Kashihara, A. et al. (Eds.) (2024). Proceedings of the 32nd International Conference on Computers in Education. Asia-Pacific Society for Computers in Education

Exploring the Effect of Marker-Based AR Gamification on Primary Students' Science Concepts and Motivation

Pawat CHAIPIDECH[ac*], Sasivimol PREMTHAISONG[b], Phattaraporn PONDEE[a], & Niwat SRISAWASDI[ac]
[a]*Faculty of Education, Khon Kaen University, Thailand*
[b]*Demonstration School International Division, Khon Kaen University, Thailand*
[c]*Digital Education and Learning Engineering Association,Thailand*
*pawach@kku.ac.th

Abstract: The integration of advanced technologies in education, such as Augmented Reality (AR) and gamification, has been recognized significant attention for its potential to improve student learning outcomes. However, there remains a gap in understanding how these technologies, particularly when combined, affect younger learners in primary education. This study addresses this gap by investigating the impact of Marker-Based Augmented Reality (MBAR) gamification on primary students' understanding of scientific concepts and their motivation to learn science. Conducted with 46 students aged 9-10 from a school in Northeastern Thailand, the study employed a pre-test post-test design to assess the effects of the MBAR intervention, which focused on teaching phase changes in matter through interactive and gamified activities. The results revealed a significant improvement in students' conceptual understanding. Additionally, the intervention revealed that intrinsic motivation, extrinsic motivation, and self-efficacy, demonstrating the effectiveness of gamified AR in enhancing both cognitive and motivational outcomes. These findings suggested that MBAR gamification can make abstract scientific concepts more accessible and learning experiences more engaging for young students.

Keywords: Game-based learning, augmented reality, elementary school, science education

1. Introduction

In recent years, there has been a growing interest in integrating advanced technologies into educational settings to enhance student learning outcomes. Among these technologies, Augmented Reality (AR) and gamification have emerged as particularly promising tools. AR provides students with interactive experiences that make abstract subjects more concrete and easier to understand (Radu, 2014). It has proven especially effective in science education, where visualizing complex phenomena can be challenging. Studies have shown that AR can enhance students' understanding of scientific concepts by offering interactive 3D models and simulations that bring these concepts to life (Ibáñez & Delgado-Kloos, 2018). For example, Lin et al. (2022) demonstrated that AR improves students' comprehension of difficult physics concepts by enabling interaction with digital simulations of real-world phenomena. Similarly, gamification has been recognized for creating a more engaging and participatory learning environment, which is crucial for maintaining student interest in traditionally challenging subjects (Sailer et al., 2017; Subhash & Cudney, 2018). Gamification, involving the integration of game design elements into educational contexts, significantly enhances student engagement and motivation through challenges, competition, and rewards (Deterding et al., 2011; Hamari et al., 2014).

Despite numerous studies advocating for the use of AR and gamification in education, there remains a notable gap in research addressing their combined impact, particularly in primary education. The existing literature focuses on secondary and higher education settings, often overlooking how these technologies can influence younger learners, who are at a critical stage in developing foundational knowledge and skills. Studies in higher education have shown that while AR can enhance students’ motivation and engagement, the addition of gamification does not always lead to further improvements in learning outcomes (Ivarson et al., 2024). Understanding the combined impact of AR and gamification on primary students is essential, as early positive experiences in science education can significantly shape students' long-term attitudes and success in STEM fields.

In the context of STEM education, AR and gamification align well with the broader goals of fostering critical thinking, problem-solving, and technological literacy. AR has been shown to make abstract scientific concepts more concrete by enabling real-time interaction with virtual models, which promotes deeper understanding (Çelik & Ersanlı, 2023). Gamification, meanwhile, enhances motivation by incorporating elements such as challenges and rewards, which keep students engaged (Faraon et al., 2020). Together, AR and gamification provide an immersive and interactive environment that supports inquiry-based learning, allowing students to actively participate in the learning process while developing skills crucial to success in STEM disciplines. This study seeks to address the gap by exploring how AR and gamification can be effectively applied to primary science classrooms.

