed. The self-efficacy scores were obtained from a self-efficacy scale administered both before and after the intervention, with post-test scores used

**Table 6** ANCOVA results for student satisfaction

| Group | *N* | Mean | SD | Adjusted Mean | Std. Error | F | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|---|---|
| Self-Regulated AR-based Gamification | 30 | 4.25 | 0.43 | 4.28 | 0.06 | 14.05 | 0.0005 | 0.20 |
| Traditional AR-based Gamification | 30 | 3.78 | 0.51 | 3.81 | 0.06 | | | |

**Table 7** ANCOVA results for student Self-Efficacy

| Group | *N* | Mean | SD | Adjusted Mean | Std. Error | F | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|---|---|
| Self-Regulated AR-based Gamification | 30 | 4.30 | 0.40 | 4.33 | 0.06 | 11.87 | 0.001 | 0.17 |
| Traditional AR-based Gamification | 30 | 3.85 | 0.48 | 3.88 | 0.06 | | | |

as the dependent variable, pre-test scores as the covariate, and the learning approach (ARBG-SRL approach vs. traditional AR-based gamification) as the independent variable.

Prior to conducting the ANCOVA, essential assumptions were tested to validate the analysis. Levene's test for homogeneity of variances was performed, resulting in $F(1, 58) = 1.92$, $p = 0.17 > 0.05$, indicating that the variances between the two groups were homogeneous. Furthermore, the homogeneity of regression slopes was confirmed, with $F(1, 56) = 0.89$, $p = 0.35 > 0.05$, allowing for the ANCOVA to proceed.

Table 7 presents the ANCOVA results for student self-efficacy. The mean post-test self-efficacy score for the group using the ARBG-SRL approach was 4.30, with an adjusted mean of 4.33, while the mean post-test self-efficacy score for the traditional AR-based gamification group was 3.85, with an adjusted mean of 3.88. The ANCOVA results showed a significant difference between the two groups, with $F(1, 57) = 11.87$, $p = 0.001 < 0.01$, $\eta^2 = 0.17$. These findings indicate that the ARBG-SRL approach significantly increased students' self-efficacy in learning science, accounting for 17% of the variance in post-test self-efficacy scores. The higher adjusted mean score in the ARBG-SRL approach group suggests that incorporating self-regulation strategies, such as goal-setting, self-monitoring, and reflective practices, positively impacted students' beliefs in their abilities to learn and succeed in science.

# 5 Discussion

## 5.1 Summary of results

The results of this study revealed significant differences between the ARBG-SRL approach and the traditional AR-based gamification approach across several key dimensions. Firstly, the findings indicated that students in the ARBG-SRL approach showed higher academic achievement compared to those in the traditional approach. This suggests that the inclusion of self-regulation strategies, such as goal-setting, self-monitoring, and reflection, positively influenced students' mastery of scientific concepts. Secondly, the ARBG-SRL approach led to significantly higher student engagement levels across all four measured dimensions: behavioral, emotional, cognitive, and social engagement. This demonstrates that the combination of self-regulation elements and AR-based gamification fostered greater involvement, enthusiasm, and collaboration among students. Thirdly, student satisfaction with the learning experience was significantly higher in the group exposed to the ARBG-SRL approach. Students in this group reported greater enjoyment and perceived relevance of the learning activities, which suggests that the integration of personalized learning strategies enhanced the overall quality of the educational experience. Finally, the findings also showed that students in ARBG-SRL approach had significantly higher self-efficacy in science learning. These students felt more confident in their ability to understand and apply scientific concepts compared to those in the traditional AR-based approach. This indicates that self-regulation strategies played a critical role in building students' confidence and motivation.

### 5.2 Theoretical implications

The findings of this study contribute several important theoretical implications regarding the integration of AR, gamification, and SRL strategies in science education. The results align with and extend constructivist learning theory and SRL theory, reinforcing the benefits of combining interactive and reflective elements within educational technologies to enhance learning outcomes.

Constructivist learning theory posits that learners actively construct their own understanding through direct interaction with learning materials (Vygotsky, 1978). In line with this theoretical foundation, the current study demonstrates how AR—by offering immersive and visually interactive experiences—helps students to engage in experiential learning, making complex scientific concepts more comprehensible. This supports earlier findings, such as those by Chen et al. (2023a, b), which highlighted that AR environments allow learners to interact with digital overlays that represent abstract scientific concepts, thereby enhancing conceptual understanding. The use of AR in the current study similarly provided students with engaging, interactive learning scenarios that made abstract content tangible, validating the notion that AR contributes to active learning and knowledge construction.

The implications extend further when considering the role of SRL, which involves processes such as goal-setting, self-monitoring, and reflective learning (Zimmerman, 2002). The integration of SRL strategies into an AR-based gamified environment enables students to not only visualize science content but also regulate their learning journey in a structured way. This aligns with Palalas and Wark (2020), who emphasized that SRL practices enhance autonomy, persistence, and self-motivation in learners, particularly when combined with adaptive learning technologies. In this study, students exposed to the self-regulated AR-based environment demonstrated greater academic achievement, engagement, satisfaction, and self-efficacy compared to those exposed to a traditional AR-based environment. This suggests that self-regulation not only complements the immersive features of AR but also enhances its impact by fostering goal-directed behaviors that are key to deeper learning (Chen et al., 2024a, b).

Self-efficacy, a construct rooted in Bandura's social cognitive theory (Bandura, 1999), emerged as a significant factor positively influenced by the self-regulated AR-based gamification. Earlier studies (e.g., Carroll et al., 2024) highlighted that self-efficacy is crucial for academic success, especially in challenging fields like science. The findings of this study indicate that students in the self-regulated group exhibited higher self-efficacy compared to those in the traditional group, which can be attributed to consistent successes achieved through the structured AR environment, personalized feedback, and opportunities for goal setting. These elements of self-regulation and gamified feedback fostered students' confidence in their ability to master scientific concepts, ultimately resulting in enhanced self-efficacy (Li et al., 2022). This finding extends Bandura's theory by demonstrating that technology-enhanced environments that support self-regulated behaviors can significantly enhance learners' confidence and resilience in science.

Gamification elements, such as badges, points, and levels, are theorized to enhance motivation by adding an element of challenge and reward to learning (Zhang & Yu, 2022). In this study, these elements were not only present but strategically integrated with SRL components, which seems to have shifted students' motivation from extrinsic to more intrinsic forms. Earlier studies (e.g., Kim & Castelli, 2021) indicated that gamification could lead to short-term increases in engagement through extrinsic motivation. However, the findings of this study suggest that combining gamification with SRL enables a deeper and more sustained form of engagement. When students were involved in setting their own learning goals and reflecting on their achievements, the motivational benefits of gamification became more personalized and intrinsic, which is a novel insight extending the existing literature on gamified learning environments.

When comparing these findings with previous studies, there are notable alignments and extensions. Earlier research involving collaborative AR tools in science education indicated enhanced student motivation and social engagement, but the focus was often limited to collaboration among peers (Ateş, 2024a). The current study expands on these findings by demonstrating that self-regulated AR-based gamification can significantly enhance not only social engagement but also cognitive, behavioral, and emotional engagement. This multi-dimensional increase in engagement highlights the importance of incorporating both self-regulatory strategies and gamification to support a richer, more comprehensive engagement with the learning material.

Furthermore, the impact on student satisfaction observed in this study aligns with findings from previous research that linked interactive and personalized learning experiences with greater learner satisfaction (Alamri et al., 2020). Students in the self-regulated AR group reported higher satisfaction due to the personalized nature of the learning activities, which offered them control over their learning processes while making the learning experience enjoyable. This suggests that gamified AR environments, when integrated with SRL elements, do not merely make learning enjoyable but also significantly enhance the perceived quality and value of the educational experience.

The theoretical implications of this study suggest a new model for designing technology-enhanced learning environments. The combination of AR, gamification, and SRL strategies serves as a comprehensive approach that enhances multiple dimensions of learning outcomes, including academic performance, engagement, satisfaction, and self-efficacy. This supports and extends constructivist learning theory by emphasizing the importance of active, goal-directed, and reflective learning in immersive environments. Moreover, the findings imply that future research should focus on the customization of AR-based content that aligns with individual learners' needs and preferences, thus maximizing the benefits of SRL and gamification.

### 5.3 Practical implications

The findings of this study offer several practical implications for educators, instructional designers, and policymakers interested in improving science education outcomes through innovative technological approaches. The integration of SRL strategies with AR-based gamification has demonstrated significant potential for enhancing not only academic achievement but also student engagement, self-efficacy, and overall satisfaction. This holistic impact suggests that AR-based gamification environments, particularly when enriched with self-regulation elements, can provide an immersive and empowering learning experience that extends beyond mere content delivery.