The combination of AR and gamification holds significant potential as a powerful educational tool. These technologies can address key challenges in teaching complex scientific concepts to young learners by making the learning process both effective and enjoyable. However, further research is needed to fully understand how this combination affects students' cognitive and motivational outcomes. To this end, the current study is guided by two key research questions: (1) What is the effect of Marker-Based Augmented Reality Gamification on primary students' understanding of scientific concepts? (2) What is the effect of Marker-Based Augmented Reality Gamification on primary students' motivation toward learning science? These questions aim to explore the educational benefits of combining AR and gamification in primary science education, with a focus on both cognitive and motivational outcomes.

2. Literature Review

2.1 Augmented Reality in Education

Augmented Reality (AR) has gained significant attention in educational contexts due to its potential to create immersive and interactive learning experiences. AR technology overlays digital information onto the real world, enhancing students' ability to visualize complex concepts and engage with content in a more meaningful way. Marker-based AR, in particular, uses physical markers to trigger the display of digital information, making it accessible and practical for classroom settings. Studies have demonstrated that AR can significantly enhance students' learning outcomes across various educational levels. For instance, Lin et. al. (2022) found that the AR learning model is effective in supporting and enhancing scientific inquiry and higher-order thinking in educational contexts. Similarly, research by Abbasi et al. (2017) revealed that AR applications in classrooms increased student interaction and satisfaction, making learning more engaging and effective. Marker-based AR, specifically, has been shown to significantly improve primary students' understanding of complex scientific concepts by providing visual and interactive experiences that traditional teaching methods may lack (Rani et al., 2024).

However, integrating AR into education is not without challenges. The cost of technology, the need for teacher training, and the potential for cognitive overload among students are significant considerations that educators must address. Despite these challenges, the growing body of evidence suggests that AR, particularly marker-based AR, holds considerable promise for enhancing educational outcomes in primary education.

2.2 Gamification in Education

Gamification, defined as the use of game design elements in non-game contexts, has been increasingly adopted in educational settings to enhance student motivation and engagement. By incorporating elements such as points, badges, and leaderboards, gamification aims to make learning activities more engaging and rewarding, thereby motivating students to participate more actively. Research in educational technology has consistently highlighted the positive impact of gamification on student motivation and learning outcomes. A meta-analysis by Li et al. (2023) reported that gamification significantly improves student engagement and learning performance across various educational contexts. In the context of STEM education, Ortiz-Rojas et al. (2019) found that gamification, through the use of leaderboards and competition, enhanced student motivation and led to better academic performance in engineering courses. Gamification not only promotes active learning but also fosters a sense of achievement and progress, which are crucial for maintaining student interest in subjects like science.

Despite its benefits, the application of gamification in education must be carefully designed to avoid potential drawbacks, such as over-reliance on extrinsic rewards, which may diminish intrinsic motivation over time (Funa et al., 2021). Additionally, the effectiveness of gamification can vary depending on the design of the game elements and the specific educational context in which they are applied.

2.3 The Integration of AR and Gamification in Science Education

The combination of AR and gamification represents a promising approach to enhancing science education, particularly at the primary school level. By merging the interactive, immersive capabilities of AR with the motivational benefits of gamification, educators can create learning environments that are both engaging and effective in promoting deep conceptual understanding. Weng et al. (2024) investigated the effects of a gamified AR approach on vocational high school students' learning outcomes and motivation in an electronics course. The study found that the integration of AR with gamification not only improved students' understanding of complex scientific concepts but also increased their intrinsic motivation to engage with the material. This suggests that the combined approach is particularly effective in contexts where visual and interactive elements can aid in the comprehension of abstract concepts.