In practice, educators are encouraged to integrate SRL strategies into AR-based learning environments to maximize their effectiveness. The use of structured components such as goal-setting, progress monitoring, and reflection is crucial to helping students take ownership of their learning journey. Teachers can facilitate these processes by guiding students in defining personalized goals, encouraging reflective practices, and supporting the development of metacognitive skills. By doing so, the AR-based gamification approach not only enhances academic performance but also fosters a sense of autonomy and lifelong learning, which are critical skills for navigating complex scientific content.

Another key implication involves the importance of increasing student engagement through interactive and reflective learning tools. This study found that AR-based gamified environments significantly increased engagement across behavioral, emotional, cognitive, and social dimensions. Teachers should utilize AR tools that incorporate game-based elements such as badges, points, and challenges to create a more dynamic and engaging classroom experience. The gamified features can be coupled with SRL practices to not only sustain students' interest but also promote a deeper level of involvement in the learning process. These findings imply that educators should go beyond using AR merely as a novel tool; instead, it should be part of a comprehensive strategy that involves encouraging students to regulate their learning behaviors and actively engage with the material.

Student self-efficacy also emerged as a critical outcome positively affected by the ARBG-SRL approach. This highlights the practical importance of providing personalized and immediate feedback within AR environments. Teachers should leverage the data collected from AR tools to offer individualized feedback, reinforcing students' successes and helping them to feel confident in their ability to master challenging scientific concepts. This approach supports students in building resilience and self-belief, which are crucial for maintaining motivation, especially in challenging subject areas like science. By cultivating self-efficacy, the AR-based gamified environment ensures that students are not only acquiring knowledge but also developing the confidence to apply it effectively.

Additionally, this study underscores the need for educators to design learning environments that not only enhance academic achievement but also increase student satisfaction with their learning experiences. Satisfaction was significantly higher among students who engaged with the self-regulated AR-based gamification, suggesting that the perceived relevance and enjoyment of learning activities play an essential role in shaping educational experiences. Teachers and instructional designers should aim to create AR-based activities that are both pedagogically sound and enjoyable, emphasizing the practical value of using engaging visuals, interactive tasks, and self-directed exploration to make learning more attractive and meaningful for students.

The successful implementation of these innovations also requires adequate teacher training. Integrating SRL with AR-based gamification is a complex task that demands not only technological know-how but also an understanding of SRL pedagogical principles. Therefore, teacher professional development should focus on equipping educators with the skills needed to design, implement, and facilitate AR-enhanced SRL environments effectively. Policies that support continuous professional development for teachers and the acquisition of technology resources in schools are essential for the effective implementation of these innovative teaching practices.

Moreover, given the diversity in students' learning preferences, the study emphasizes the importance of tailoring AR-based content to meet different learner needs. The ability of AR tools to provide adaptive, personalized content allows teachers to differentiate instruction more effectively, ensuring that all students are able to engage with science content at their own pace and according to their unique learning paths. This is particularly useful in science education, where students often need different levels of support and challenges to stay motivated and achieve their learning goals. Adaptive AR environments thus provide an opportunity for creating inclusive educational experiences that cater to a wide range of learners, including those who may require additional support or those seeking more advanced challenges.

Finally, collaborative elements should be integrated into AR-based gamified learning environments to further enhance engagement and learning outcomes. While the current study primarily focused on individual self-regulation, the potential for collaborative learning within these environments is significant. Educators can use AR-based tools to facilitate group work, encourage peer learning, and promote social interactions that are essential for scientific inquiry and problem-solving. Collaborative tasks using AR can lead to greater student agency and improved interpersonal skills, which are increasingly recognized as critical components of 21st-century education.

### 5.4 Limitations and suggestions for future researchers

Despite the promising findings of this study, several limitations need to be acknowledged, which also point toward opportunities for future research.

One notable limitation concerns the sample size and representativeness. The study was conducted with a relatively small sample of middle school students, all of whom were from a similar geographic and educational background. This limits the generalizability of the findings to broader populations, as the effects of AR-based gamification and SRL might vary depending on cultural, socio-economic, and regional contexts. Future researchers are encouraged to conduct studies with larger and more diverse samples to determine whether the positive impacts observed in this study can be replicated across different educational settings and demographics.

Additionally, the duration of the intervention was limited to eight weeks, which may have been insufficient for capturing long-term effects of AR-based gamification on various learning outcomes, such as sustained motivation and knowledge retention. The short-term nature of the study means that while improvements in academic achievement, engagement, satisfaction, and self-efficacy were observed, it remains unclear whether these benefits would persist over a longer period or translate into other academic areas. Future research could extend the duration of interventions to examine the long-term impact of integrating AR-based gamified learning environments with SRL strategies and their sustained effects on students' academic development and attitudes toward learning.