Additionally, research by Pedaste et al. (2020) proposed a framework for contemporary inquiry-based AR learning, emphasizing the potential of AR to support inquiry-based learning environments that foster higher-order thinking and scientific inquiry. The study highlighted the effectiveness of AR in creating immersive learning experiences that encourage students to explore scientific concepts actively and collaboratively, further enhanced by the motivational aspects of gamification. The integration of AR and gamification in primary science education offers a novel approach to addressing the challenges associated with traditional teaching methods. By providing students with engaging, interactive, and personalized learning experiences, this combined approach has the potential to significantly improve both conceptual understanding and motivation.

3. Methods

This study utilized a pre-experimental pre-test post-test design to assess the effect of marker-based Augmented Reality (AR) on primary students' understanding of phase changes in matter and their motivation to learn. The pre-test post-test design was selected to provide a comparative analysis of students' conceptual understanding and motivation before and after the intervention as showed in figure 1, thereby measuring the efficacy of the AR-based instructional approach.

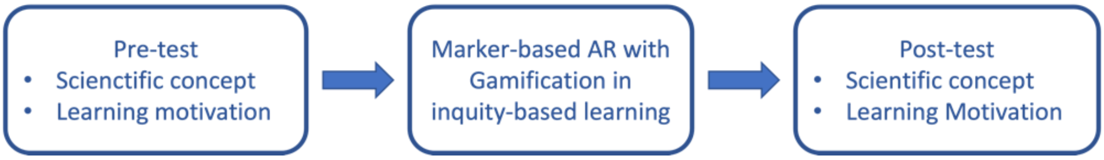

Figure 1. The research design of this study

3.1 Participants

The study was conducted with 46 primary school students, consisting of 29 males and 17 females, aged 9 to 10 years, from a school in the Northeastern region of Thailand. All participants had prior experience with mobile learning in science, which ensured their familiarity with digital learning tools—an important prerequisite for the effective implementation of the AR intervention. The selection of this age group was intentional, as it focused on students at a developmental stage where foundational scientific concepts are typically introduced, and where motivation plays a crucial role in academic success.

3.2 Research Instruments

To evaluate the outcomes of the intervention, two research instruments were employed including, a conceptual understanding test and a learning motivation questionnaire. The conceptual understanding test, consisting of 10 items, was designed to assess students' knowledge of phase changes in matter, covering key concepts such as states of matter, and the processes of melting, freezing, condensation, and evaporation. In addition, the learning motivation questionnaire was adapted from the framework developed by Pintrich et al. (1991) and was customized to measure students' intrinsic motivation, extrinsic motivation, and self-efficacy in learning and performance. The questionnaire included 16 items, distributed across three dimensions: intrinsic motivation (4 items), extrinsic motivation (4 items), and self-efficacy for learning and performance (8 items). Each item was rated on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Sample items included statements such as, "In a class like this, I prefer course material that arouses my curiosity, even if it is difficult to learn" for intrinsic motivation, "Getting a good grade in this class is the most satisfying thing" for extrinsic motivation, and "I'm confident I can do an excellent job on the assignments and tests in this course" for self-efficacy. The original Cronbach's alpha for the questionnaire was 0.79, indicating a high level of internal consistency.

3.3 Materials

The Augmented Reality along with a set of two paper blocks was recommended to be a suitable mobile AR device in science classroom (Yang, Mei, & Yue, 2018). In this study, an Augmented Reality (AR) application was developed and utilized to facilitate the teaching of phase changes in matter to primary students. The AR system was designed to work in conjunction with physical markers placed on two paper blocks, which students could manipulate to explore different scientific concepts related to phase changes. The AR application was accessed through mobile devices, such as tablets or smartphones, allowing students to scan the physical markers using the device's camera. The application was designed to recognize these markers and generate a corresponding 3D visualization on the device's screen, creating an interactive learning experience as showed in figure 2.