Another limitation is the absence of qualitative data on students' subjective experiences with AR-based SRL activities. While quantitative measures provided robust insights into academic performance, engagement, satisfaction, and self-efficacy, this study did not include data from student interviews, focus groups, or observations. Incorporating qualitative perspectives would have enriched the findings by offering a deeper understanding of how students perceive and interact with these technologies. Unfortunately, due to time constraints and the conclusion of the intervention, collecting qualitative data retrospectively was not feasible. Future researchers are encouraged to adopt a mixed-methods approach that combines quantitative and qualitative data to capture both measurable outcomes and the nuanced experiences of students. Such an approach could illuminate specific elements of the intervention that are most effective or engaging from the students' perspective.

The technological infrastructure required for AR-based gamification presents another limitation, particularly for schools with limited resources. This study assumed that all participants had access to appropriate devices, reliable internet connections, and supportive digital infrastructure, which may not be feasible for many educational settings. Future research should consider exploring the use of AR-based SRL in resource-constrained environments to understand how the findings might differ when technological access is limited. Additionally, studies could focus on developing more accessible versions of AR tools that can be used in schools with varying levels of technological readiness.

In terms of teacher involvement, this study did not explicitly account for the varying degrees of teacher facilitation required in AR-based gamified environments. Although teachers played a supportive role in guiding students through SRL strategies, the extent of this involvement was not systematically analyzed. It remains uncertain whether variations in teacher support might impact the effectiveness of the intervention. Future research could explore the role of teacher facilitation more explicitly, including investigating how different levels of teacher guidance affect student outcomes in AR-based SRL environments. Understanding the teacher's role is crucial to determine how much autonomy students can have while still receiving the scaffolding they need to succeed.

The measurement tools used in this study also present a limitation. Although validated scales were used to assess engagement, satisfaction, and self-efficacy, these measures rely on self-reported data, which may be subject to response biases such as social desirability or exaggerated reporting. Future studies might benefit from including more objective measures of engagement and learning, such as behavioral analytics collected from the AR platform itself (e.g., time spent interacting with AR content, frequency of goal-setting activities, etc.). This would provide a richer, more nuanced picture of how students are engaging with the AR environment and how their behaviors relate to the observed outcomes.

Lastly, the study focused primarily on the individual use of AR-based gamification with SRL, and collaborative aspects were not explored in depth. However, collaborative learning is a vital component of science education, where group inquiry and peer interaction can significantly enhance learning experiences. Future research could expand on this by integrating collaborative learning opportunities within AR-based environments to examine how peer interactions, combined with SRL strategies, might influence both engagement and academic achievement. Studying collaborative dynamics in gamified AR settings could provide insights into optimizing these environments for both individual and group learning outcomes.

## 6 Conclusions

This study investigated the effects of integrating SRL strategies into AR-based gamification on middle school students' science education outcomes. The findings revealed significant improvements in academic achievement, engagement, self-efficacy, and satisfaction for students exposed to the self-regulated AR-based gamification compared to those using a traditional AR-based approach without explicit self-regulation components. These results demonstrate the powerful potential of integrating SRL into AR-enhanced environments to foster both effective and autonomous learning. The study highlights that combining AR-based gamification with SRL strategies provides students with a structured yet engaging framework, enhancing their ability to set goals, monitor progress, and reflect on outcomes, which directly improves academic performance. Moreover, the addition of SRL elements led to increased cognitive, emotional, behavioral, and social engagement, making learning more interactive and enjoyable. The findings also suggest that this approach bolstered self-efficacy, allowing students to build greater confidence in their abilities to succeed in science, which is crucial for their future academic pursuits. Higher student satisfaction was also observed, indicating that self-regulated AR-based gamification not only supports learning but also makes the educational experience more rewarding and motivating. Overall, this study provides strong evidence that integrating self-regulation strategies with AR-based gamified learning can significantly enhance educational outcomes, supporting the design of technology-enhanced, student-centered science learning environments that promote deeper understanding, self-motivation, and engagement.

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**Data availability** The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

**Ethics approval and consent to participate** This study was approved by a governmental ınstitution in Turkey. All participants provided informed consent before participation.

**Consent for publication** Consent for publication was obtained from all participants involved in the study.

**Competing interests** The authors declare that they have no competing interests.



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