The two paper blocks served as the primary interactive components in the AR experience. Each face of these blocks contained a unique marker that represented different factors related to the phase changes of matter. For instance, the markers symbolized the three states of matter—solid, liquid, and gas—as well as the processes of adding or removing heat energy, which are critical to understanding phase transitions. When students attached the two blocks together, aligning specific markers, the AR application would trigger a visual representation of the corresponding phase change on the device's screen. For example, if students aligned markers representing a solid state and the addition of heat, the AR would display the process of melting, showing the transition from solid to liquid. The visualizations were accompanied by relevant data, such as temperature changes, to further enhance the educational experience.

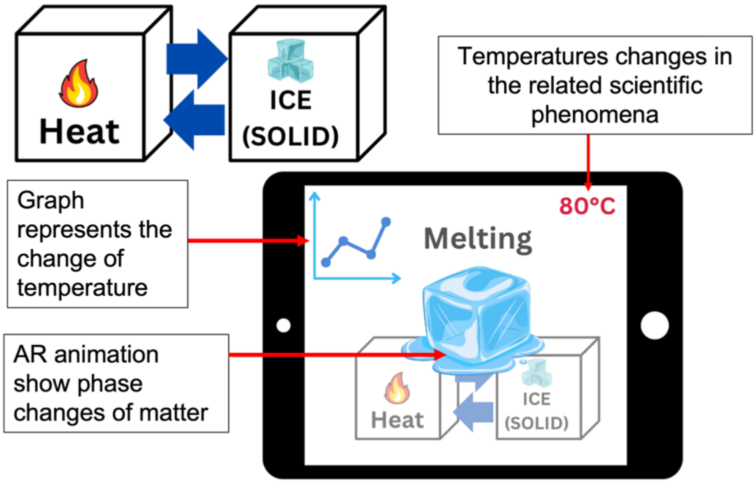

Figure 2. The example illustration of blocks of phases changing in AR

3.4 Data Collection and Analysis

The data collection was designed to evaluate both the cognitive and motivational effects of the instructional approach, which integrated inquiry-based learning (IBL) with gamification and marker-based augmented reality (MBAR). The study included 46 fourth-grade students, and employed a pre-test and post-test design to measure learning outcomes and shifts in motivation. Initially, a 15-minute science concept test focusing on the phase changes of matter was administered to assess the students' baseline understanding of concepts such as melting, freezing, evaporation, and condensation. Following this, a 15-minute motivation questionnaire was conducted to measure the students' initial learning motivation in the subject.

The instructional phase (250 minutes), comprised a series of lessons structured within the IBL framework, emphasizing active learning and student engagement. These lessons incorporated gamification elements, such as group challenges, dice-rolling games, and AR interactions in order to enhance the students' exploration of phase changes in matter, as illustrated in Figure 3. Through marker-based AR technology, the students could visualize and interact with 3D models representing different phase changes. These activities were seamlessly integrated into the gamified learning process, where students worked in groups to complete tasks, collect phase change cards, and record their findings on worksheets. The instructional sessions were conducted over multiple periods, with each session building on the previous one, aiming to deepen the students' understanding of the relationship between temperature and changes in the state of matter, as well as the application of these concepts to real-life scenarios.

At the conclusion of the instructional period, the same science concept test on phase changes of matter was administered as a post-test, allowing for a direct comparison of the students' knowledge before and after the intervention. Additionally, the motivation questionnaire was re-administered to detect any changes in the students' motivation towards learning science. For data analysis, this study utilized the paired t-test to evaluate the effect of this intervention on the participants' scientific conceptual understanding. Moreover, to measure the effect on their learning motivation, the repeated-measure MANOVA analysis technique was used via IBM SPSS version 28.

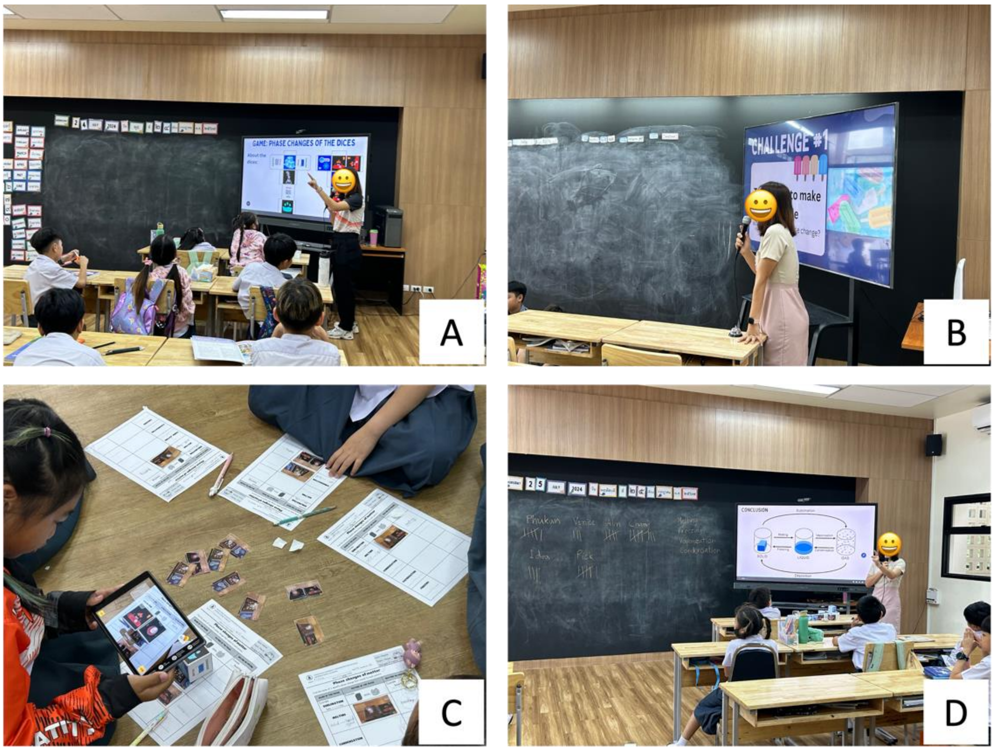

Figure 3. The Marker-based AR (MBAR) learning activities: A) the introduction to the lesson, B) the challenge in gamification, C) the MBAR participation, D) the conclusion of the lesson.

4. Results

4.1 Science Concept on Phase Changes of Matter

According to the first research question, the results presented in Table 1 illustrate the outcomes of the t-test analysis conducted to evaluate the impact of the instructional intervention on students' understanding of phase changes in matter. The analysis compared the mean scores of 46 students on a science concept test administered both before and after the intervention.

Table 1. *Results of The Science Concept on Phase Changes of Matter by Using t-test Statistical Analysis*

	N	Pre-test		Post-test		t-score	p-value
		Mean	S.D.	Mean	S.D.		
Science concept	46	4.46	1.63	6.39	1.61	-6.441	.001**

Note: **p < 0.01

The results from the t-test analysis indicate a statistically significant improvement in students' understanding of the science concept on phase changes of matter (t = -6.441, $p<.001$). As shown in Table 1, the mean score for the science concept increased from 4.46 (SD = 1.63) in the pre-test to 6.39 (SD = 1.61) in the post-test. These findings suggested that the instructional intervention was effective in enhancing students' conceptual understanding of phase changes of matter.

In summary, the result indicated that the educational intervention was effective in enhancing students' understanding of key science concepts, as evidenced by the statistically significant improvement in their test scores.

4.2 The Learning Motivation

To answer the second research question, the results of the repeated-measure MANOVA analysis was presented in Table 2. it provided insights into the effects of the instructional intervention on students' learning motivation, specifically examining changes in intrinsic motivation, extrinsic motivation, and self-efficacy in learning and performance.

Table 2. *Results of The Learning Motivation by Using Repeated-measure MANOVA Statistical Analysis*

Scale	Pre-questionnaire (N = 46)		Post-questionnaire (N=46)		F-score	η^2	p-value
	Mean	S.D.	Mean	S.D.			
Intrinsic Motivation	13.63	3.73	14.85	2.72	6.367	0.124	.015*
Extrinsic Motivation	14.54	2.61	15.72	2.70	9.427	0.173	.004*
Self-efficacy in Learning and Performance	26.11	6.36	29.48	5.08	17.222	0.277	.000*

Note: $^*p < 0.05$

The results of the analysis showed a significant increase in students' intrinsic motivation after the intervention (F = 6.367, *p*< .05). The mean score for intrinsic motivation improved from 13.63 (SD = 3.73) in the pre-questionnaire to 14.85 (SD = 2.72) in the post-questionnaire. Additionally, the partial eta squared ($\eta^2 = 0.124$) suggests a moderate effect size, demonstrating that the intervention positively impacted students' intrinsic motivation.

Similarly, the analysis revealed a significant enhancement in extrinsic motivation (F = 9.427, *p*< .05). The mean score for extrinsic motivation increased from 14.54 (SD = 2.61) in the pre-questionnaire to 15.72 (SD = 2.70) in the post-questionnaire. The effect size (η^2 = 0.173) is moderate, indicating that the instructional approach effectively fostered students' extrinsic motivation. Furthermore, the most considerable improvement was observed in students' self-efficacy in learning and performance (F = 17.222, *p*< .05). The mean score increased from 26.11 (SD = 6.36) in the pre-questionnaire to 29.48 (SD = 5.08) in the post-questionnaire. The partial eta squared ($\eta^2 = 0.277$) indicates a large effect size, highlighting the significant impact of the intervention in enhancing students' confidence and perceived competence in their learning abilities.

In summary, the findings from the MANOVA analysis indicate that the instructional intervention had a significant and positive impact on all three dimensions of learning motivation: intrinsic motivation, extrinsic motivation, and self-efficacy. These results suggested that the integration of inquiry-based learning, gamification, and augmented reality not only improved students' scientific conceptual understanding with the subject matter but also enhanced their overall motivation and confidence in their academic performance.

5. Discussion and Conclusion

This study presented the insights into the effects of Marker-Based Augmented Reality (MBAR) combined with gamification on primary students' understanding of scientific concepts and their motivation toward learning science. The remarkable improvement in students' post-test scores revealed that the integration of the intervention was effective in enhancing primary learners' comprehension of scientific concepts, such as phase changes in matter. These findings are consistent with prior studies by Wang (2022) and Rani et al. (2024), which demonstrated that AR could facilitated the understanding of abstract concepts by making them more interactive and immersive.

The observed increase in both intrinsic and extrinsic motivation further underscores the motivational benefits of a gamified learning environment. The integration of challenges, rewards, and competition within the MBAR technology illustrated to have successfully engaged students, fostering a more positive attitude toward science learning. This is supported by the findings of Li et al. (2023) and Ortiz-Rojas et al. (2019), who emphasized the role of gamification in enhancing student motivation and engagement. Moreover, the significant rise in students' self-efficacy, reflected in their increased confidence in learning and performance. This suggested that the combination of AR and gamification not only aids in knowledge acquisition but also reinforces students' belief in their academic abilities. These outcomes align with Weng et al. (2024), who highlighted the effectiveness of this approach in creating a more engaged and confident learning environment. Despite the absence of a control group, the results show significant gains in both student engagement and learning outcomes. This suggests that the AR with gamification approach is effective in promoting science learning, even without the comparison of a traditional teaching. Moreover, the inclusion of a control group in future studies will allow for a more comprehensive validation of these findings and further highlight the approach effectiveness in diverse educational contexts.

In conclusion, this study demonstrates the effectiveness of integrating Marker-Based Augmented Reality with gamification in primary science education. The significant improvements in students' understanding and motivation highlighted the potential of these technologies to enhance educational outcomes. Educators are encouraged to consider adopting AR and gamification in their teaching practices to create more engaging and effective learning experiences. Continued research in this area is essential to fully understand the broader implications of these technologies and optimize their application in educational settings.

6. Limitation

This study provides valuable insights into the effectiveness of Marker-Based Augmented Reality (MBAR) combined with gamification in enhancing primary students' understanding of scientific concepts and motivation. However, several limitations must be acknowledged. Firstly, the study’s small sample size of 46 students from a single school in Northeastern Thailand may limit the generalizability of the findings. The participants' specific cultural, socio-economic, and educational backgrounds could introduce biases that may not reflect other regions or contexts. Additionally, the students' prior familiarity with mobile learning may have contributed to the positive outcomes, further limiting the applicability of the results to broader populations. Secondly, the pre-experimental pre-test post-test design did not include a control group, which limits the ability to attribute the observed improvements solely to the MBAR intervention. While the study did not include a control group, the statistically significant improvements observed in both students' conceptual understanding and motivation suggest that the intervention had a meaningful impact. Although a control group would provide additional rigor, the findings indicate that the AR and gamified elements contributed to improved learning outcomes, which can be further validated through future studies. Furthermore, the study focused on short-term cognitive and motivational outcomes, measured immediately after the intervention. Long-term retention of knowledge and sustained motivation were not assessed, leaving open questions about the persistence of the intervention's benefits over time.

Future research should involve larger, more diverse samples, include control groups, and incorporate follow-up assessments to examine long-term effects. Additionally, exploring the applicability of MBAR in other subjects and educational settings will be essential for understanding the full potential and scalability of this technology.

Acknowledgements

The authors would like to express sincere thanks to science teachers and primary school students in the school for their kind participations in this study. In addition, ethical approval was obtained from the Human Research Ethics Committee of Khon Kaen University (Ref. HE673390). This project is funded by National Research Council of Thailand (NRCT).

References

Abbasi, F., Waseem, A., & Ashraf, E. (2017). Augmented reality-based teaching in classrooms. *In Proceedings of 2017 International Conference on Communication, Computing and Digital Systems, C-CODE 2017* (pp. 259-264). IEEE. https://doi.org/10.1109/C-CODE.2017.7918939

Cai, S., Niu, X., Wen, Y., & Li, J. (2021). Interaction analysis of teachers and students in inquiry class learning based on augmented reality by iFIAS and LSA. *Interactive Learning Environments, 31*(9), 5551–5567. https://doi.org/10.1080/10494820.2021.2012808

Çelik, F., & Ersanlı, C. Y. (2022). The use of augmented reality in a gamified CLIL lesson and students' achievements and attitudes: a quasi-experimental study. *Smart Learning Environments, 9*(1). https://doi.org/10.1186/s40561-022-00211-z

Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). From game design elements to gamefulness: Defining "gamification". *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*.

Faraon, M., Rönkkö, K., Wiberg, M., & Ramberg, R. (2019). Learning by coding: A sociocultural approach to teaching web development in higher education. *Education and Information Technologies, 25*(3), 1759–1783. https://doi.org/10.1007/s10639-019-10037-x

Funa, A., Gabay, R., & Ricafort, J. (2021). Gamification in Genetics: Effects of Gamified Instructional Materials on the STEM Students' Intrinsic Motivation. *Jurnal Pendidikan IPA Indonesia, 10*(4), 462-473. https://doi.org/10.15294/jpii.v10i4.32143

Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does gamification work? -- A literature review of empirical studies on gamification. *In Proceedings of the 47th Hawaii International Conference on System Sciences* (pp. 3025-3034). IEEE. https://doi.org/10.1109/HICSS.2014.377

Huang, B., & Hew, K. F. (2022). Using gamification to enhance intrinsic motivation, facilitate classroom engagement, and improve academic performance: A systematic review. *Journal of Educational Technology & Society, 25*(1), 114-128.

Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education, 123*, 109-123. https://doi.org/10.1016/j.compedu.2018.05.002

Ivarson, E., Erlandsson, V., Faraon, M., & Khatib, S. (2024). Augmented reality and gamification in higher education: Designing mobile interaction to enhance students' motivation and learning. *E-Learning and Digital Media*. https://doi.org/10.1177/20427530241239981

Li, M., Ma, S., & Shi, Y. (2023). Examining the effectiveness of gamification as a tool promoting teaching and learning in educational settings: A meta-analysis. *Frontiers in Psychology, 14*, 1253549. https://doi.org/10.3389/fpsyg.2023.1253549

Lin, X. F., Hwang, G. J., Wang, J., Zhou, Y., Li, W., Liu, J., & Liang, Z. M. (2022). Effects of a contextualised reflective mechanism-based augmented reality learning model on students' scientific inquiry learning performances, behavioral patterns, and higher order thinking. *Interactive Learning Environments, 31*(10), 6931–6951. https://doi.org/10.1080/10494820.2022.2057546

Ortiz-Rojas, M., Chiluiza, K., & Valcke, M. (2019). Gamification through leaderboards: An empirical study in engineering education. *Computer Applications in Engineering Education, 27*(4), 777-788. https://doi.org/10.1002/cae.12116

Pedaste, M., Mitt, G., & Jürivete, T. (2020). What is the effect of using mobile augmented reality in K12 inquiry-based learning? *Education Sciences, 10*(4), 94. https://doi.org/10.3390/educsci10040094

Pintrich, P. R. (1991). A manual for the use of the motivated strategies for learning questionnaire (MSLQ).

Radu, I. (2014). Augmented reality in education: A meta-review and cross-media analysis. *Personal and Ubiquitous Computing, 18*(6), 1533-1543. https://doi.org/10.1007/s00779-013-0747-y

Rani, S., Mazumdar, S., & Gupta, M. (2024). Marker-based augmented reality application in education domain. *In N. Chauhan, D. Yadav, G. K. Verma, B. Soni, & J. M. Lara (Eds.), Machine learning, image processing, network security and data sciences: MIND 2023 (Communications in Computer and Information Science, Vol. 2128)*. Springer, Cham. https://doi.org/10.1007/978-3-031-62217-5_9

Sailer, M., Hense, J., Mayr, S. K., & Mandl, H. (2017). How gamification motivates: An experimental study of the effects of specific game design elements on psychological need satisfaction. *Computers in Human Behavior, 69*, 371-380. https://doi.org/10.1016/j.chb.2016.12.033

Subhash, S., & Cudney, E. A. (2018). Gamified learning in higher education: A systematic review of the literature. *Computers in Human Behavior, 87*, 192-206. https://doi.org/10.1016/j.chb.2018.05.028

Weng, C., Tran, K. N. P., Yang, C. C., Huang, H-I., Chen, H. (2024). Can an augmented reality-integrated gamification approach enhance vocational high school students' learning outcomes and motivation in an electronics course? *Education and Information Technologies, 29*, 4025–4053. https://doi.org/10.1007/s10639-023-11966-4

Wu, H. K., Lee, S. W. Y., Chang, H. Y., & Liang, J. C. (2013). Current status, opportunities, and challenges of augmented reality in education. *Computers & Education, 62*, 41-49. https://doi.org/10.1016/j.compedu.2012.10.024

Yang, S., Mei, B., & Yue, X. (2018). Mobile augmented reality assisted chemical education: Insights from elements 4D. *Journal of Chemical Education, 95*, 1060–1062. https://doi.org/10.1021/acs.jchemed.8b00017